UNIVERSITY OF SOUTHAMPTON

Faculty of Science
Department of Geography

The effects of mechanised forest harvesting on soil physical properties

by Matthew J. Wood

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Abstract

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The effects of mechanised forest harvesting on soil physical properties in the UK employing the shortwood system of extraction have, until now, remained largely unknown. In addition, whilst the use of designated extraction routes armoured with logging residues (brash mats) has the potential to reduce soil disturbance, the efficacy of this and other preventative measures, was uncertain. Throughout 1998 and 1999, field trials were undertaken at upland mechanised forest harvesting sites in north-east England and south-west Scotland to (a); investigate the degree and nature of disturbance on selected forest soils and (b), examine the efficacy of ground protection measures. Soil density and soil strength (soil penetration resistance) measured directly beneath the machine wheel tracks on gleyed mineral and deep peat soils (considered previously to be at risk of severe disturbance) exhibited only minor changes despite high levels of trafficking. This was ascribed to (a); the protective effect of the brash mats (b), the slow rates of densification associated with saturated fine textured mineral soils (in a confined state) and (c), the inherent strength and elastic recovery of overlying fibrous peat soils (retained *in situ* as a result of the brash mats). A marked, though statistically insignificant, reduction in the saturated hydraulic conductivity of the mineral soils directly beneath the machine wheel tracks was measured, with implications for the hydrological regime of the organic soil layers (considered to represent the tree rooting zone). The lateral distribution of soil impacts, (trafficked soil penetration resistance), measured both between and adjacent to the machine wheel tracks, suggested that as much as 50% of the site area (based on the total area of brashed extraction routes) may be subject to some degree of soil disturbance. The implications for site productivity of all measured changes in soil structural properties were discussed in relation to previously reported soil thresholds known to limit root and tree growth. In recognition of the increasing mechanisation of forest harvesting operations, quantitative guidelines were developed for use at an operational level. These included; (a) a provisional pre-harvest soil sensitivity analyses based on observations made during this study in combination with fundamental soil mechanical theory and (b), a means of maximising the efficacy of brash mats based on forest character, ground conditions and machine specification. The need for further research into the effects of machine harvesting on long term site productivity, and role of restock cultivation in ameliorating soil disturbance on a wider range of soils, is emphasised.

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*all data - EXCEL 2000

Glossary.

References.

Symbols and abbreviations used.

μm	Micrometer
π	PI
α	Parameter of $f(t)$
β	Parameter of $f(t)$
γ	Parameter of $f(t)$
γ_w	Density of water
A	Area (of felling coupe); upper portion of mineral soil horizon
A-E	Layer combining upper (A) and lower (E) mineral soil horizons.
A	Shape factor
B	Drain blocked
B_{width}	Width of the brash mat
D	Drain walls damaged
D_{width}	Drift width
d	Depth of water at equilibrium
E	Soil transport (by flowing water) along wheel ruts
EX_{tot}	Areal extent of brash mats for a given coupe
F	Water flowing along wheel ruts
F_{area}	Footprint area (of wheel)
$f(t)$	An inflation factor used in the calculation of V_{total}
g	Correction factor (for proportion of saleable stem lost during conversion) used in the calculation (where $g = 0.06$)
K	Hydraulic conductivity
K_s	Saturated hydraulic conductivity
kPa	Kilopascal
L	Log damage
ln	Natural logarithm
MPa	Megapascal
O	Organic soil horizon
O-A	Transitional layer between lower organic (O) and upper mineral (A) soil horizons
O_{weight}	Unladen operational machine weight

P	Ponding of water along wheel tracks
p	Mean static ground pressure
R	Repeated trafficking (off brash mat)
r	Correction factor (for root volume) used in the calculation of V_{branch} (where r = 0.85); radius
s	Depth of soil to an impermeable or infinitely permeable layer
sc	The extent of consolidation settlement
T	Turning (off) brash mats
T_{load}	Timber load
t	Age (years); time
t_{min}	Parameter of $f(t)$
t_0	Start time
t_1	Finish time
y_0	Initial water depth (in piezometer)
y_1	Final water depth (in piezometer)
W	Water logged areas
W_{load}	Wheel load
W_{max}	Maximum applied wheel load
W_{rb}	Number of wheels on rear bogie of vehicle
W_{tot}	Number of wheels on vehicle
w	Length of cavity at the base of a lined bore hole
V_{branch}	Volume of branch wood
V_{brash}	Total volume of non-marketable material
$V_{brashmat}$	Denotes 'effective ground protection' - volume of brash mat where non-effective components (V_{loptop}) have been omitted.
V_{comp}	Volume of branch wood for an entire coupe (of uniform character).
V_{loptop}	Volume of saleable timber lost during conversion
V_{stem}	Volume of saleable timber
V_{total}	Total tree volume

Chapter 1 - Introduction.

This chapter introduces the concept of sustainability in forest management, the importance of forest soils and potential impacts on these soils of mechanised forest operations. The objectives of this study are presented, and a review of current literature details key components in the chain of events leading to adverse soil impacts during mechanised forest harvesting. Emphasis is placed upon UK silvicultural practice, though experience from overseas is considered where appropriate. A glossary of silvicultural and soil science terminology is appended.

1.1. Introduction.

Much is known regarding the impacts of timber production on soil and surface water environments. However, additional demands placed upon forests such as recreation, wildlife habitat and watershed protection, are growing. In response, forest management must fully understand the soil environment to protect this resource (e.g., Pritchett and Fisher, 1987; Moffat, 1991; Furuberg-Gjedtjernet, 1995). As a medium for tree growth and that of associated plants and other organisms, soils also offer habitat to a variety of vertebrates and invertebrates, facilitate the cycling of nutrients and organic matter, regulate the hydrology and chemistry of adjacent watercourses and provide a sink for atmospheric deposition (Worrell and Hampson, 1997).

Despite the trend towards smaller less damaging machinery throughout Europe (Wästerlund, 1989) and the USA (Korane, 1997), there remains concern regarding impacts on the soil physical environment resulting from forest traffic, which, over a single rotation, may cover 30% of the site (Wästerlund, 1992). A great deal has been achieved in understanding the impacts of machinery on lowland arable soils, though literature regarding soil compressibility remains limited (Bradford and Gupta, 1986). Many of these agricultural studies are relevant to forest soils (Greacen and Sands, 1980), though it has been argued (Wästerlund, 1994) that the associated homogeneity of the former precludes any direct application in many cases to forest soils of greater spatial complexity.

In the UK, poorly managed harvesting operations present the greatest risk to the physical condition of the soil (Forestry Commission, 1998) and may result in soil compaction, erosion, and with time, loss of productivity. The extent of soil disturbance is a function of site topography, antecedent soil structural and hydrological conditions, machine specification, the intensity of traffic over a given area, and the effectiveness of controls aimed at minimising impacts. Despite published information from overseas, Hornung *et al.* (1986) noted that few published data existed in the UK regarding such impacts. In addition, while the use of designated extraction routes armoured with logging residues (brash mats) has the potential to reduce soil disturbance, the efficacy of such preventative measures remains untested (Wall and Saunders, 1997). As a result, current guidelines aimed at reducing disturbance to the soil environment in the UK (e.g., Forestry Commission, 1998; Forestry Commission, 2000) remain largely qualitative.

Given the current trend towards expansion of the UK forestry industry, and thus the soil area potentially at risk, a quantitative approach to minimising soil disturbance based upon sound theory and empirical data would allow the development of more informed production guidelines (thus maximising the social, economic and environmental benefits of forestry activities). The design of future harvesting systems and associated machinery could then be based upon known limits of soil trafficability particularly where impacts to long-term productivity are of concern.

1.2. Study aims and objectives.

In receipt of grant aid from the Scottish Forestry Trust, collaborative research between the Forestry Commission Research Agency and Southampton University (Department of Geography) was undertaken to investigate the effects of harvesting machinery on the physical properties of forest soils. The aims of the project were:

- to establish the degree and nature of soil disturbance caused by mechanised timber harvesting on selected forest soils,
- to determine the efficacy of ground protection measures (brash mats),
- to examine the role of restock cultivation (time permitting) in ameliorating soil damage during harvesting, and
- to provide recommendations for incorporation in future Forests and Water, and Forests and Soil Conservation, Guidelines.

1.3. Literature review.

The impacts of forest machinery on the soil environment manifest themselves both at the surface, and at varying depths within the soil column. The former includes deep rutting, displacement and mixing of soil material with the potential for erosion. The latter involve less obvious though potentially more adverse changes to the soil physical and hydrological character. A generalised soil profile is presented below (Figure 1.1) to illustrate the relevant soil horizons.

Figure 1.1. Idealised profile of a forest soil (after Pyatt, 1970).

Organic (O) horizons	**L**	Leaf litter layer
	F	Fermenting layer
	H	Humus layer
Zone of eluviation (outwashing)	**A**	Mixed mineral/organic horizon - dark coloured (stained by down-washed humus)
	E	Less organic material, clay and calcium (removed by water) – and lighter colour than A horizon
Zone of illuviation (inwashing)	**B**	Brighter colour due to deposition of clay and/or humus and/or iron oxides
Weathered parent material *in situ*	**C**	Little altered mineral horizon
Bedrock (unaltered)	**R**	Hard, consolidated

In previous studies of forest soils, the process of compaction has been used to describe increases in density of an unsaturated soil whereby soil air only is expelled during loading. The rate and extent of compaction is dependent upon soil permeability, pore continuity, particle size distribution and water content, and in many instances occurs instantaneously (Hillel, 1982). This is particularly true of forest soils with a low density mineral (A) horizon (Wingate-Hill and Jakobsen, 1982). At the point of saturation when all the air has been expelled, further volume changes are governed by soil permeability and rate at which excess water drains and increased pore water pressures dissipate. This process is termed consolidation, which, given the viscosity of water (c. 50-100 times that of air) generally occurs at a much slower rate than compaction (Hillel, 1982). Following displacement of the upper (A) and lower mineral (E) horizons (a result of deep rutting), the stronger mineral (B) horizons are typically of sufficient bearing capacity to maintain vehicle mobility.

1.3.1. Harvesting systems and soil disturbance.

Subsequent to harvesting, either by hand or using purpose built harvesting machinery, the most common (and cheapest) form of mechanised extraction is the tree-length system (whole or stem-only) with extraction (dragging) by a skidder (predominant in the USA). Another method is the shortwood system (common in the UK) where cutting and sorting is undertaken on site by purpose built harvesting machinery before removal (carriage) and stacking at roadside by a forwarder (Plates 1.1 and 1.2, p. 5). The tree-length system involves a large number of machine passes and wide roads, the shortwood system requires much less in terms of roads and landing areas as machinery is confined to designated extraction routes (Wästerlund, 1994). In addition, and associated predominantly with coniferous forests, the shortwood system often produces large volumes of logging residues (mainly branch wood, but also any material from the main stem <7 cm diameter) which may be used to armour designated extraction routes (brash mats). Cable and skyline extraction is generally avoided on economic grounds except where access and terrain limit conventional operations. However, studies in New Zealand (Terlesk, 1987), where soil conditions rather

Plate 1.1. Felling, snedding and cross-cutting by a purpose-built harvester (Kielder Forest, UK). Note branch wood laid directly in front of the machine to provide ground protection (brash mat).

Plate 1.2. Extraction of sawn timber by a forwarder (Kielder Forest, UK) travelling along a brash mat. (Photograph: John Walton).

than terrain limit machine access, have shown that cable crane systems can be both economic and environmentally acceptable.

Approximate ground contact pressures for common harvesting systems (Table 1.1) were summarised by Greacen and Sands (1980). Based upon the weight of the vehicle divided by the total ground contact area, these values do not account for variations in load distribution as a function of topography or during the handling of cut timber, nor do they account for the effect of brash mats (Roger Sands, 2000; personal communication)[1]. However, in the absence of direct measurement they illustrate the range that may be expected in the context of forest studies.

Table 1.1. Approximate ground contact pressures for a range of harvesting systems (after Greacen and Sands, 1980).

Harvesting system	Ground contact pressure (kPa)
Cable and skyline logging	0*
Flexible tracked skidder	30-40*
Crawler tractor	50-60*
Rubber tyre skidder	50-90**
Forwarder	90-200

*does not account for ground disturbance caused where logs are dragged intermittently along the ground. **exerts high ground shear forces.

During harvesting operations the highest loads are generally associated with extraction machinery. Forwarders are associated with both the highest ground contact pressures and greatest range (90-200 kPa). In addition to the factors described above, load distribution may be influenced by the use of low-pressure tyres, crawler tracks or bandtracks which serve to increase the machine footprint area and reduce the load applied to the ground surface (section 1.3.3.1). However, it has been established that pressure distribution across the footprint area is seldom uniform, and for tracked machinery may be as much as three times that of the mean (e.g., Rowland, 1972; Hillel, 1982), whilst for wheeled machinery twice that of the mean (Lynse and Burditt, 1983).

---

[1] Roger Sands, School of Forestry, University of Canterbury, New Zealand.

Loads applied to the ground surface become less with depth (Soehne, 1958). However, for the first depth interval of around half the tyre width (approximately 20-30 cm for most forest machines) attenuation may be as little as 20% of the surface load and, as such, may have serious consequences for site productivity (section 1.3.2.1). For example, the upper 0-30 cm of the soil profile generally contains between 70-90% of the total root biomass, and represents by far the most important zone for nutrient supply (Kalela, 1949; Kostler *et al.,* 1968) and overall site productivity (Colin Smith, 1998; personal communication)[2]. However, on a poorly drained soil such as peat, up to 90% of root biomass may occur in the top 10 cm of the soil (Wronski and Murphy, 1994).

As a general rule the largest changes in soil structure occur during the first few machine passes (e.g., Hatchell *et al.,* 1970; Burger *et al.,* 1984). In many instances the first pass may contribute as much as 50% of measured changes compared to the next 9 or 19 trips (Furuberg-Gjedtjernet, 1995), while studies of skidder extraction by Lynse and Burditt (1983) found up to 70% compaction by the fifth trip. Based upon the experience of the Australian and New Zealand forest industry, Greacen and Sands (1980) summarised the number of machine passes associated with a range of forest operations (Table 1.2.).

Table 1.2. Forest operations and the associated number of machine passes (after Greacen and Sands, 1980).

Site	Operation	Number of machine passes
Plantation	Ploughing and ripping	1
	Planting	1
	Thinning	6-300
	Clear felling	2-300
Native forest	Selective logging	2-50
	Clear felling	2-300

During thinning or clear felling, the number of machine passes at any single point may be as many as 300. However, where forest machines are concerned, there is often too little variation in both the total machine weight and applied ground

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[2] Colin Smith, Institute for Commercial Forestry Research, University of Natal, South Africa.

pressure to allow the formulation of useful predictive models (Wästerlund, 1992). In addition to the number of machine passes, the direction of travel up- or down-slope (Froelich and McNabb, 1984) along with the incidence of specific vehicle manoeuvres rather the number of machine passes *per se* can influence the degree of ground disturbance, further complicating predictive modelling of disturbance based on traffic intensities and/or machine ground pressures. For example, Myhrman (1990) found that the depth of ruts formed during forwarding more than doubled at turning points, reflecting the increased stresses applied to the ground during turning.

Surface-soil composition and the structural characteristics of the soil column itself define the bearing capacity, or trafficability, of a specific soil in relation to the compactive effect of machine loading. Recognised strength components of the forest floor include gravel and boulders, humus, ground vegetation and root mats. Bjorkhem *et al.* (1975) suggested that the presence of a dense root network might increase the compressive strength of forest soils by up to 70%, while Mellgren (1982) suggested that soil shear strength might be increased by a similar magnitude as a result of root material. However, in a review of surface characteristics typical of podzolised forest soils in Sweden, Wästerlund (1989) stated that both the collective and individual contributions of these strength components remained largely unknown.

More commonly documented has been soil response at depth and the influence of internal soil properties (notwithstanding a high degree of variability) including particle density, mineralogy (Howard *et al.* 1981) and more notably, soil moisture, organic matter content and particle size distribution (Smith, 1996). For example, organic matter has been shown to reduce the susceptibility of clays to compaction (Greacen and Sands, 1980). Soils with water contents at or around field capacity often possess sufficient strength to resist compaction under moderate loading (Wingate-Hill and Jakobsen, 1982) though in contrast Braunack and Dexter (1978) stated that the largest structural changes generally occur around field capacity. Well graded coarse-medium textured soils of c. 10-15% clay will compact to very high densities (Wingate-Hill and Jakobsen, 1982), whilst fine textured soils are far less likely to be compacted to high densities (Froelich and

McNabb, 1984) given their large proportion of micropores (pores <50 μm) and subsequent increases in load bearing pore water pressures due to lower permeability.

A frequently used indicator of physical disturbance following forest harvesting operations is soil bulk density (Wingate-Hill and Jakobsen, 1982). However with regard to site productivity, subtle changes in soil structure and subsequent soil hydraulic character may be of greater significance (Seixas and McDonald, 1997). Soil response to compaction includes increased soil strength and reduced total porosity at the expense of larger macropores (pores >50 μm), concomitant increases in volumetric water content and field capacity, reductions in air content, water infiltration rates and hydraulic conductivity (Greacen and Sands, 1980). In addition, the authors cited associated reductions in water supply, restricted root space, poor aeration and the onset of anaerobic conditions leading to reductions in annual growth increment of up to 50% for a range of species, which lasted well into subsequent rotations.

Given the range of harvesting systems employed globally, the diversity in both investigative approach and published data (a function of the harvesting system employed, soil type and experimental methodology) is no surprise. It is unfortunate that few replicated trials allowing direct comparison of impacts under a range of conditions have been undertaken. The majority of previous studies have been carried out overseas, and have considered the impacts of skidding machinery, while the impacts of forwarding traffic and cable extraction have been considered to a much lesser extent.

1.3.1.1. The effect on soil of skidding cut timber.

The impacts of uphill skidding (slope 9-35%) with rubber tyres on wet (12-35% moisture by volume) sandy and silt loam soils in northern Mississippi were reported by Dickerson (1976). Soil cores were collected from the upper 0-5 cm two months after extraction and showed increases in dry bulk density averaging 20% (to 1.55 g cm^{-3}) for wheel rutted soils, and 10% (to 1.42 g cm^{-3}) between wheel ruts due to log dragging. Macroporosity fell 68% (to 4%) along wheel ruts, and 38% (to 9%) between wheel ruts and for log disturbed soils respectively, with an overall increase in microporosity of around 7%. Soil conditions after five years were considered such that seedling survival and tree growth would be adversely affected.

Following studies of a clay loam soil under wet conditions within the Oregon Coast Ranges (USA), increases in bulk density were found to correlate most strongly with the logarithm of the number of passes of a low ground-pressure skidder (Sidle and Drlica, 1981). Regression analysis showed increases in bulk density at 7.5 cm depth following nine passes to be in the order of c. 25% (to c. 0.61 g cm^{-3}) and c. 45% (to c. 0.71 g cm^{-3}) for downhill and uphill skidding respectively. Based on annual average moisture contents (around 45% by volume) and reported soil moisture-density relationships, the authors suggested that the site would be susceptible to significant levels of compaction throughout much of the year.

Extraction by a wheeled tractor skidder on a surface water gley in Co. Leitrim (Ireland) was studied by Boyle *et al.* (1982). Brash mats were not used, and mean bulk densities under wheel ruts of 1.36 g cm^{-3} (5-10 cm) and 1.45 g cm^{-3} (10-15 cm) were measured representing increases of 45% and 15% respectively from the undisturbed mean values of 0.93 g cm^{-3} (5-10 cm) and 1.26 g cm^{-3} (10-15 cm). Under the prevailing soil moisture, organic matter and textural conditions, and based on previous work by Bodman and Constantin (1965), these values were considered representative of maximum attainable levels. No increase in bulk density between wheel ruts was found, which may be attributed to the churning effect of the dragged timber. Measured total porosity at 0-5 cm (53%), 5-10 cm (41%) and 10-15 cm (40%) under wheel ruts (reductions of 12%, 32% and 16% respectively) were also reported, though these were considered to remain within the range common to forest soils of 30-65% (Pritchett, 1979).

Severe disturbance including reductions in organic matter, available moisture holding capacity, and available phosphorus, calcium and potassium were observed during both skidder (rubber-tyres) and skyline extraction by Miller and Sirois (1986) on loamy forest soils in south-western Mississippi, USA. Following both treatments, increases in bulk density of c. 30% (from 1.1-1.2 g cm^{-3} to 1.4-1.5 g cm^{-3}) were recorded, though under skyline extraction (uphill log dragging) increases in soil bulk density often extended deeper into the soil profile than following log skidding. It was also suggested that erosion channels resulting from wheel ruts and log dragging (an unavoidable occurrence when trafficking bare ground, and again more prominent under skyline extraction), may be slow to stabilise.

Skidding by crawler-tractor in southern Victoria (Australia) caused bulk density increases (0-6 cm depth) of 27% and 30% along major skid trails and landing areas respectively on a silty clay loam (Incerti *et al.*, 1987). Macroporosity fell between 8% and 19% after trafficking. Geometric mean values of saturated hydraulic conductivity (based on laboratory measurement of intact soil cores) fell from 1.42×10^{-2} mm s^{-1} in undisturbed soils to 8.22×10^{-6} mm s^{-1} along skid trails and 1.49×10^{-6} mm s^{-1} at log landings. Given that saturated hydraulic conductivity measured in this way can often be over-estimated (e.g., Jakobsen and Moore, 1981), the authors suggested that the perceived erosion risk as a result of increased overland flow may be greater still.

Changes to soil physical and hydrological properties at 0-10 cm depth were reported by Rab (1994), five months after skidder extraction (rubber tyres and tracked machinery) in south-eastern Australia on clay loam and silty loam soils. No direct comparison of the relative impacts of rolling gear type was made, though changes following both treatments were comparable in magnitude. Approximately 72% of the coupe area showed significant changes in all measured parameters. Maximum increases in bulk density of 64% to 1.13 g cm^{-3} occurred along secondary extraction routes. The greatest reductions in organic carbon (53% to 5%) and organic matter (42% to 14%) due to the mixing and removal of topsoil, total porosity (22% to 54%) and saturated hydraulic conductivity (98% to 3.82×10^{-4} mm s^{-1}) were recorded along primary extraction routes. Of all areas measured, 35% were subject to changes considered unsuitable for tree growth, while soil structural weaknesses largely associated with reduced organic matter content were cited as a potential source of increased erosion of mineral soil.

1.3.1.2. The effect on soil of forwarding cut timber.

Jakobsen and Greacen (1985) investigated the impact of repeated passage of a wheeled forwarder (gross weight 26 tonnes) over coarse-textured sandy soils under wet conditions. Along new routes, maximum increases in bulk density of 34% (to c. 1.72 g cm^{-3}) were reported, with smaller increases at depths deeper than 80 cm. Where old thinning tracks had been re-trafficked, smaller increases in bulk density of up to 5% (to c. 1.81 g cm^{-3}) were recorded. However, bulk densities for these areas were already larger than those measured for newly trafficked routes. Though increasing linearly with the logarithm of the number of passes, the authors suggested that disturbance thresholds critical to growth might be exceeded after only a few passes.

The effect of controlled forwarder loading (gross weight 13.6 tonnes fully laden) in Wisconsin (USA) was compared to skidder extraction during thinning operations (red oak, red maple and aspen) on the surface layers of a coarse-loam soil by Shetron *et al.,* (1988). In both cases, measured bulk densities under wheel tracks increased significantly above that of control areas by as much as 83% and 90% on low and high use routes respectively. No relationship between disturbance, machine load and number of passes was found. One year later, the study demonstrated that recovery took longer where disturbance was associated with forwarding rather than skidding, and ascribed to the loosening effect of dragging timber during the latter.

Despite a growing reliance on the harvester-forwarder combination in the UK, few studies have undertaken any detailed investigation of the associated impacts upon the soil environment. Balfour (1987) described the combined impacts of harvesting and forwarding traffic on a surface-water gley (north-east England). Soil compaction under brashed wheel tracks and deep rutting with liquefaction of surface soil in areas subject to localised brash failure were observed. In some instances, rut depth was such that mineral B horizons were exposed leaving areas subject to erosion. The resultant soil loss was estimated at 266 m^3 ha^{-1} yr^{-1} along steeper tracks. The number of machine passes correlated strongly with levels of site disturbance (percentage area disturbed and volume of soil displaced). Harrison (1992) reported the impacts of similar treatments on a brown earth (Glentress, Scotland). Volumetric disturbance of soil was reported for 10% of the felled area. Rooting depths were found to be altered as a result of soil 'rut' (7% of area disturbed) and 'displacement' (3% of area disturbed). These changes were not considered detrimental to tree growth, and based on visual observations along previously trafficked areas, soil recovery was considered exponential and complete within c. 12 years. Persistent deep ruts were cited as presenting an erosion risk, but soil permeability was considered adequate such that soil losses were unlikely (Douglas Malcolm, 1999; personal communication)[3].

1.3.1.3. Off-site impacts.

As a direct result of harvesting traffic, reductions in hydraulic conductivity and increases in overland flow may initiate soil erosion processes (e.g., Kamaruzaman and Nik Muhamed, 1987; Ole-Meiludie and Njau, 1989), particularly on soils of low bearing capacity and prone to deep rutting. Derived from 'on-site' sources (e.g., wheel ruts, skid trails) and adjacent unsealed roads and log landings, such losses may have consequences in terms of both site productivity and downstream impacts to aquatic flora and fauna. In a review of UK studies, Moffat (1988) noted that the majority of reported problems had occurred on mineral soils with shallow organic horizons. Associated in many cases with ploughing activities, the author stated that erosion approaching 'natural rates' of around 500 kg ha^{-1} yr^{-1} were not uncommon in the UK. However, in the USA where skidding of cut timber is more common, Farrish *et al.* (1993) considered soil to be most at risk during the 'fallow' period between harvesting and re-planting.

In the UK, Lewis and Neustein (1971) undertook an investigation of soil erosion following clear felling on a freely drained brown earth. They found little risk of serious erosion on slopes of up to 35° (despite high rainfall) where the brash mat remained intact. However, given the low density mineral (A) horizon inherent in many forest soils, the occurrence of deep rutting is common, especially where

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[3] Douglas Malcolm, Institute of Ecology and Resource Management, University of Edinburgh, UK

brash mats are absent or subject to localised deterioration. Following the latter, observations during field trials by the author in 1998 found obvious (though unquantified) erosion taking place on an upland peaty gley where the mineral (A and E) horizons had been exposed. Similar phenomena have been reported by Spencer (1991), where the areal extent of deep ruts, contributing to channelled water and sediment, was observed to be about 70% at one site. In an unpublished note to the UK Forestry Commission, Armstrong (1994) observed a number of incidents where damage to drain walls and subsequent sediment input had occurred following careless machine operations. While it must be stressed that such instances are isolated, for the UK in general the overall extent and contribution of individual sources to erosion remain poorly quantified (Carling *et al.,* 2001).

1.3.2. Soil recovery.

The persistence of machine induced changes in soil structure depends largely on both soil type and the level of disturbance, and in some cases the effects have been shown to remain for several decades. For a range of soil types, Hatchell *et al.* (1970) and Dickerson (1976) suggested that 12-18 years were required for sufficient recovery to pre-disturbance levels. However, Greacen and Sands (1980) found sandy soils under Radiata pine remained significantly compacted after 50 years, while the effects of compaction along pioneer timber extraction routes were evident 100 years after their use (Munns, 1947). In addition, the rate of recovery varies with depth, and a return to approximate pre-treatment conditions will often take much longer in the lower horizons (e.g., Froelich, 1979; Froelich and McNabb, 1984).

In the absence of measures aimed at reducing soil impacts and tillage treatments designed to reverse the detrimental effects of soil disturbance (section 1.3.3.3), the effects on long-term productivity are subject to the process of natural soil recovery. Depending on temperature and moisture extremes, and specific mineralogical conditions, these processes include volume changes over time associated with frost heave, freeze-thaw cycles and the wetting-drying (involving swelling-shrinking) of clay particles and the influence of biological activity (Froelich and McNabb, 1984). The latter was considered to be of little relative importance by Wronski and Murphy (1994), though Sands *et al.* (1979) stated that this may be the only means by which natural recovery can take place within coarse soils low in clay content where recovery, if any, is often much slower (Wingate-Hill and Jakobsen, 1982). Freeze-thawing was considered by Froelich and McNabb (1984) to be of little value due to the low expansion of water (approximately 9%) during freezing while frost-heave, generally responsible for larger volume changes, was subject to exacting thermal conditions where the rate of soil cooling is balanced by the heat released during freezing. In both cases, the effectiveness of either freeze-thaw or frost heave was considered to diminish with lower moisture contents.

1.3.2.1. The implications for site productivity.

Given the longevity of changes in soil character, the potential for a reduction in site productivity has become a major concern. Detrimental impacts to long-term site productivity depend on the soil's natural capacity for recovery to pre-disturbance thresholds (section 1.3.2) the timing and efficacy of restock tillage treatments and the physiological characteristics and requirements of individual tree species (described below). In the UK the structure and physiology of Sitka spruce roots have received more attention than many other trees because of their economic importance (Coutts and Philipson, 1987), though the interrelationships between factors affecting root growth remain poorly understood. The significance of soil disturbance in relation to productivity depends largely on the maturity and scale of the forest industry (Wronski and Murphy, 1994). Where supply exceeds demand, for example as a result of large scale native forest cover, site degradation may have little or no immediate economic impacts. However, the introduction of management and associated restrictions on exploitation as the industry matures, introduce potential limits to supply.

In a review of studies undertaken during the period 1970 to 1977 Greacen and Sands (1980) noted that of 117 individual studies 82% reported a decline in yield, the remaining 18% reported either no change, increases or increases and decreases in yield. Mid-rotation impacts during thinning can result in an immediate reduction in growth and ultimate stand yield (e.g., Wingate-Hill and Jakobsen, 1982; Wästerlund, 1992). Cumulative disturbance associated with repeated clear felling might further reduce site productivity despite both natural soil recovery and ameliorative measures. In addition, at any stage in the forest rotation careless planning of mechanised operations, such as thinning, may result in a direct loss of regeneration stock (Pothier, 1996). The root system allows the uptake of water and nutrients, and provides tree stability, though Coutts and Philipson (1987) noted that optimal root morphologies for important species such as Sitka spruce remained unknown. In the UK, windthrow continues to be a major source of economic loss (e.g., Anderson *et al.,* 1989; Rodgers *et al.,* 1995), and restricted root development due to compaction has the potential to further exacerbate this problem.

Dry soil bulk densities limiting tree root establishment have been determined to lie in the range of 1.4 g cm^{-3} (Senyk and Craigdallie, 1997) to 1.5 g cm^{-3} (Wronski and Murphy, 1994), though values as low as 1.2 g cm^{-3} have been suggested where clay content is greater than 30% (Canarache, 1990). However, Heilman (1981) stated that even small increases in dry bulk density can have a significant effect on growth, citing studies by Froelich (undated) where increases in dry bulk density of 8-10% resulting in a final dry bulk density of 1.0 g cm^{-3} had a significant effect on the height growth of Douglas fir seedlings. The response in terms of root and tree growth also varies with species. In laboratory experiments, Minore *et al.* (1969) found root penetration of lodgepole pine, Douglas fir, red alder and Pacific silver fir uninhibited at dry bulk densities of 1.32, 1.45 and 1.59 g cm^{-3} respectively, while that of Sitka spruce, western hemlock and western red cedar was reduced at each density.

Greacen and Sands (1980) stated that the relationship between soil strength and root growth was poorly understood and, as such, limiting values of the former are subject to uncertainty. Greacen *et al.* (1969) suggested a mean value of 2.5 MPa with a range dependent on species and soil type. A similar limit was reported by Gayel and Voronkov (1965) for Scots pine, and later for an unspecified range of pine species (Zyuz, 1968), all growing on sandy soils. Root growth of Radiata pine was found to be limited at values of 3 MPa on sandy soils (Sands *et al.,* 1979), but under similar conditions Greacen and Gerard (unpublished study reported in Greacen and Sands, 1980) showed that root growth continued, though at a much reduced rate, where soil strengths reached 7 MPa.

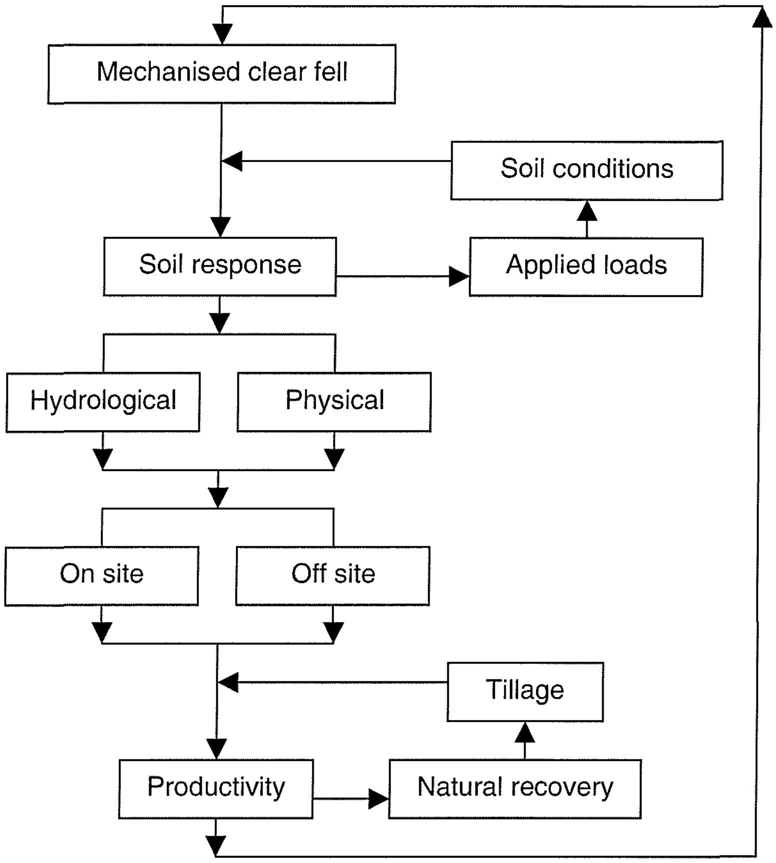
However, following compaction, reduced root penetration and tree growth varies significantly according to soil type and the physiological response of individual tree species, and it appears difficult to ascribe growth reductions to a single soil factor (e.g., Foil and Ralston, 1967; Froelich and McNabb, 1984; Bengough, 1991), while often a combination of factors may exert a compensatory effect. As such the application of, for example, critical values of bulk density (Froelich and McNabb, 1984) or any other soil property is very much site and soil specific as relationships generally indicate an association rather than direct effect, hence limiting values should be considered indicative rather than absolute.

1.3.3. Management options aimed at minimising soil disturbance.

The chain of events leading to soil disturbance associated with harvesting machinery is summarised in Figure 1.2 (p.18). A range of factors must be considered when designing minimum impact harvesting systems. These include topography, season, machine specification, number of passes, location of extraction routes, forest stand characteristics, soil type and depth, moisture content, the amount of surface woody debris, the longevity of impacts, the efficacy of ameliorative treatments and crop response.

Currently, adverse soil impacts are reduced according to 'best management options currently available'. Seldom 'proven' these options include: (1) the implementation of ground protection measures (e.g., the use of high flotation tyres to reduce loads and brash mats to protect the soil); (2) the distribution of extraction routes and regulation of traffic to avoid ground potentially susceptible to disturbance; (3) the application of restock cultivation where necessary, and more recently; (4) the development of minimal impact harvesting systems employing predictive models of soil traffickability.

Figure 1.2. The chain of events leading to soil disturbance during mechanised forest harvesting operations.



1.3.3.1. Machine choice and specification.

Warkotsch *et al.* (1994) suggested that compaction associated directly with wheel action could be greatly reduced by using the correct machinery. However, Greacen and Sands (1980) believed this to be incompatible with harvesting efficiency and productivity. The composition and mechanical strength of the ground surface largely dictates the tractive efficiency and rolling resistance of a specific track or tyre, which in turn, influences the form and distribution of applied loads. A reduction in machine ground pressure may be achieved by increasing the tyre diameter and reducing the inflation pressure (Furuberg-Gjedtjernet, 1995), while increasing the number of wheels has been shown to have similar effects (Bailey and Burt, 1981). The use of high flotation tyres on wet ground has been advocated by Mellgren and Heidersdorf (1984) though tyre width may be limited by spacing especially during thinning operations (Furuberg-Gjedtjernet, 1995).

Comparative studies on a sandy clay loam of tracked and tyred extraction machinery were undertaken by Burger *et al.* (1984). Changes in soil bulk density and porosity under both treatments were comparable in magnitude, despite a contact pressure ratio of 3:7 respectively. In a similar study, Jansson and Johansson (1998) investigated the impact of both wheeled and tracked machinery on a podzol (silty loam texture). Despite a lowered ground pressure for the latter, bulk density, soil penetration resistance, air permeability, saturated hydraulic conductivity, porosity and pore size distribution showed similar sized responses under both treatments.

Variations in rolling gear (wide and narrow tyres, rear steel tracks, and six or eight wheels) of forwarding traffic were studied by Seixas and McDonald (1997). Despite ground pressures for the range of treatments varying by a factor of two, traffic-induced changes in bulk density, soil strength, rut formation and porosity were small under the moisture conditions encountered. Under steel tracks or rubber tyres, difference in the levels of structural change within the soil column appeared small. However, the type of surface disturbance may be of more significance. For example, the tearing and cutting of surface soil layers and tree roots associated with tracked machinery has been cited as a potential source of growth reductions (Pothier, 1996), while deep rutting associated with tyred machinery can lead to serious soil losses through erosion.

The relationship between tyre deflection (the change in tyre cross sectional height according to load/tyre inflation pressure) and applied load has received considerable attention overseas, particularly with regard to the development of Central Tyre Inflation (CTI) technology. Performance studies of logging trucks with CTI systems were reported by Sturos *et al.* (1995). Following increases in tyre deflection (achieved by lowering inflation pressures), a drop in rut depths from c. 41 cm to 10 cm and increases in the incidence of rut ‘healing’ were reported, the latter resulting from redistribution of previously displaced soil material with each successive machine pass. Improvements in traction on snow, ice and loose sand, and reduced rolling resistance over loose sand were also observed. In addition, the authors cited significant reductions in machine and road maintenance costs (the latter up to 62 %), which may allow extended haulage operations.

1.3.3.2. Direct ground protection.

Subject to availability, logging residues (largely branch wood) may be used to armour designated extraction routes so that machine loads are reduced, while direct contact between machinery and the ground is avoided, and the integrity of the upper soil horizons maintained. The latter is of particular importance as the presence of organic matter in surface horizons (leaf litter, roots and peaty soil material) has been shown previously (Soane, 1990) to significantly reduce the impacts of harvesting machinery. The author ascribed this to the high degree of elasticity under compression leading to an increase in soil resistance to compressibility during loading, and rebound following load removal. Following the retention of surface organic matter (predominantly leaf litter) Johnson *et al.* (1979) noted that wheel rut soil strength following skidding operations was 20% less than areas where litter had been removed. More recently, (Wästerlund, 1994) suggested that on the podzolic soils of boreal coniferous forests in Switzerland, where up to 50% of the total root biomass is contained within the humic layers, tolerable machine ground pressures may be increased by as much as 75% where the root mat was retained during trafficking.

Despite widespread use of brash mats in the UK, official guidelines regarding their design and application remain largely qualitative (e.g., Jones, 1991; Spencer, 1991; Wall and Saunders, 1997; Murgatroyd, 1997a: Forestry Commission, 1998 and 2000). Ultimately, the protection they afford and their longevity under repeated trafficking is a function of tree species, stand age and previous management, crown density, orientation and distribution of logging residues, and boom reach of the harvester (Derry Neil, 1998; personal communication)[4].

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[4] Derry Neil, Technical Development Branch, Forest Research, UK.

Following thinning operations on a mineral soil, Fries (1974) found the incidence of rupture/compression of the humus layers to be much reduced where logging residues were retained. Jakobsen and Moore (1981) found saturated hydraulic conductivity to be 46% higher where brash mats were used, though their effect fell with increasing vehicle passes. More recently, McMahon and Everson (1994) reported increases in bulk density of 16% and 25% following the passage of harvesting machinery over brashed and un-brashed areas respectively. Following trials on an upland peaty-gley (Wall and Saunders, 1997; Hutchings *et al.,* In press), increases in dry bulk density (unspecified) were observed under 4, 6, 8 and 10 row (rows of trees) derived brash mats respectively. The latter was considered representative of the maximum achievable thickness under normal harvesting conditions (Colin Saunders, 1998; personal communication)[5].

A further benefit of the brash mat is the provision of traction. In a review of tyres and traction aids currently in use by the UK Forestry Commission, Murgatroyd (1997b) cited traction as a major factor in relation to both machine performance and soil disturbance. Dwyer *et al.* (1976) stated that maximum tractive efficiency was associated with a given amount of wheel slip of c.18%, itself a major contributor to compaction and displacement of surface horizons. Further to this, sustained off-road vehicle mobility requires a degree of surface shear failure, compaction and rut formation (Karafiath and Nowatski, 1978; Jakobsen and Greacen, 1985). However, with brash mats in place the incidence of both surface disturbance (deep rutting, erosive loss and root cutting) and adverse structural changes within the soil column itself may be greatly reduced, whilst improving tractive efficiency (Wronski *et al.,* 1990).

1.3.3.3. Re-stock cultivation and tillage treatments.

Given the complexities of soil and vegetation response to disturbance, and the time scales involved during recovery, data relating to the success of re-stock cultivation and ameliorative tillage treatments are regrettably few. Tillage operations such as deep ripping may allow the reversal of such impacts, though

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[5] Colin Saunders, Technical Development Branch, Forest Research, UK.

the results can be highly variable (Froelich, 1973; Hogervorst and Adams, 1994), and growth seldom compares to that on undisturbed soils (Savill and Evans, 1986). For example, the effects of soil compaction on the growth of Sitka spruce in the UK on a gley soil (sandy loam texture) reported by the Forestry Commission (1983) remained uncertain. Following moderate and severe disturbance (compaction and compaction/churning respectively) both with and without tillage, growth of Sitka spruce and lodgepole pine were assessed over a six year period. Growth reductions were reported even after tillage, though no statistical significance was found. After three growing seasons, growth differences between treatments were negligible.

In addition, tillage has been shown to present further limits to growth. For example, moist clay soils often shatter into larger persistent clods (Andrus and Froelich, 1983). Similarly, on coarse textured soils in south-east Australia, Jakobsen and Greacen (1985) suggested that recovery from disturbance at depths in excess of 80 cm was unlikely, and that deep ripping may prove counter-productive due to the formation of larger aggregates. Coutts and Philipson (1987) reported studies in the UK by Zehetmayr (1954), Yeatman (1955) and Hendrick *et al.* (1984) where Sitka spruce roots had become aligned with the direction of ploughing, with consequences for root growth and tree stability (section 1.3.2.1).

1.3.3.4. Minimum impact harvesting systems based on soil traffickability.

In view of changing harvesting technologies and the growing demand for timber, regular review of guidelines aimed at minimising site disturbance will be necessary if forest operations are to maintain or improve forest soil quality. However, where the guidelines are based upon a quantitative experimental assessment of likely soil response, the need for such revisions may be greatly reduced. During harvesting operations, soil is regarded as both an operational (immediate) and environmental (immediate and long term) variable (Conway, 1982). Under the former, certain soil conditions will not support harvesting machinery while under the latter, erosive processes may be initiated and structural changes may reduce site productivity. Increasingly, decisions regarding the design of extraction systems may apply a 'harvesting equipment selection process' such as that presented by Olsen *et al.* (1996) or (similarly) a hierarchical approach such as that proposed by Krcmar-Nozic *et al.* (1998). In each case, early consideration of environmental impacts, specifically those relating to the soil environment, may indicate the appropriate extraction system.

Regrettably, quantitative data to aid the decision making processes are often lacking, particularly with respect to cumulative temporal and spatial impacts (Boyle *et al.,* 1997). Limiting factors include both the quality and quantity of data, poor understanding of cause-effect relationships, non-linear processes, and poorly developed analytical and predictive methodologies necessary for assessing basin wide impacts (both environmental and market driven). Despite the multi-faceted nature of harvesting operations and general uncertainties regarding soil response to machine traffic, much has been done in an attempt to limit the adverse soil impacts associated with harvesting and extraction, and the use of site trafficability assessments developed in previous studies, and their successful application in UK forestry is of great interest.

Unfortunately, inferences based on models of trafficability are generally site specific and of limited value in other contexts. For example, given the importance of moisture status in soil trafficability, Wronksi and Humphreys (1994) suggested that a reduction or complete halt to logging operations during wet seasons may offer significant benefits in terms of ground protection despite the potential interruption to timber supplies and associated economic implications. However, the scale of timber production in the UK, and fact that soil water content is only one of several factors affecting soil susceptibility to disturbance (section 1.3.1), make this impractical. Though impacts are often more pronounced on wet soils which are close to their plastic limit, a number of authors have noted the increased bearing capacity of frozen soils. Though unlikely in the UK, harvesting operations may be extended, particularly in areas of high precipitation and prolonged sub-zero temperatures where frozen ground conditions persist. Shoop (1995) presented a means of predicting operable conditions for frozen ground based upon forest operations on peatlands, and similarities in the strength behaviour of peat compared with those of frozen soil.

Faced with the same problem as UK foresters (e.g., that of year-round harvesting and wet soils), a comprehensive set of compaction risk categories was developed for a range of South African forest soil types (Smith *et al.*, 1997a and 1997b). Based upon water content and applied pressure, for a sandy loam and to a lesser extent a silty clay, increases in compaction occurred independently of water content, whilst a sandy clay loam was found to be extremely sensitive to water content. For the former, no benefit was perceived in restricting harvesting to dry periods, so limiting machine load and the number of passes was considered the best approach to reducing disturbance levels. For the latter, similar advantages were considered possible by limiting operations to drier periods. More importantly, the study showed that compaction susceptibility (a function of compressibility and compactibility) could be accurately predicted using routinely measured soil properties. Particle size distribution rather than organic carbon content was found more closely related to compaction susceptibility, while the importance of organic carbon content increased at lower clay contents. It was therefore suggested that the local geology through its influence on soil texture might provide an early indicator of the compaction behaviour of forest soils.

1.3.4. Conclusion and rationale for present study.

The design of harvesting systems should, where economically feasible, be a function of soil bearing capacity or trafficability to ensure that soil disturbance is maintained below thresholds limiting to growth. However, soil-vehicle interactions for a range of harvesting scenarios and, more notably, the long-term effect of soil properties on root and tree growth for all major economic species remain poorly understood. In addition, the efficacy of ameliorative measures are subject to a high degree of uncertainty. Despite the limitations of previous studies of harvesting machinery on operational clear fells which lacked experimental control (Burger *et al.,* 1984), observations made under 'normal forestry practice' of the key components in the chain of events leading to soil disturbance offer the best means of devising low impact harvesting systems.

All soil types are at risk from physical disturbance, but in the UK wet soils of low bearing capacity (Table 1.3), notably surface-water and peaty gleys, peaty ironpan soils and peats are considered particularly susceptible (Forestry Commission, 1998). This study firstly considered the response of two of these soil types (deep peat and peaty gley), and secondly that of a single soil type (peaty gley) where the effects of variations in individual soil properties and role of the brash mat in reducing soil disturbance were explored. Field trials took place between June-November 1998 and April-November 1999 at sites employing the shortwood harvesting system (Figure 1.3, p. 26), reflecting common operational practice throughout the UK uplands (Saunders, 1996., Colin Saunders, 1998; personal communication)[6].

Table 1.3. Risk of ground disturbance associated with harvesting operations (after Forestry Commission, 1998).

Risk	Soil type (Forestry Commission, 1982)
Low	Brown earths, podzols, rankers, skeletal soils, limestone and littoral soils except sand subject to a shallow or very shallow water table
Medium	Shallow peaty soils (peat <45 cm deep), surface- and ground-water gleys, and ironpan soils
High	Peatland soils (peat >45 cm deep) and littoral soils subject to a shallow or very shallow water table

The implications of measured soil response for the sustainability of harvesting operations were considered in association with previously reported limiting thresholds to growth. Natural soil recovery rates and the efficacy of ameliorative measures have been described previously (sections 1.3.2 and 1.3.3.3) but direct investigation was not undertaken. Guidelines are presented for use in the design

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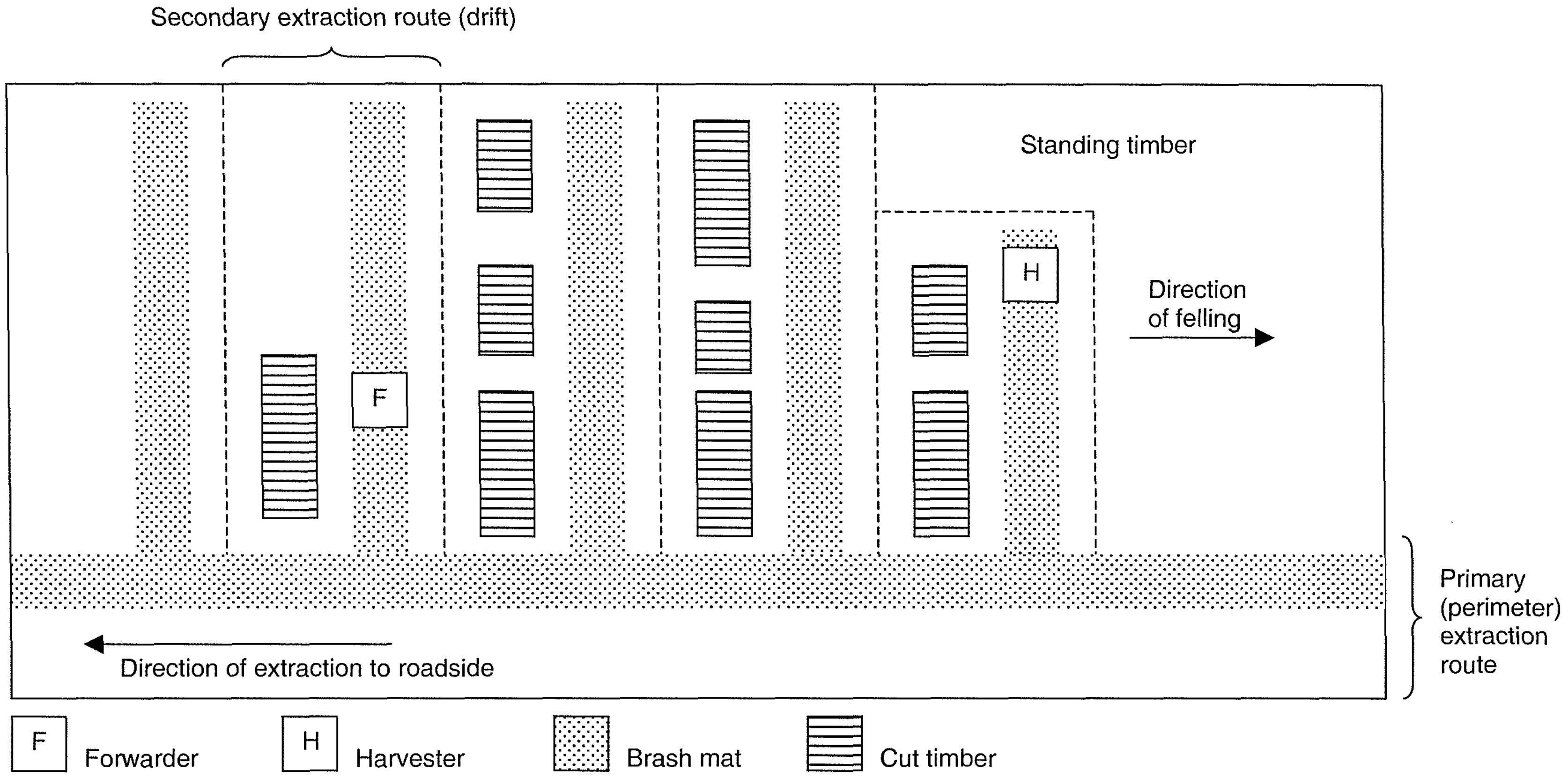
[6] Colin Saunders. Technical Development Branch, Forest Research, UK.

Figure 1.3. Stylised representation of the shortwood extraction system (not to scale).



Primary (perimeter) extraction routes are cut first, followed by secondary extraction routes (drifts). Cut timber is stacked adjacent to each brashed extraction route and systematically collected by the forwarder (working from the back of each drift) and taken to designated log landings.

of future harvesting systems, specifically the design of extraction routes and a means of maximising ground protection measures based upon known forest stand character, soil and terrain properties and machine specification.

Chapter 2 - Field and laboratory methods.

This chapter describes field and laboratory methods employed during the investigation of soil physical properties relating to soil compaction during field trials. Accepted field and laboratory methods are reviewed where appropriate, and justification of their inclusion in this study is based upon their reported efficacy under similar trials.

2.1. Introduction.

Between January-March 1998, Forest Enterprise Forest District managers in North and South Scotland, North and East England, and Wales were asked to help identify suitable experimental sites. Further consultation took place (April-June 1998) at Aberfoyle and Newton Stewart (South Scotland region), and Kielder Forest Districts (North and East England region). These areas were chosen primarily for their size and productive output which offered the greatest range of operational sites.

Working sites were visited between June-November 1998 (year 1 trials - sites 01K, 02N and 03K) and March-November 1999 (year 2 trials - sites 04K, 05K and 06K). At each site a suitable experimental plot was located following an assessment of stand character relative to the progress of harvesting operations. This procedure included identification of three adjacent secondary extraction routes (drifts) where species, age, planting regime and ground features (slope, roughness, presence of drains etc) remained uniform (Plate 2.1, p. 29). A soil pit (Plate 2.2, p. 29) and profile description (Box 2.1, p. 30) were completed at site 01K, using the classification system described by Pyatt (1970), and considered applicable to sites 03K, 04K, 05K and 06K where the rooting zone was confined to the organic horizons. Given the relatively homogeneous nature of the deep peat profile at site 02N (based on bore hole observations), a pit profile description was not undertaken. Forest and plot descriptions, and machine specifications at each site visited are summarised in Tables 2.1 (p. 31) and 2.2 (p. 32).

Plate 2.1. A typical clearfell site visited during year 1 and year 2 trials. Primary extraction routes running top to bottom, and secondary extraction routes (drifts) running right to left (site 04K).

Plate 2.2. Soil profile typical of a peaty gley soil (site 01K). See Box 2.1 (p. 30) for profile description.

Box 2.1. Soil profile pit description (site 01K).

Date and location:	31st August 1998, Kielder Forest, UK (NGR: NY 652942).
Sample team:	Matt Wood and Marthijn Sonneveld.
Conditions:	Overcast, sunny intervals.
Soil type and parent material:	Peaty gley/clayey glacial till.
Slope, elevation, aspect:	10°-14° (N-S), 360 m.
Drainage* and erosion:	Poor to moderate/none.
Course fragments:	None.
Rock outcrops:	None.
Ground cover and species:	Needle litter/Sitka spruce (planted 1951).
L (0-2 cm) layer	Abrupt, Sitka spruce needles, cones and twigs.
F (2-7 cm) layer	Abrupt, wet, apedal, roots (fine, common, fibrous).
H (7-22 cm) layer	Abrupt, dark reddish brown (5 YR 2.5/2), wet, apedal, roots (fine,few, amorphous).
Ah (22-32 cm) layer	Abrupt, black (5 YR 2.5/1), silty clay loam, wet, coarse sub angular structure weakly developed, roots (very fine, few, fibrous).
Eg1 (32-52 cm) layer	Abrupt, light yellowish brown (10 YR 6/4), sand, slightly stony large, angular, pebbly), moist, very coarse angular structure moderately developed, root remains (fine, few, fibrous).
Eg2 (52-65 cm) layer	Clear, light brownish grey (2.5 Y 6/2), mottles: dark yellowish brown (10 YR 4/6), many, very fine, prominent, loamy sand, moderately stony (medium, sub-angular, pebbly), moist, very coarse sub-angular structure moderately developed, root remains (fine, few, fibrous).
B1 (65-82 cm) layer	Clear, greyish brown (2.5 Y 5/2), mottles: dark yellowish brown (10 YR 4/6), many, fine, prominent, loamy sand, moist, apedal, root remains (fine, few, fibrous).
B2 (82 cm+) layer	Clear, dark grey (2.5 Y N/4), mottles: dark yellowish brown (10 YR 4/6), many, fine, prominent, sandy clay, wet, apedal.

*Author's assessment.

Table 2.1. Site and experimental plot characteristics - year 1 and year 2 sites.

	Site					
Site description	01K	02N	03K	04K	05K	06K
NGR	NY 645945	NX 375885	NY 685905	NY 745905	NY 675935	NY 715855
Soil type	Peaty gley	Deep peat	Peaty gley	Peaty gley	Peaty gley	Peaty gley
Species	Sitka spruce	Sitka spruce	Sitka spruce	Sitka spruce	Sitka spruce	Sitka spruce and Scots pine**
Planting date	1951	1950	1948	1948	1951	1951
Spacing (m)#	1.7	1.7	1.7	1.7	1.7	1.7
Terrain class+	4:2:3 (4:1:2)	5:2:2 (5:2:2)	4:1:1	4:3:1	4:2:1	4:1:1
Windthrow class	5	5	5	4	5	4
Sampling period	15th-21st Jul 98	24th-31st Aug 98	12th-23rd Oct 98	10th-25th May 99	20th Jun-26th Jul 99	14th Sep-4th Oct 99
Plot dimensions	4 x 150 m x 16 m	3 x 150 m x 16 m*	3 x 150 m x 12 m	3 x 150 m x 12 m	3 x 150 m x 10 m	3 x 150 m x 15 m
Product mix (m)	Poles (4.9) logs (2.5) pulp (1.9)	Poles (4.9) logs (2.5) pulp (1.9)	Poles (4.9) logs (3.7 x 2 diameter) pulp (1.9)	Poles (4.9) logs (2.5/3.7 x2 dm) pulp (1.9)	Poles (4.9 x2 dm) logs (2.5/ 3.7 x2 dm) pulp (1.9) chip	Poles (4.9) logs (2.5/ 3.7) pulp (1.9) chip
Total products	3	3	4	6	8	4

at time of planting (personal communication; Dave Woodhouse, 2000)[1]. + based on author's assessment of terrain class within experimental plot, figures in parentheses represent the UK Forestry Commission classification for whole site where available (Forestry Commission, 1996). * drifts 1 and 2 were adjacent to each other, drift 3 was located some distance away in the same stand. ** alternating between two rows Sitka spruce and two rows Scots pine (dead, planted originally as a nurse species.).

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[1] Dave Woodhouse, Forest Enterprise, Kielder Forest District, Northumberland, UK.

Table 2.2. Specification of harvesting and forwarding machinery - year 1 and 2 sites.

	Site					
Site description	01K	02N	03K	04K	05K	06K
Harvester	Excavator[1]	Excavator	Timberjack 1270B[2]	Timberjack 1270B	Valmet 911[3]	Timberjack 1270B
Weight (kg)	15000	15000	16850*	16850*	15000*	16850*
Boom reach (m)	8.85 m	8.85 m	8.80 m	8.80 m	9.50 m	8.80 m
Forwarder	Hemek TD81[4]	Valmet 860[5]	Timberjack 1210[6]	Hemek TD81	Valmet 860	Valmet 890[7]
Weight (kg)	13000	13770	16000	13000	13770	17000
Load capacity (kg)	12000	12000	12000	12000	12000	18000

[1] Spencer (1997a), [2] Spencer (1997b), [3] Spencer (1997c), [4] Harding (1993), [5] Spencer (1993), [6] Spencer (1995), [7] Spencer and Saunders (1998).

2.2. Measurement of soil physical and hydrological properties.

Methods considered suitable were those allowing measurement of pre- and post-traffic soil properties over relatively short time periods, while affording some indication of future impacts on site productivity. At all sites soil dry bulk density was measured, threshold values of which have been frequently cited in previous studies in relation to limited root and tree growth (chapter 1, section 1.3.2.1). However, the strength of such relationships can be affected by additional factors relating to compactability such as soil strength, moisture status, organic matter content and particle size distribution (Campbell, 1994), hence their inclusion in this study in addition to soil dry bulk density. The spatial variability in soil properties is such that there were advantages in determining both a reference state and treatment impact based on the same soil sample. However, due to the dynamic nature of operational clear fells and the difficulties in determining specific experimental plots prior to operations, *in situ* instrumentation to assess impacts on soils subsequent to machine traffic was not possible.

2.2.1. Measurement of soil bulk density.

Bulk density under field conditions was defined by Campbell (1994) as the wet soil bulk density (the mass of both soil particles and soil water per unit volume). However, for comparison at a range of water contents, dry bulk density (mass of oven dried soil per unit volume) is often preferred allowing in addition the simultaneous calculation of water content and total porosity. Further to this, analysis of bulk soil parameters (organic matter content, particle size distribution, etc) can be carried out on the remaining soil material.

In previous studies of forest soil compaction, the chosen approach to measurement of soil bulk density has balanced the effectiveness of a specific technique with the level of sampling required. Nuclear methods have been used successfully (Sidle and Driica; 1981; Jakobsen and Greacen, 1985) based on the attenuation or back scatter of radiation, along with excavation methods (Boyle *et al.,* 1982; Shetron *et al.,* 1988) whereby intact earth clods are removed and moisture-density relationships determined under laboratory conditions. However in the majority of cases, hammer driven coring (Snider and Miller, 1985; Kamaruzaman and Nik Muhamad, 1987; Incerti *et al.,* 1987) or manually inserted core tins (Dickerson, 1976; Miller and Sirois, 1986; Rab, 1994) have been used to remove samples of a known volume from the upper soil horizons, though rarely below 20-30 cm depth.

Unfortunately the problems associated with determining a representative measure of bulk density under normal field conditions are exacerbated when considering forest soils due to high levels of spatial variability. In view of this, Page-Dumroese *et al.* (1999) undertook a comparison of methods aimed at investigating bulk density under such conditions. Excavation methods generally were found to reduce variability due to larger sample sizes when compared to core collection, the latter often experiencing a drop in accuracy with depth (due to deformation of the sample by the coring device and presence of rock fragments). Nuclear measurements though instantaneous were considered impractical given cost and safety implications. In addition, a number of comparative studies considered previously by Campbell (1994), suggested that despite the obvious advantages of nuclear methods involving non destructive sampling, derived results were generally in agreement with other methods.

The collection of intact undisturbed soil cores, an approach well suited to cohesive soils at or beyond field capacity, was undertaken during this study and considered a suitable compromise between sample accuracy and resolution. Coring apparatus may by inserted under a constant pressure or a series of hammer blows, which under certain conditions may result in either compression or shattering of the soil sample (Baver *et al.,* 1972). Alternatively, insertion in a rotary fashion, despite the risk of torsional shear (Campbell and Henshall, 1991) may be appropriate, particularly where soils are prone to shattering. It is essential, particularly when using rotary methods that the cylinder cuts through the soil column. Additional precautions to further reduce core distortion include the use of a rigid thin walled coring tin (Road Research Laboratory, 1952) and increased diameter and lubrication of the cylinder immediately behind the cutting edge (Veihmeyer, 1929; Buchele, 1961).

Trials of two coring methods at Kershope Forest, Cumberland (May, 1998) on a peaty gley soil planted with Sitka spruce were undertaken by the author. Attempts to remove intact cores using plastic pipes (110 mm outside diameter, 3 mm wall thickness, 500 mm length) and steel core tins (102 mm outside diameter, 3 mm wall thickness, 75 mm length) inserted under a series of hammer blows were unsuccessful. Disturbance to the cores and immediate sampling area, and the extraction time were considered excessive precluding the use of this approach on a large scale. The performance of a soil column cylinder auger[2] inserted using a Pionjar-120 hammer action petrol driven percussion drill[3], was tested during initial trials at site 01K described below (section 2.3), and later employed throughout all subsequent trials. The cylinder auger comprised a steel pipe of 1200 mm (c. 110 mm inside diameter) with a bevelled (30°) cutting edge (c. 100 mm inside diameter) thus reducing friction between the soil core and main body of the auger. Used in similar investigations (Hutchings *et al.,* In press), the device allowed the collection of intact soil cores at depths of up to 1 m. The derivation of additional bulk soil parameters was undertaken in accordance with standard methodologies, details of which are given below where appropriate.

2.2.2. Measurement of soil strength.

While bulk density may be employed as an index of relative compaction, it does not allow direct assessment of soil strength (Greacen and Sands, 1980). The latter is desirable given that soil strength itself determines compaction and has been employed widely as a means of predicting soil traffickability. Penetration tests employing a cone-tipped soil penetrometer have been used as a means of assessing untrafficked and trafficked soil strength in a number of previous studies (Sands *et al.,* 1979; Jakobsen and Greacen, 1985; Jansson and Johansson, 1998; Hutchings *et al.,* In press) given the relative ease and speed at which data can be collected.

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[2] Eijkelkamp Agrisearch Equipment, Van Walt Ltd, Surrey, UK.
[3] Atlas Copco Ab Ltd, SE-105 23, Stockholm, Sweden.

Penetrometer characteristics including cone angle, cone base and shaft diameter, surface roughness and rate of penetration have all been shown to influence penetration resistance (Perumpral, 1983; Bradford, 1986; Campbell and O'Sullivan, 1991). For comparative studies, the influence of cone diameter can be ignored (assuming a range of 11-25 mm) where cone angle remains constant (Campbell and O'Sullivan, 1991). Friction at the soil-shaft interface may increase penetration resistance, though this was considered to be of little consequence by Campbell and O'Sullivan (1991), and may be greatly reduced where cone diameter exceeds that of the shaft (Freitag, 1968).

The influence of penetration rate is complicated by soil conditions, notably pore water pressures ahead of the advancing cone and the dilatency properties of the soil under shear (Bradford, 1986). Guidelines for penetration rates are difficult to prescribe, and for hand held penetrometers specific rates are difficult if not impossible to maintain. Fortunately, cone resistance appears relatively insensitive to expected variations in penetration rate between operators (Campbell and O'Sullivan, 1991) aiming for a standard rate of 30 mm s^{-1} as proposed by Farrell and Greacen (1966).

Penetration resistance is also a function of a number of soil parameters. Summarised by Campbell and O'Sullivan (1991), these include bulk density, water content, structure, and composite variables such as texture, particle size, shape and orientation, clay mineralogy, amorphous oxide content and chemical composition, organic matter and stone content. Cone resistance falls with increasing water content or matric potential and increases with increasing bulk density. The rate of change is generally higher where initial bulk densities are high and water contents low. Where water content and bulk density remain constant, penetration resistance increases with decreasing particle size and organic matter content. Penetration resistance is usually lower in surface layers as a result of different failure mechanisms where upper layers are dominated by shear failure and lower layers combining both shear failure and compression (Farrell and Greacen, 1966). This may be of consequence particularly when comparing penetrations from different depths or where weaker horizons are overlain by stronger layers (Campbell and O'Sullivan, 1991).

A modified hand held recording penetrometer[4] described by Anderson *et al.* (1980) and used in similar UK forest investigations (Hutchings *et al.,* In press) was tested during initial trials described below in (section 2.3) and then adopted throughout the remainder of this study. The device provided a means of collecting large amounts of high resolution data (at 3 cm depth increments up to a depth of 45 cm) over a relatively short period of time, inserted manually and with minimal disturbance to the sample area.

2.2.3. Measurement of hydraulic conductivity.

Numerous authors have reviewed the physical laws of water flow through a porous medium, their theoretical development and measurement under both saturated and unsaturated conditions (e.g., Klute and Dirksen, 1986; Dirksen, 1991). However, there remains the question of the relative importance of both saturated and unsaturated flow. Pritchett and Fisher (1987) stated that water movement under the latter condition is of greater importance, especially in relation to tree growth, though often more difficult to determine. Under such conditions, macropores are largely filled with air and micropores with water, while water movement itself is slowed by decreasing pore space.

Given the nature of UK upland gley and peat soils under plantation forestry (often at and regularly exceeding field capacity), measurement of saturated flow was undertaken (section 2.4.4) during year 2 trials. Laboratory methodologies based on Darcy's law were considered prior to field trials. The simplest approaches involve the use of a permeameter (Klute and Dirksen, 1986; Youngs, 1991), where water is allowed to drain through an intact soil sample (collected using a manually inserted coring tin) and the infiltration rate based on measurement of the hydraulic gradient and rate of discharge. Core tin diameter and length in the range of 75-100 mm were advocated (Loveday, 1974), while a more commonly adopted specification of 50 mm long by 75 mm diameter allowing rapid equilibration was described by Ball and Hunter (1988). However, Reeve and Carter (1991)

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[4] Holtech Associates, Rough Rigg, Harwood-In-Teesdale, Co., Durham, DL12 0XY, UK.

suggested diameters of 100 mm to be more practical for measurement of soil water potential in the 0-100 kPa range, with the length of the core tin equalling that of its diameter.

During trials at site 04K, attempts to collect intact cores from the upper mineral horizons using steel core tins (102 mm outside diameter, 3 mm wall thickness, 75 mm length) were unsuccessful due to the presence of tree roots and a high water table. Subsequent attempts to determine sub-surface infiltration *in situ* at sites 05K and 06K based on measurement of the rise and fall of water levels in bore holes proved successful (section 2.4.4). In a review of similar approaches, Smiles and Youngs (1965) concluded that the choice of method depended largely on site conditions, available resources and individual preference. Common problems when sinking wells include the presence of multi-layered, stony or unstable soils prone to slumping. In clayey soils, smearing of side walls leading to a reduction in conductivity may be alleviated by pumping out each well and allowing in-flowing water to unblock pores (Youngs, 1991) prior to measurement.

2.3. Data collection - year 1 sites.

Year 1 field trials comprised three experimental sites. The first (Kielder Forest District, site 01K) was used to allow development of the experimental procedure (sections 2.3.1 and 2.3.2). In addition, observations of general working practice, specifically the shortwood system, allowed the development of an approach to allow experimental replication of machine ground treatments at future sites. The second (Newton Stewart Forest District, site 02N) and third (Kielder Forest District, site 03K) sites provided untrafficked and trafficked data for an organic soil and a mineral soil respectively, allowing a comparative study of their response to harvesting traffic. At each site, the moisture status of the mineral soil (sites 01K and 03K) was considered saturated as the water table lay within the organic horizons typically at a depth of 15-30 cm below the litter layer (based on unrecorded observations made of water levels in bore holes).

2.3.1. Replicating machine/ground treatments at a plot scale.

In UK forest clearfell operations employing the shortwood system, the distribution of extraction routes is uniform across the entire site. However, the number of passes by machinery along these routes, and therefore the potential levels of disturbance to soil physical properties, may vary considerably. Experimental control at each site was not feasible given that these were operational sites and that changes to the extraction schedule would have financial implications, and so a means of quantifying the distribution of traffic under operational conditions was sought which would allow the experimental replication of ground treatments.

In the study of forest soils, there are few examples where harvesting operations have been modified to meet pre-determined experimental objectives. These examples relate to controlled loading experiments (Shetron *et al.,* 1988) and pre-traffic instrumentation (Jakobsen and Greacen, 1985) within plots determined prior to felling and re-planting. In the absence of experimental control, the definition and replication of ground treatments has varied in complexity. The approach used (in the past) has often been specific to a given harvesting system and the chosen level of coverage (e.g., individual plots or whole stand scale). The basic approach in small scale studies has been to sample and replicate sub-units according to the nature/location of disturbance (Dickerson, 1976, Boyle *et al.,* 1982). At a larger scale, comprising the entire stand where the areal extent of disturbance is of interest, replication has been based upon ranking designated extraction routes. Invariably, this has been based on the number of machine passes (Sidle and Drlica, 1981) or defined disturbance classes within a randomised block design (Snider and Miller, 1985; Miller and Sirois, 1986; Kamaruzaman and Nik Muhamad, 1987).

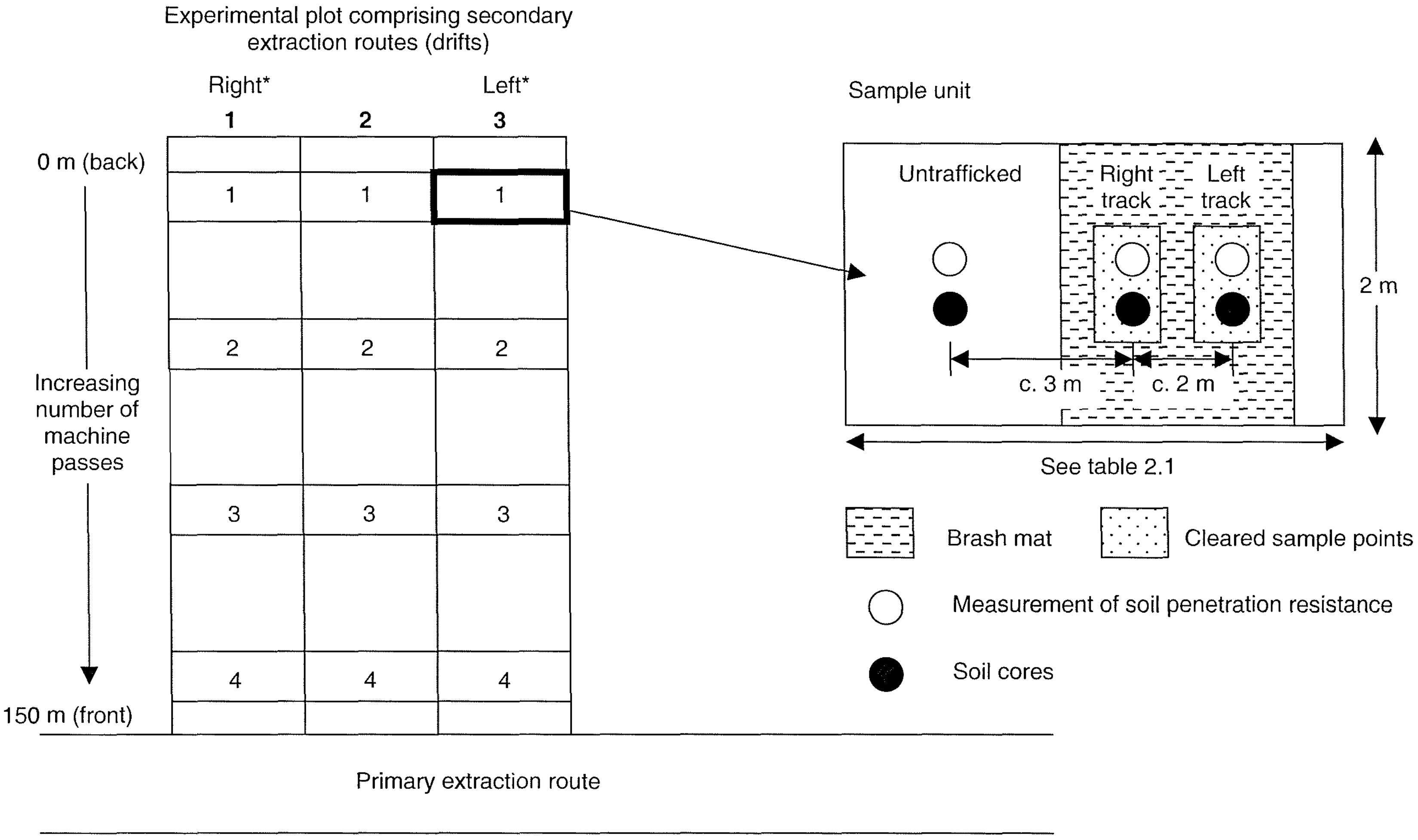
It has been consistently reported (Jakobsen and Moore, 1981; Hatchell *et al.,* 1970) that the majority of disturbance to the soil structure occurs during the first few machine passes when trafficked directly, though the effect of brash mats on this relationship is unknown. However, this information would be more useful if it were to include either estimates or direct measures of applied load. These loads might then be related to measured changes in soil structural properties and to thresholds limiting to root/tree growth, and practical recommendations regarding the design and distribution of machinery could be made.

At site 01K a total of ten sample units (cross sectional areas of the brashed extraction route comprising the brashed/trafficked area and adjacent untrafficked bare ground) were selected randomly from four adjacent secondary extraction routes. Upon removal of all timber from each extraction route, the total number of machine passes (harvester and forwarder) across each unit ranged from one to 16. The design of the experimental plot was standardised at sites 02N and 03K (Figure 2.1, p. 41), and in each case comprised the first 150 m of three adjacent secondary extraction routes. For both harvesting and forwarding machinery, the direction and number of machine passes along each drift was recorded (including approximate time intervals between passes). In addition, during each forwarder pass, the points at which (a) loading of cut timber began, and (b) capacity load was reached were recorded. At site 02N, this information was used to estimate the total and average machine loads for each sample unit, located at 5 m, 55 m, 105 m and 160 m from the back of each extraction route, and deemed representative of minimum, low, high and maximum ground disturbance (intensity of trafficking) respectively. At site 03K, estimates of the average load were used to determine the location of the sample units along each drift. In doing so, the lowest and highest average load (common to all three drifts) along with the 33rd and 66th percentile of this range, defined the areas of minimum, maximum and low and high disturbance respectively. In some cases, sample unit were re-located (± 1 m in either direction) to avoid roots, stumps and drain channels.

2.3.2. Measurement of soil physical properties – year 1 sites.

At site 01K, sample points within each sample unit (Figure 2.1, p. 41) were prepared by removing an area of the brash mat (0.75 m^2) under each wheel track to expose the soil surface. Measurement of soil penetration resistance was carried out using the penetrometer (section 2.2.2) fitted with a 12.9 mm diameter/30° cone.

Figure 2.1. Experimental plot layout - sites 02N and 03K (not to scale).



* Right and left as viewed from back of each drift

Six penetrations were made at each sample point. Additional measurements of soil penetration resistance were taken, firstly from an unfelled/untrafficked area of the operational site and secondly from an adjacent untrafficked ride to provide controls. In both cases, six penetrations were made at ten randomly selected locations, each 0.75 m^2 in area. Intact soil cores (one from under each wheel track) were collected using the power corer (section 2.2.1). Four additional cores were taken from an unfelled/untrafficked area of the operational site to provide a control. Upon removal from the auger, each soil core was sealed in polythene and placed in a plastic case for transportation. Cores were stored for a maximum of 72 hours at room temperature prior to derivation of bulk soil properties (this section).

At sites 02N and 03K, sample points were prepared as for 01K. Measurement of soil penetration resistance was increased to ten penetrations at each sample point. Additional measurements of soil penetration resistance were taken (increased to ten penetrations from an area of 0.75 m^2) adjacent to the brash mat within each sample unit (c. 4 m to the right of the right hand wheel track), to provide controls. Intact soil cores were collected from each sample unit as for 01K. A further six cores were taken (two chosen randomly from the four sample units along each extraction unit, c. 3 m to the right of the right hand wheel track and extending to a depth of 75 cm) to provide controls. In the laboratory, soil cores were divided at 5 cm intervals, weighed and dried for 42 hours at 105°C (e.g., Rowell, 1994) and both soil dry bulk density (g cm^{-3}) and gravimetric soil water content (expressed as percentage) determined using:

$$\text{Dry bulk density } (\rho_b) = \frac{M_s}{V_t} \qquad \text{[Eqn. 2.1]}$$

where M_s is the mass of dried soil and V_t is the total volume of soil, and:

$$\text{Gravimetric soil water content} = \quad = \frac{M_w}{M_s} \qquad \text{[Eqn. 2.2]}$$

where M_w is the mass of water and M_s the mass of dry soil. Core sections from site 01K were often poorly formed as a result of breakage, stones and coarse organic material. To overcome this problem, core sections from sites 02N and 03K were sub-sampled to provide a clean sample using a coring tin (5 cm length, inside diameter 5 cm) prior to determination of soil dry bulk density and water content. Samples with a high stone content (> 10% based on a visual assessment) were discarded. For site 03K, dried soil material from the upper (A) and lower (E) mineral horizons was sub-sampled to determine organic matter content (expressed as percentage of the dry soil mass) where:

$$\text{Organic content} = ((\text{Dry mass} - \text{Ashed mass}) / \text{Dry mass}) * 100 \qquad \text{[Eqn. 2.3]}$$

Material was taken from the upper 20 cm (0-5, 5-10, 10-15 and 15-20 cm), the deepest sample (c. 70-75 cm) and from the midpoint (c. 45 cm). This material was then ground lightly prior to ignition at 550°C for 2 hours to ensure removal of all organic material (A. Quinn, personal communication)[5].

2.4. Data collection - year 2 sites.

Based upon the results of year 1 field trials, year 2 trials considered the response of a specific soil type to harvesting traffic. Gleyed mineral soils overlain by a thin organic horizon were chosen. Three sites located in the Kielder Forest District (site 04K, 05K and 06K) were visited between May and November 1999. This ensured that trials took place under a range of weather conditions, while accounting for additional variation in key soil parameters, notably soil moisture status, organic matter content and particle size distribution. The experimental campaign was extended to allow observation of a number of additional key issues. These included:

- The effects of traffic on the brash mat.
- Changes to surface topography beneath the brash mat.
- Lateral distribution of soil impacts.
- Preliminary investigation of impacts on soil hydrology.

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[5] Andy Quinn, Department of Geography, Lancaster University, Lancaster, U.K.

The design of the experimental plot at sites 04K, 05K and 06K is shown in Figure 2.2 (p. 45). The locations of sample units were determined as for 03K, this time using values of total load. This was found to replicate more closely the number of machine passes within each disturbance class. Again, some relocation of sample points was necessary (± 1 m in either direction) to avoid roots, stumps and drain channels. At site 05K, drift 1 formed part of a circular route (machine entry from the rear via an adjacent extraction route), and as such the number of machine passes was the same at any point. When determining the location of sample units, to avoid any influence on the calculated cumulative loads for extraction routes 2 and 3, extraction route 1 was treated separately (using the same process as for drifts 2 and 3). Soil moisture status at each site was considered saturated where the water table rose just below the surface of the upper organic horizons. At site 04K, 05K and 06K this was based on observations of water levels in bore holes resulting from the collection of soil cores. Working from the back of each extraction route at each site, sample points were exposed by removing an entire cross-section of the brash mat within each sample unit. For soil bulk density and bulk soil analyses, intact soil cores were collected as for 02N and 03K. However, given the levels of variation in background soil properties observed during year 1 trials, the number of control cores was increased from six to 12 (one from each sample unit).

Determination of dry bulk density and water content was carried out (as for year 1 trials). Oven-dried material from the upper (A) and lower (E) mineral samples was sub-sampled to determine organic matter content (as for site 03K). A second set of sub-samples were taken from the dried upper (A) and lower (E) mineral horizons (as for derivation of organic matter content) for analysis of particle size distribution using a Coulter Laser Sizer[6]. To ensure accurate measurement of the particle size distribution, it was necessary to dissaggregate soil material and remove organic matter. Sub-samples were placed in 250 cm^3 glass beakers and 50 cm^3 of Calgon (4% solution) added.

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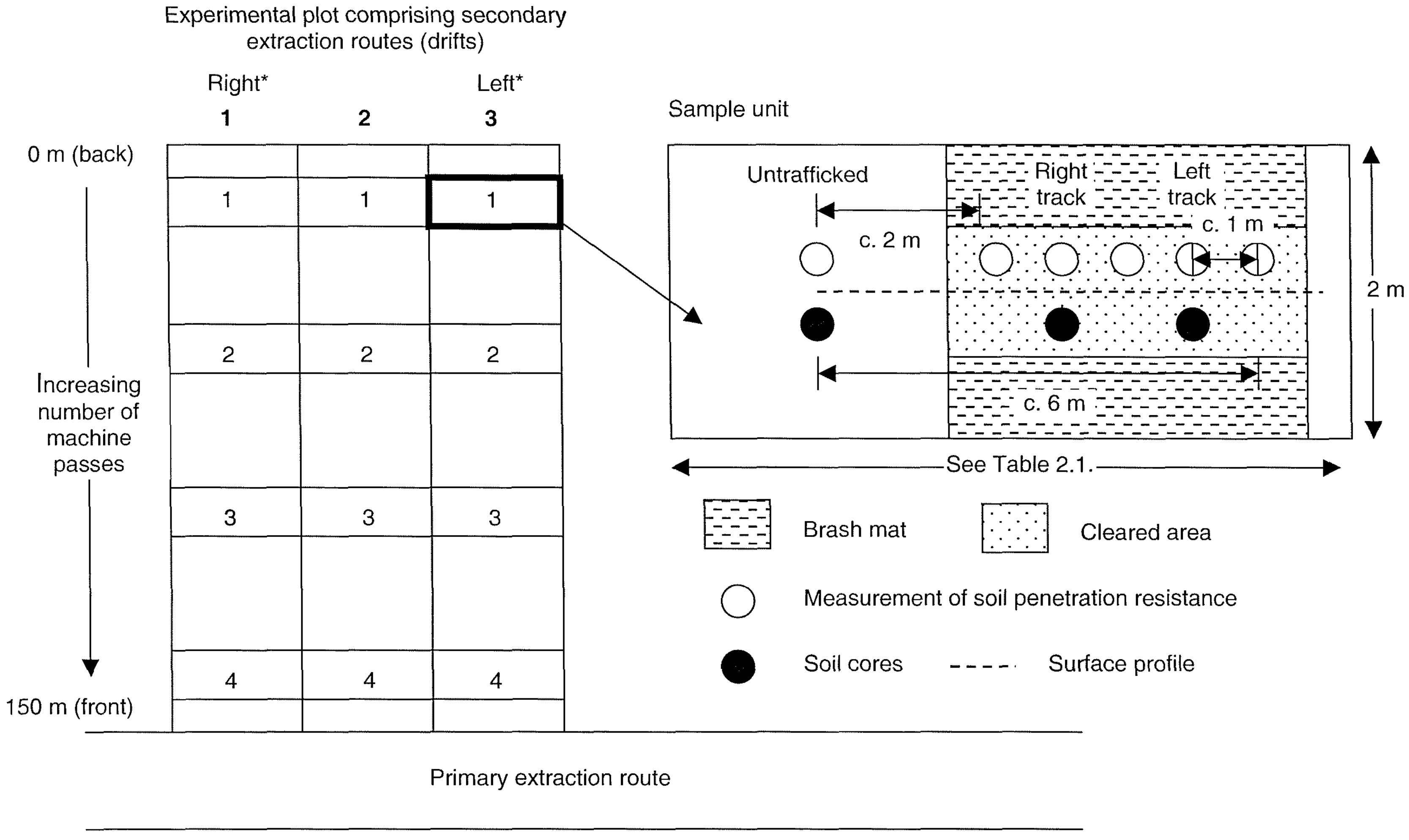
[6] Beckman Coulter (UK) Ltd, Oakley Court, High Wycombe, Buckinghamshire, HP11 1JU, UK.

Figure 2.2. Experimental plot design - sites 04K, 05K and 06K (not to scale).



* Right and left as viewed from back of each drift

100 cm^3 with distilled water. Samples were then placed in a Sonicator for 20 minutes to initiate dissaggregation and then left over-night to ensure the process was complete (A. Quinn, personal communication)[7]. Excess Calgon was drained off each sample and 50 cm^3 of sodium hydroxide (0.1 M) added to remove any organic matter. Samples were placed on a hot-plate for 20 minutes, and then left for a further 72 hours. Excess sodium hydroxide was removed, and the remaining solution diluted to 250 cm^3 with distilled water.

2.4.1. Measuring the response of the brash mat to harvesting traffic.

The response of the brash mat to machine traffic during year 2 trials was considered using both a quantitative and qualitative approach. Attempts to measure the distribution of brash material (referenced to the adjacent bare ground) using a relief-meter[8] were unsuccessful as timber extraction from the experimental plot began before the survey could be completed. A second approach involved a visual survey, at 1 m resolution, of each wheel track along the brash mat (subsequent to trafficking) and the bare ground either side of each brash mat employing the classification system in Table 2.3 (p. 47) developed after observations by the author during year 1 trials.

Untrafficked areas adjacent to the brash mat (class 0) may be subject to log disturbance (L) or standing water (W). The former occurs during the placement or removal of cut timber resulting in displacement of surface litter and exposure of the upper peat horizons, whilst the latter is indicative of poor drainage. Drains (class 1) adjacent to the brash mat may be damaged structurally (D) during the placement or removal of cut timber, or blocked by brash material (B) where crossed by the extraction route. Instances of machines running off the brash mat (class 2) may be single events (T) where machinery has to turn or repeated (R) along the edges of the brash mat. General wear and tear of the brash mat (class 3) is characterised by deflection and/or breakage of the upper layers, while

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[7] Andy Quinn. Dept., Of Geography, Lancaster University, Lancaster, UK.
[8] Spectra-Precision Ltd, UK.

excessive deflection results in exposure of the ground surface (class 4). In both cases, ponding of water (P) along wheel tracks may be apparent. These areas quickly degrade with rutting/churning of the upper (0-10 cm) and lower (10-20 cm) peat horizons (classes 5 and 6 respectively). Without immediate repair, repeated trafficking of these areas may expose the upper (20-50 cm) and lower (> 50 cm) mineral horizons (classes 7 and 8 respectively). In all cases (classes 5-8), standing surface water (P) is common. On steeper ground, water flowing along wheel ruts (F) may result in transport of exposed mineral material (E).

Table 2.3. Classification system used in assessment of brash mat condition.

Class	Description	Suffix (and application)
0	Untrafficked area adjacent to brash mat	L – Log disturbance (class 0) W – Water logged (class 0)
1	Drain channel adjacent to/crossed by brash mat	D – Drain walls damaged (class 1) B – Blocked (class 1)
2	Traffic running off brash mat	T – Machine turning (class 2) R – Repeated trafficking (class 2)
3	Deflection/breakage	P – Ponded water along wheel tracks (classes 3-8)
4	Ground surface exposed	
5	Upper peat horizon exposed	F – Water flow along wheel rut (classes 3-8)
6	Lower peat horizon exposed	E – As F with soil transport (classes 3-8)
7	Upper mineral horizon exposed	
8	Lower mineral horizon exposed	

2.4.2. Measuring ground surface topography.

Following removal of brash material at each sample point, trafficked ground surface profiles were constructed (Figure 2.3a, p. 48), measured right to left across each sample unit (viewed from the back of each drift) at 20 cm intervals. Ground features including logging residues, tree stumps, exposed roots, drains and plough furrows were recorded where present directly along the transect. To provide an estimated untrafficked reference (projected ground surface), the data were plotted and a line of best fit was applied (Figure 2.3b, p. 48):

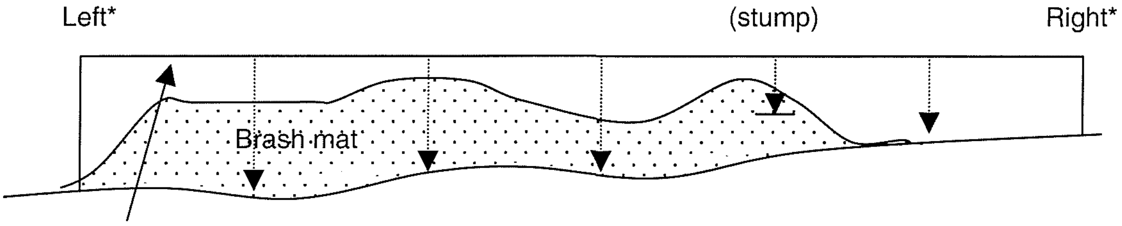
$$y = a + bx \qquad \text{[Eqn. 2.4]}$$

where y represents the vertical height above the horizontal reference x. Using this relationship the right-left slope angle (degrees) was then calculated where:

$$SLOPE = ATAN\left(\frac{y}{x}\right) \times \left(\frac{180}{\pi}\right) \qquad \text{[Eqn. 2.5]}$$

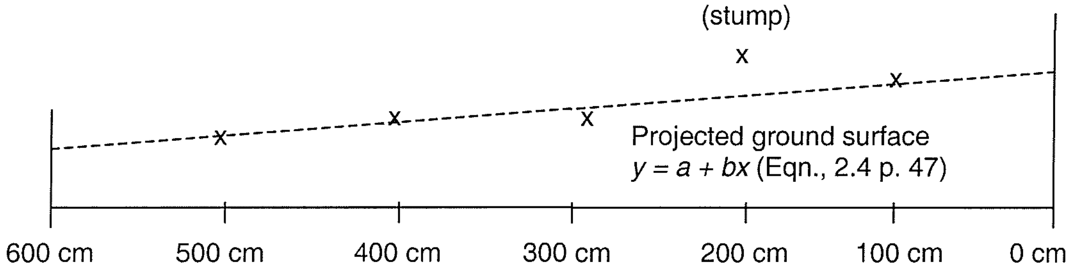
Figure 2.3. Measurement of cross-sectional surface topography (not to scale) and approximate position of sample points within each sample unit.

a. Construction of post-traffic ground surface profile.

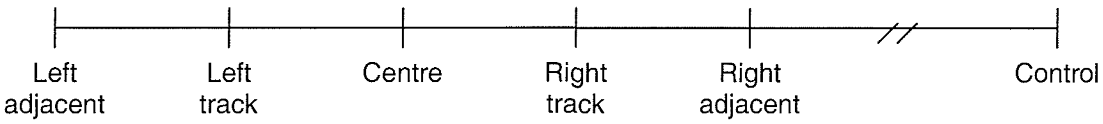


Horizontal reference comprised steel wire held under tension between wooden posts and aligned using a spirit level

b. Construction of pre-traffic ground surface profile.



c. Sample point location for profiles of soil penetration resistance (section 2.4.3).



*Viewed from the back of each drift (see Figures 2.1 and 2.2, p 41 and 45).

To assess the influence of prominent ground features (drains, furrows, exposed roots, stumps and logging waste) on the projected ground surface, the process described above (Eqns., 2.4 and 2.5) was repeated with these features and their associated $x{:}y$ position omitted. At sites 04K and 06K the removal of recorded ground features resulted in differences of up to 1° and 7° respectively when compared with the original. However at site 05K the effect was to reverse the slope angle at four of the nine sample points from an incline of c. 5° to a decline of c. 5°. As a result, prominent ground features were removed from subsequent analyses.

To quantify the depth of surface depressions (wheel tracks) beneath the brash mat due to machine passage, the projected ground surface over the right and left wheel tracks was considered in relation to the measured surface topography of the wheel tracks themselves. A total of five measurements was considered from each wheel track - the approximate centre of each and an additional four measurements (two from either side of the defined centre). The largest positive difference between the measured depth and height of the reference was used as an estimate of maximum rut depth.

2.4.3. Measuring the lateral distribution of soil impacts.

To allow observation of any soil impacts extending laterally beyond the area of the wheel track, a profile of soil penetration resistance was constructed for each sample unit (Figure 2.3c, p. 48). Five sample points (each 0.75 m^2) were distributed evenly under the right and left wheel tracks, centrally between the two wheel tracks and to the right and left of each wheel track. A sixth sample point was located c. 3 m to right of the right wheel track to provide a control. A total of ten measurements of soil penetration resistance was made at each sample point using the penetrometer.

2.4.4. Measuring soil hydraulic conductivity.

At sites 04K and 05K, attempts to measure saturated hydraulic conductivity and the water release characteristic in the laboratory were unsuccessful. Collection of intact soil cores from the upper mineral horizons at 04K using steel coring tins (102 mm outside diameter, 3 mm wall thickness and 75 mm length) was impeded by saturated soil conditions and a dense root mat. Samples from 05K of the upper mineral horizon (sub-sampled from the larger single core using the coring tins described above) underwent structural deterioration during storage, and were subsequently abandoned. *In situ* measurement of surface infiltration rates at site 05K using a single-cylinder infiltrometer (inside diameter 69 mm and length 250 mm) were unsuccessful. After a period of six hours no fall in water level was observed, and the experiment was abandoned. The absence of infiltration was a likely result of the close proximity of the water table to the ground surface and resulting saturated condition of the upper organic horizons.

Saturated hydraulic conductivity of the upper mineral horizons was successfully measured at sites 05K and 06K. At each sample point (control, right and left tracks, Figure 2.2, p. 45), the litter layer was removed using a narrow-bore auger (50 mm diameter) and a PVC pipe inserted (c. 50 cm long with an inside diameter 50 mm) to a depth of c. 25 mm. This acted as a coring device, and upon removal contained a soil core comprising organic material. This material was discarded and the process repeated until the upper mineral horizon was reached. The pipe was then replaced, with the base driven firmly into the upper mineral horizon to a depth of c. 25 mm. As a result of the high water table at site 05K, water levels were allowed to equilibrate over 72 hours. Each piezometer was then partially evacuated, and the rate at which the water level returned to equilibrium recorded. In the absence of a high water table at site 06K each tube was filled with water and the rate at which the water level fell observed. This was carried out four times to ensure saturation, and the fourth measurement used to calculate the infiltration rate (K mm s^{-1}) from:

$$K = \frac{\pi r^2 \ln(y_0 / y_1)}{A(t_1 - t_0)} \qquad \text{[Eqn. 2.6]}$$

where y_0 and y are the initial and subsequent depths of water respectively in the well either below equilibrium (site 05K) or above (site 06K) at time t_0 and t (Youngs, 1991), and A is a shape factor based upon tabulated data (Youngs, 1991) where:

$$A = f(d/r,\ w/r,\ s/r) \qquad \text{[Eqn. 2.7]}$$

where (*d*) is the depth of water in the well at equilibrium, (*w*) the length of the cavity at the bottom of the well, and (*s*) the depth of the soil to an impermeable or infinitely permeable layer, all measured relative to the radius (*r*) of the well. At each site, *A* was taken as 5.7, an mean based on the suggested range of *A* (Youngs, 1991) for a piezometer positioned without a cavity ($w/r = 0$) and where the depth to an impermeable layer is unknown (s/r = infinite) irrespective of variation in d/r.

2.5. Comparing soil horizons and calculating additional soil properties.

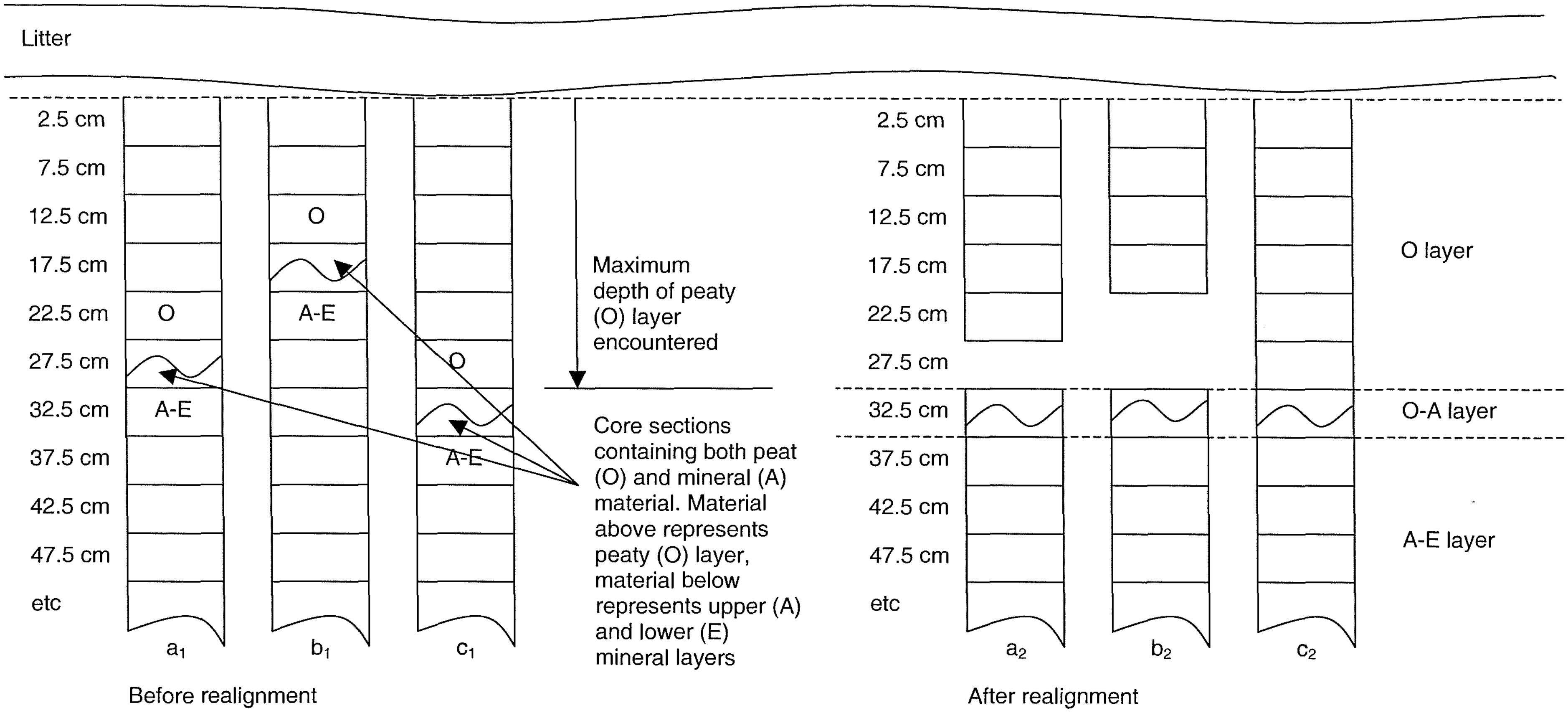
To ensure that comparisons of data relating to soil bulk density and bulk soil properties from each intact soil core were made at equal depth increments, the depth reference of each sample was modified as described in Figure 2.4 (p. 52). Each intact core was firstly split at the approximate boundary between the peaty (O) and upper mineral (A) layers, and the upper portion of the mineral (A) layer containing some peaty material was termed the peat-mineral (O-A) layer. The upper extent of the peaty layer was then aligned as shown, and samples labelled accordingly where 2.5 cm (0-5 cm), 7.5 cm (5-10 cm) etc. Additional soil properties were calculated using standard techniques using:

$$\text{Soil void ratio (e)} \quad = \frac{V_p}{V_s} \qquad \text{[Eqn. 2.8]}$$

where V_p is the volume of pores and V_s the volume of solids, and total porosity (expressed as a percentage total soil volume) using:

$$\text{Soil total porosity } (\varepsilon) \; = 1 - \frac{\rho_b}{\rho_p} \qquad \text{[Eqn. 2.9]}$$

Figure 2.4. Adjusting the depth reference of the soil cores taken from each site (not to scale).



where ρ_b is dry bulk density and ρ_p is soil particle density. An average particle density of 1.4 g cm^{-3} (Rowell, 1994) was assumed for the upper organic horizons. This was in agreement with the range suggested by Boyle *et al.* (1982) for organic material of 1.35 to 1.50 g cm^{-3}, and that presented by Lide (1992) for cellulose of 1.27-1.60 g cm^{-3}. For the O-A layer a particle density of 2.4 g cm^{-3} (Rowell, 1994) was applied and for the A-E layer 2.65 g cm^{-3} (Hillel, 1982; Rowell, 1994) was used.

2.6. Estimating the loads applied to the surface of the brash mat.

When calculating machine ground pressures, several factors should be considered including (a) the tyre footprint or circumferential tyre area (Figure 2.5a, p. 54) in contact with the soil surface (b) the type of tyre and tread pattern (c) the specification of band tracks where fitted and (d) the weight distribution of the forest machine. A formula quoted by Murgatroyd (1997b) represents a simple approach to calculating mean wheeled ground pressures:

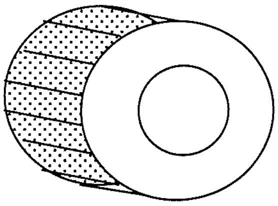
$$p = \frac{W_{load}}{F_{area}} \qquad \text{[Eqn. 2.10]}$$

where p is the mean calculated static ground pressure (kg cm^{-2}), W_{load} is the wheel load (kg) and F_{area} the footprint area (cm^2) which assumes 15% of the tyre circumferential area (for each tyre) is in contact with the ground surface.

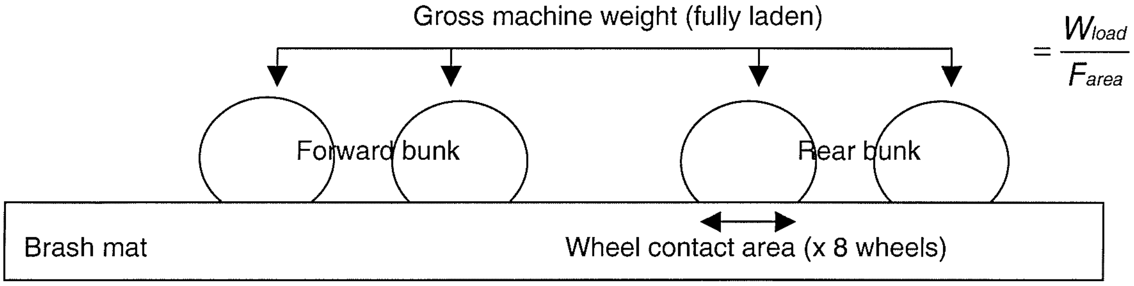
At all sites except site 06K, the gross weight of the harvesting machinery exceeded that of the unladen forwarding machinery. However, under operational conditions, applied loads under the forwarding machinery would generally be greater due to a timber load. As such, average and maximum contact pressures were calculated for the forwarding machinery only. Firstly, average applied loads for the entire contact area were calculated (Figure 2.5b, p. 54) using Eqn. 2.10, where the gross machine weight (fully laden) was divided by the total contact area (which assumed in each case that loads were distributed evenly across the entire machine).

Figure 2.5. Estimating maximum applied machine loads (side view not to scale).

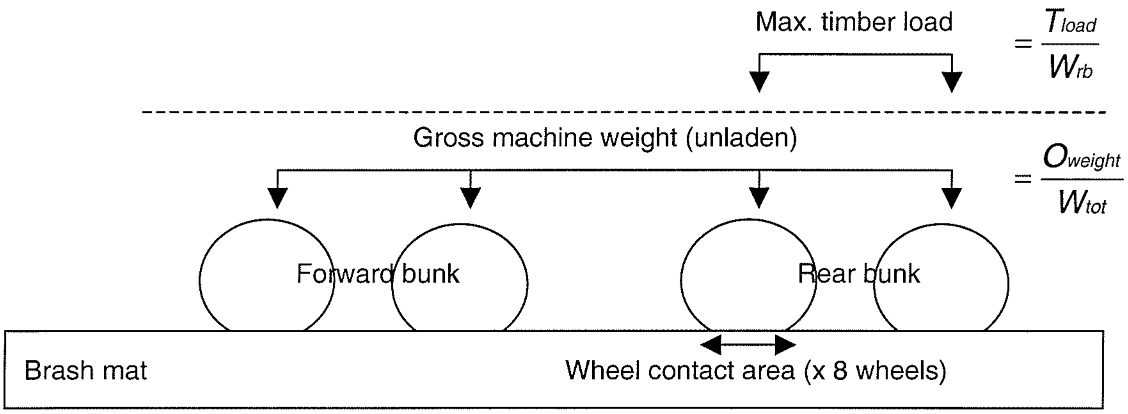
a. Circumferential tyre area (shaded) where the footprint area is the proportion of the shaded area in contact with the ground surface



b. Average applied load



c/d. Maximum applied load



Secondly, when calculating the maximum applied load (W_{max}) for an individual wheel, the weight distribution across the machine was considered non-uniform using:

$$W_{\max} = \left(\frac{O_{weight}}{W_{tot}}\right) + \left(\frac{T_{load}}{W_{rb}}\right) \qquad \text{[Eqn. 2.11]}$$

where O_{weight} is the unladen operational machine weight and W_{tot} the total number of wheels (Figure 2.5c), T_{load} the timber load and W_{rb} the number of wheels on the rear bogie (Figure 2.5d). Hence values represent the maximum applied load under a single wheel of the rear bunk. The timber load (T_{load}) was based on the manufacturer's recommended load capacity (Table 2.2, p. 32), though in practice this was subject to variation associated with the specification of cut timber and ground conditions. In view of this, and the fact that the load distribution across the entire machine was considered uniform [Eqn. 2.10], the additional load of wheel chains where fitted, and estimated at c. 500 kg for a pair (Colin Saunders, 1999; personal communication)[9] and acting solely over the rear wheels of the front bunk was not included in these calculations.

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[9] Colin Saunders. Technical Development Branch, Forest Research, UK.

Chapter 3 - Results.

In this chapter, soil properties and traffic treatments are summarised for each experimental plot. Post-extraction ground conditions, both along and adjacent to trafficked areas within each experimental plot, and the condition of the brash mat following multiple machine passes are then characterised. Trafficked soil conditions within each experimental plot are described using soil dry bulk density, soil strength (soil penetration resistance) and saturated hydraulic conductivity. Soil response in relation to the intensity of traffic, and the pattern of response at successive depth increments is also illustrated. All data are presented as mean values unless otherwise stated (individual data are appended) and considered to be approximately normally distributed (based on histogram analyses). Statistical procedures are described where appropriate.

3.1. Untrafficked soil conditions - year 1 and year 2 sites.

Mean values of soil water and organic content, and particle size distribution for untrafficked areas are summarised in Tables 3.1a-b, (p. 57-58). Additional parameters (soil dry bulk density, soil penetration resistance etc) are considered in relation to values from trafficked areas later in this chapter. For the peat (O) layer and peat-mineral (O-A) layer at each site, all samples were combined to give the respective means, while mean values derived for the mineral (A-E) layers at each site were based on the upper 30 cm portion only. The latter represented the maximum depth of interest, beyond which sample replication fell markedly throughout all field trials.

Notwithstanding the inherent differences between the deep peat (site 02N) and peaty gleys (sites 01K, 03K, 04K, 05K and 06K), soil bulk density, water and organic matter content (chapter 2, section 2.3.2), showed little site-to-site variation across the peat (O), peat-mineral (O-A) and mineral (A-E) layers despite the timing of each trial. The water table at all sites visited during year 1 trials and sites 04K and 05K (year 2 trials) extended into the peat layer (at site 02N the water table was observed on average at c. 30 cm below the ground surface). At site

Table 3.1a. Summary of untrafficked soil properties - year 1 sites.

	Site																				
	01K							02N							03K						
	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max
Soil type	Peaty gley							Deep peat							Peaty gley						
Peaty (O) layer thickness (cm)	21	4	2.50	12	± 1.25	20	25	> 45							18	6	10.80	59	± 4.41	5	35
Water table depth (cm)*																					
Gravimetric soil water content (%)																					
O	346	17	108	31	26.2	176	573	640	37	138.18	22	22.72	286	950	399	13	94.58	24	26.23	216	575
O-A	42	3	2.05	5	1.18	39	43								76	6	44.23	58	18.06	52	165
A-E	29	13	6.97	24	1.93	17	40				Na				30	28	9.00	30	1.70	20	64

Where O, O-A and A-E refer to the peat, peat-mineral and upper (A) and lower (E) mineral layers respectively. *mineral layer (sites 01K and 03K) considered saturated and organic layer (site 02N) saturated beyond c. 30 cm based on un-recorded auger hole observations. N (number of samples), Std (standard deviation), Cv (coefficient of variation - %), Se (standard error), Min (minimum) and Max (maximum).

Table 3.1b. Summary of untrafficked soil properties - year 2 sites.

	Site																				
	04K							05K							06K						
	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max
Soil type	Peaty gley							Peaty gley							Peaty gley						
Peaty (O) layer Thickness (cm)	22	12	7.18	33	± 2.07	5	35	21	12	13.16	62	± 3.80	10	55	11	12	5.15	48	± 1.49	0	20
Water table depth (cm)				*				16	9	2.38	15	± 0.79	12	19	29	10	9.85	34	± 3.11	11	45
Gravimetric soil water content (%)																					
O	364	28	111.77	31	21.12	220	554	477	45	93.33	20	13.91	204	662	249	10	49.36	20	15.61	156	317
O-A	94	12	47.34	51	13.67	38	176	128	9	60.55	47	20.18	79	255	44	8	22.48	52	7.95	25	80
A-E	44	66	38.29	88	4.71	14	214	42	52	23.81	57	3.30	21	181	32	64	7.54	24	0.94	15	48
Soil organic matter content (% total dry soil mass)																					
O	81	18	12.79	16	± 3.01	47	94	86	23	11.23	13	± 2.34	60	95	87	9	9.91	11	± 3.30	65	95
O-A	21	12	15.40	74	± 4.44	5	47	25	8	14.57	59	± 5.15	7	46	11	8	9.57	84	± 3.38	6	34
A-E	9	45	12.04	136	± 1.79	1	61	7	37	9.08	122	± 1.49	2	51	6	37	1.76	30	± 0.29	1	9
Particle size distribution (A/E layer)																					
% sand	9	9	27.27	300	± 9.09	0	82	29	8	39.74	138	± 14.05	0	82	0	7					
% silt	58	9	16.96	29	± 5.65	15	72	40	8	18.47	46	± 6.53	15	60	51	7	12.47	25	± 4.71	36	70
% clay	33	9	11.97	37	± 3.99	3	41	31	8	22.66	73	± 8.01	3	56	49	7	12.47	25	± 4.71	30	64

Where O, O-A and A-E refer to the peat, peat-mineral and upper (A) and lower (E) mineral layers respectively. *taken as mean depth of O layer where water table extended into the O layer (unrecorded field observations). N (number of samples), Std (standard deviation), Cv (coefficient of variation - %), Se (standard error), Min (minimum) and Max (maximum).

06K, the position of the water table was on average 20 cm below the lower boundary of the peaty layer. Particle size distribution for the mineral horizons remained consistent from site to site, and the textural class was predominantly silty clay (with occasional loamy texture).

3.2. Machine/ground treatments - year 1 and year 2 sites.

The number of machine passes at any point along each extraction route within each plot varied considerably. Given the successive modifications to the way in which ground treatments were replicated during year 1 trials, variation in the distribution of machine traffic is demonstrated in Figures 3.1a - 3.1c (p. 60) using year 2 traffic records where the sampling methodology remained uniform. At site 04K, the number of machine passes and distribution of machinery along each extraction route was relatively even, that of site 06K less so. At site 05K, extraction route 1 formed part of a circular extraction route so the same number of machine passes was recorded at all points along that route. Based on average load (year 1 trials) and total load (year 2 trials) the number of machine passes at each site and within each disturbance class (Table 3.2) were well replicated.

Table 3.2. The number of machine passes within each sample unit at each site.

	Site											
	01K				02N				03K			
Sample*	Min	L	H	Max	Min	L	H	Max	Min	L	H	Max
Drift 1	4	6	12	16	9	9	9	9	10	12	14	14
Drift 2	1	2	-	-	6	12	16	22	10	12	14	16
Drift 3	1	2	-	-	6	14	24	28	8	10	10	12
Drift 4	2	2	-	-	-	-	-	-	-	-	-	-
	04K				05K				06K			
Sample*	Min	L	H	Max	Min	L	H	Max	Min	L	H	Max
Drift 1	10	10	16	18	13	14	13	13	9	11	15	19
Drift 2	10	12	16	16	12	14	16	18	9	11	15	17
Drift 3	10	12	16	18	11	13	13	17	10	12	16	18

*Labelled to indicate sample unit and ground treatment - minimum (Min), low (L), high (H) and maximum (Max) number of machine passes.

Figure 3.1a. Distribution of machine passes - site 04K.

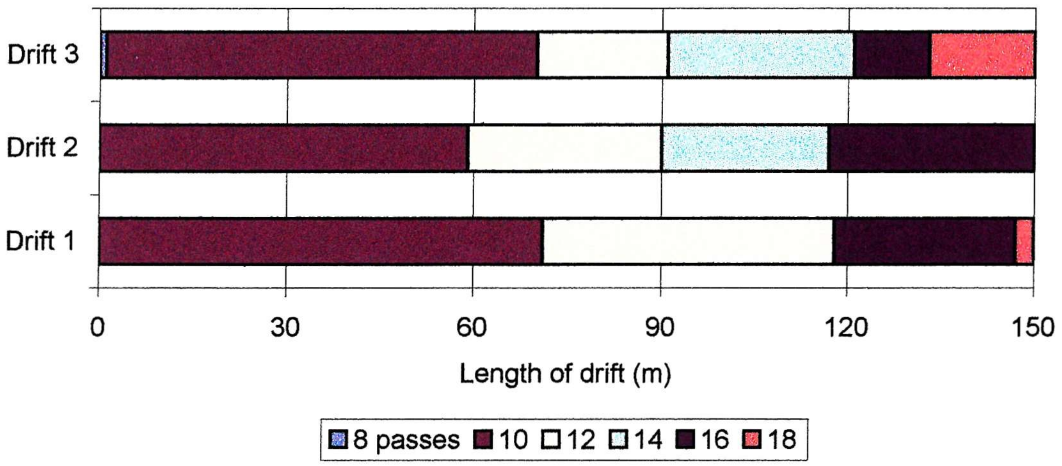


Figure 3.1b. Distribution of machine passes - site 05K.

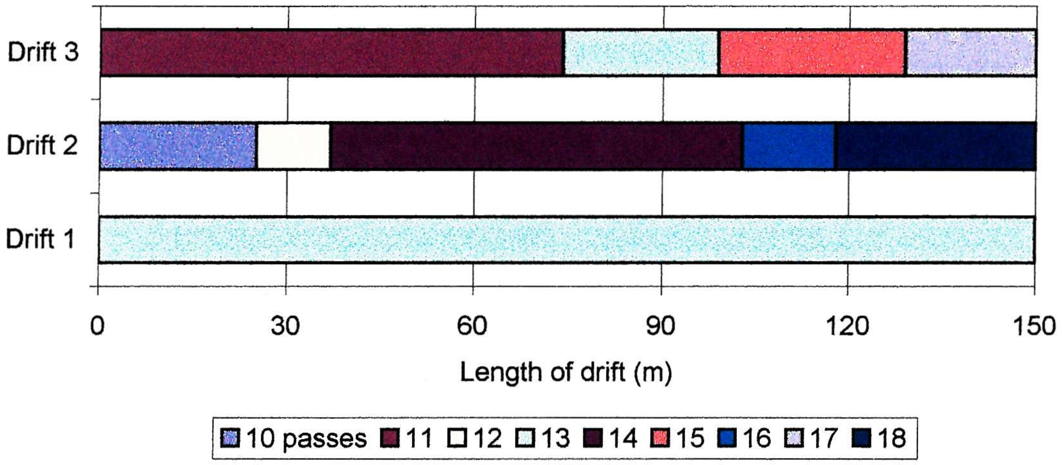
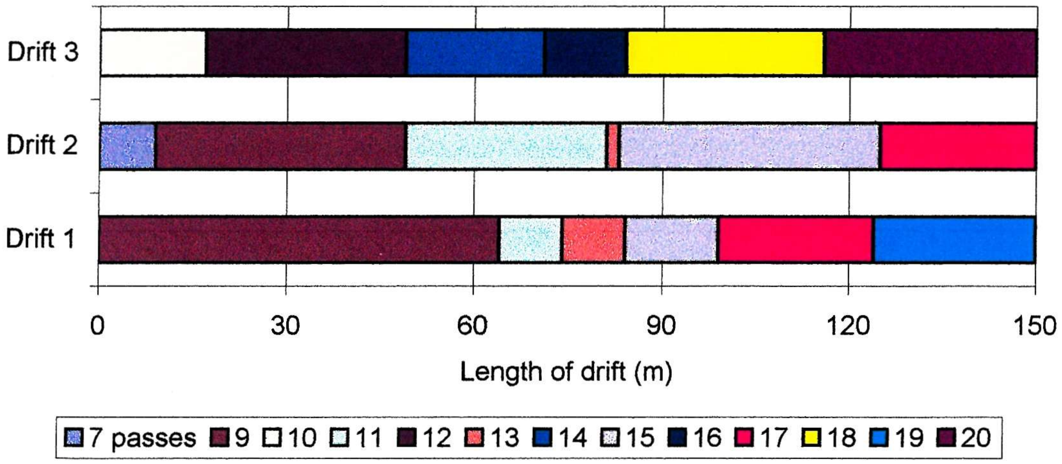


Figure 3.1c. Distribution of machine passes - site 06K.



At the majority of sites, there was a general lack of low pass data other than those gathered at site 01K (e.g., one to four passes, and made available during machine down time before all remaining cut timber was removed). However, this reflects the large numbers of machine passes associated with the shortwood system rather than an oversight in the approach to the replication of ground treatments. At any point along the designated extraction route the number of passes generally comprised at least two by the harvester and then an additional number by the forwarder. The latter was dependent on the volume and specification of cut timber (generally three to four products) resulting in a minimum of six to eight forwarder passes.

3.2.1. Applied machine loads.

Estimates of the average and maximum pressures applied to the surface of the brash mat during a single machine pass are presented in Table 3.3. Unfortunately, tyre pressures of the machinery were unavailable for comparison.

Table 3.3. Applied pressures to the surface of the brash mat.

		Site					
Circumferential contact area	Contact pressure	01K	02N	03K	04K	05K	06K
15%	Average pressure (kPa)	65	67	72	65	67	90
	Max pressure (kPa)	96	98	103	96	98	137
		(192)	(196)	(206)	(192)	(196)	(274)
10%	Average pressure (kPa)	97	100	108	97	100	136
	Max pressure (kPa)	143	146	155	143	146	205
		(286)	(292)	(310)	(286)	(292)	(410)

Values in parentheses indicate potential values at centre of the footprint area where loads of up to twice that of the mean may be expected (chapter 1, section 1.3.1).

Assuming a circumferential contact area of 15% (chapter 2, section 2.6), estimated average loads at all but site 06K were well below the range of 90-200 kPa associated with forwarding machinery (Greacen and Sands, 1980) suggesting that the contact area may be overestimated. Applied loads were recalculated where a circumferential contact area of 10% was assumed (considered more appropriate based upon observations in the field by the author). Subsequently, derived average loads ranged between 97-136 kPa represented the low end of the range presented by Greacen and Sands (1980). The maximum contact pressures under individual wheels (assuming non-uniform loading where the timber load acts solely over the rear bunk) were greater (143-205 kPa) when based on a circumferential contact area of 10% rather than one of 15% (96-137 kPa). Given the non-uniformity of loading across the footprint area, maximum loads based on a 15% contact area approached the upper end of the proposed range, while for a 10% contact area the estimated maximum loads in all cases exceeded the upper limit of the proposed range (200 kPa).

3.2.2. The spatial extent of extraction routes.

The spatial extent of extraction routes at each site visited is summarised in Table 3.4.

Table 3.4. Ground surface area of designated extraction routes.

	01K			02N			03K		
Year 1 trials	m	m^2	% area	m	m^2	% area	m	m^2	% area
Plot area	4x150x16	9600		3x150x16	7200		3x150x12	5400	
Wheel track area*	6x150x1	900	9	6x150x1	900	13	6x150x1	900	17
Brashed routes**	4x150x5	3000	31	3x150x5	2250	31	3x150x5	2250	42
	04K			05K			06K		
Year 2 trials	m	m^2	% area	m	m^2	% area	m	m^2	% area
Plot area	3x150x12	5400		3x150x10	4500		3x150x15	6750	
Wheel track area*	6x150x1	900	17	6x150x1	900	20	6x150x1	900	13
Brashed routes**	3x150x5	2250	42	3x150x5	2250	50	3x150x5	2250	33

*based on average width of tyre imprint in brash material, **based on the area of the brash mat.

The size of the machine footprint area represents the area of ground immediately at risk and assumes that with each successive pass the machine follows the exact course as that taken previously. In reality the machinery deviated from its previous course during each pass, 'snaking' from side to side due to inconsistencies in the degree of traction and presence of tree stumps, the latter forcing the machinery momentarily off course (though seldom off the brash mat itself). As a result of this, the area of the brash mat is considered a more accurate estimate of the ground area potentially at risk at each site, more than doubling the area estimated by that of the wheel tracks alone. Given the even spacing of each stand, the spatial distribution of the brash mats within the experimental plot is considered representative of that across the entire clearfell. As such, the ground area potentially at risk ranges from 31% to as much as 50% of the total clearfell.

3.3. The effect of traffic on the brash mat and ground surface topography.

Results of the semi-quantitative survey of trafficked brash mat condition (year 2 trials only) are summarised in Table 3.5 (p. 64) combining data from all three sites. The extraction routes and adjacent areas are treated as two separate units, and sub-groups not encountered during the survey are omitted, cells are left empty where no observations of a single sub-category were made.

The bare ground adjacent to the extraction routes showed little disturbance (96.3% of total observations) other than occasional displacement of surface litter (a result of the placement and collection of cut timber). In addition, and at site 04K only, where drains were crossed by extraction routes (1.7% of total observations), water logging was observed up-slope where drains were blocked with brash material. Almost half (48%) of observed drain channels were blocked in this way, although structural damage to the drain walls during the placement or collection of cut timber was less evident (13%). Incidence of machinery running off designated extraction routes was rare and limited to isolated cases where, in the absence of circular extraction routes, machinery turned mid-way along the extraction route. For the brash mats, general wear and tear accounted for 95.6% of total observations on completion of harvesting and extraction operations. The remaining 4.4% of total observations comprised isolated instances where the ground surface, upper and lower peat and upper mineral horizons were exposed.

Table 3.5. Summary of trafficked ground/brash mat condition.

		Sub-group**					
	% total observations*	Log disturbance	Water logged	Drain damage	Drain blocked	Single incident	Ponding along wheel tracks
Bare ground adjacent to brash mats							
0 Untrafficked	**96.3**	3	3				
1 Drain channel	**1.7**			13	48		
2 Trafficked	**2.0**					100	
Extraction routes (brash mats)							
3 General wear and tear	**95.6**						1
4 Ground surface exposed	**1.5**						5
5 Upper peaty horizon exposed	**1.9**						69
6 Lower peaty horizon exposed	**0.8**						100
7 Upper mineral horizon exposed	**0.2**						100
8 Lower mineral horizon exposed	**0.0**						

*Values in bold represent % total observations falling into major class (0-8), **values in light type represent % of total observations subject to specific sub-group, empty cells represent zero observations.

Figures 3.2a-3.2i (p. 65-67) illustrate the trafficked ground surface profiles recorded at each sample unit during year 2 trials. The dashed line illustrates the projected ground surface while breaks in the plotted data result from the removal of recorded ground features from each data set. Such obstacles would often throw the vehicle off line, changing the anticipated location of the measured ground surface depression in relation to the pattern of deflection along the surface of the brash mat. The depths of all corresponding surface depressions directly beneath the wheel tracks (to the nearest 0.5 cm), considered indicative rather than absolute, and estimated cross-sectional slope angles (to the nearest 1^{o}) for all sample units are given in Table 3.6 (p. 68). After extraction, the surface litter beneath the brash mat was found to be wholly intact at each sample unit, and in the majority of cases displayed no visible sign of trafficking except in rare cases where minor depressions relative to the surrounding ground level were recorded. During the period of each trial, these depressions became smaller suggesting that

Figure 3.2a. Trafficked ground surface topography - site 04K (drift 1).

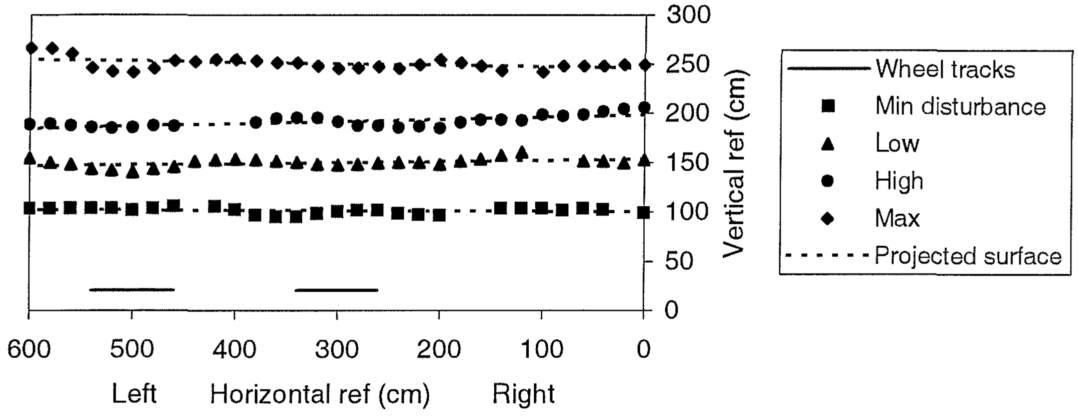


Figure 3.2b. Trafficked ground surface topography - site 04K (drift 2)

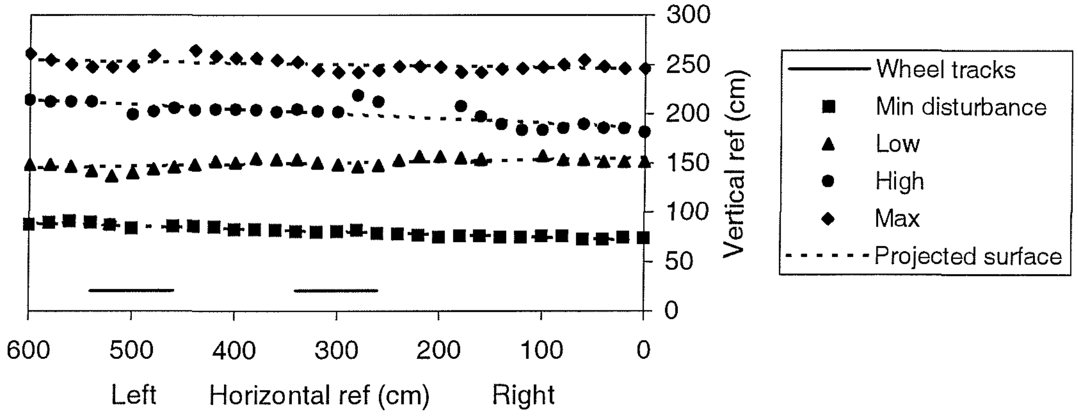
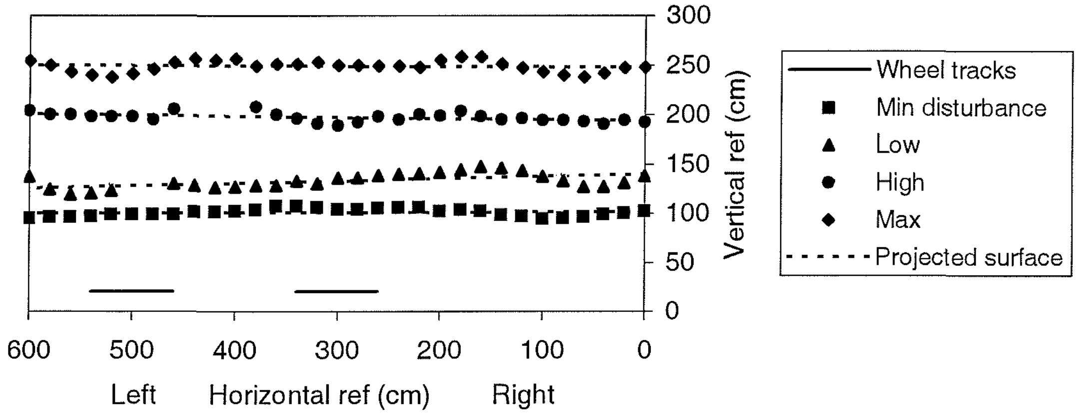


Figure 3.2c. Trafficked ground surface topography - site 04K (drift 3)



Min (minimum), low, high and max (maximum) disturbance - increasing machine passes.

Figure 3.2d. Trafficked ground surface topography - site 05K (drift 1).

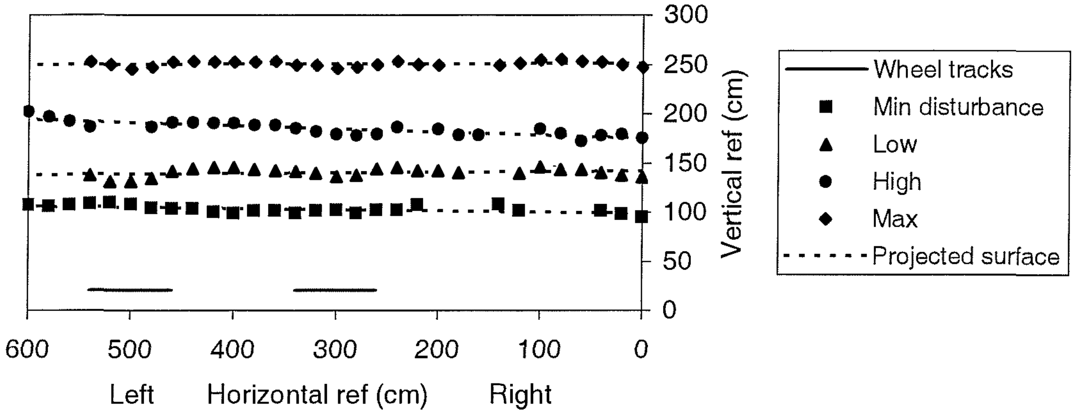


Figure 3.2e. Trafficked ground surface topography - site 05K (drift 2).

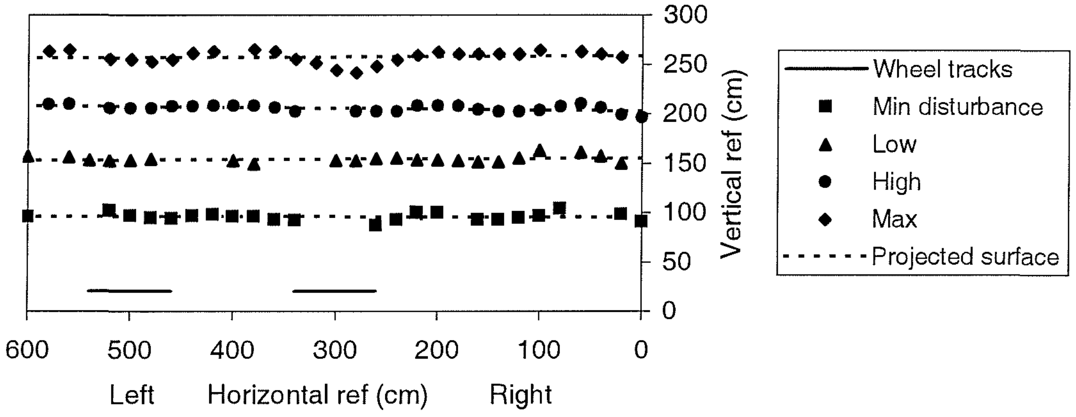
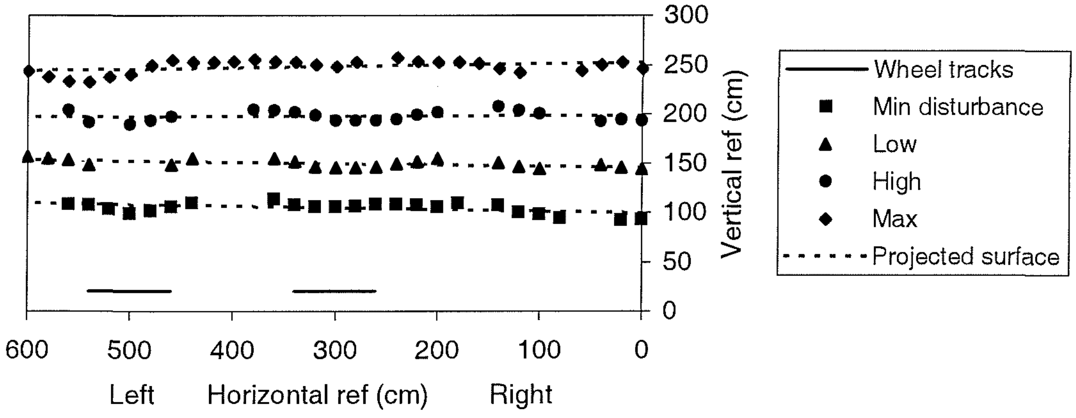


Figure 3.2f. Trafficked ground surface topography - site 05K (drift 3).



Min (minimum), low, high and max (maximum) disturbance - increasing machine passes.

Figure 3.2g. Trafficked ground surface topography - site 06K (drift 1).

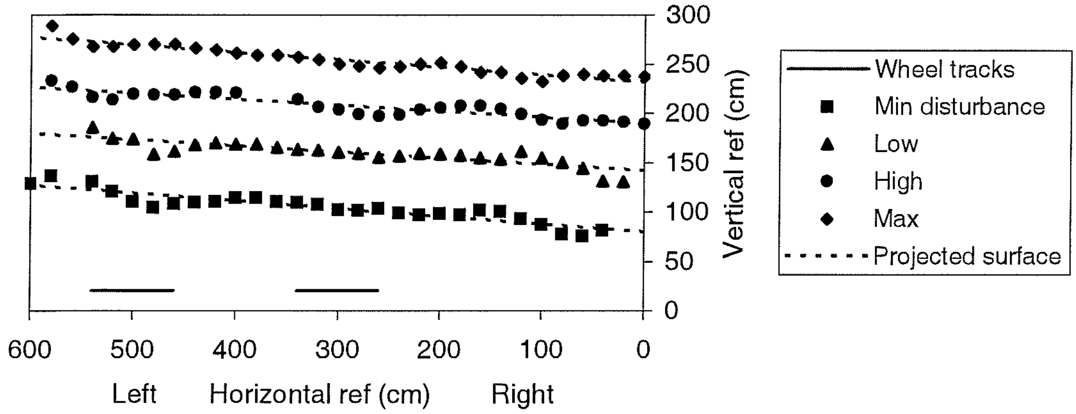


Figure 3.2h. Trafficked ground surface topography - site 06K (drift 2).

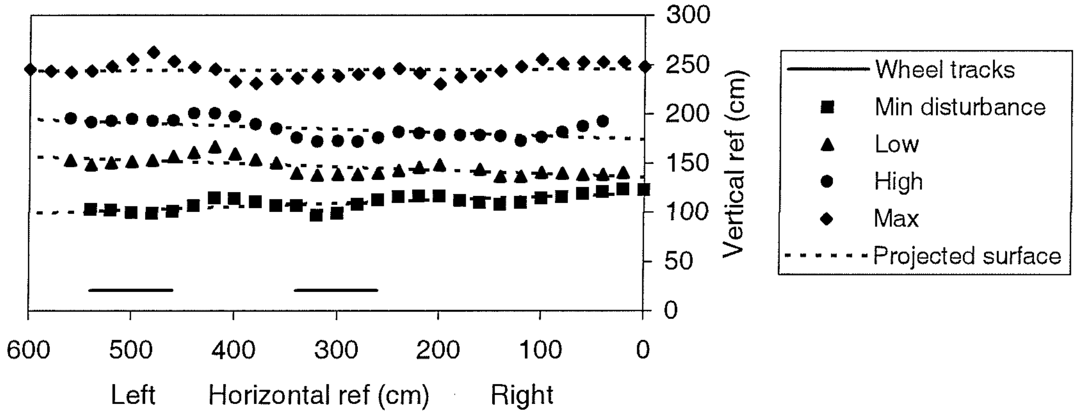
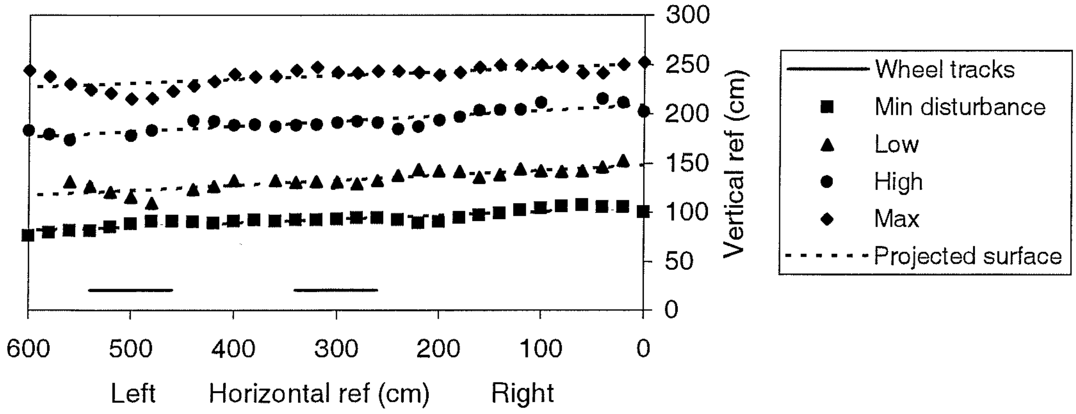


Figure 3.2i. Trafficked ground surface topography - site 06K (drift 3).



Min (minimum), low, high and max (maximum) disturbance - increasing machine passes.

they represented an immediate compression of surface litter only, followed by rapid elastic recovery. In addition, such small scale changes in ground level suggest that the brash mats effectively increase the machine footprint area, and distribute loads over a larger area.

Table 3.6. Depth of wheel track depressions (cm) and right-left (R-L) slope angles (degrees) at year 2 sites.

	04K			05K			06K		
Sample unit and disturbance class	Left track	Right track	R-L slope	Left track	Right track	R-L slope	Left track	Right track	R-L slope
Drift 1 (min)	0	6	5	1	4	5	14	1	7
Drift 1 (low)	8	3	4	8	4	4	14	3	8
Drift 1 (high)	2	5	3	6	6	4	8	8	7
Drift 1 (max	12	5	5	5	4	5	6	5	7
Drift 2 (min)	3	2	4	2	9	4	4	12	5
Drift 2 (low)	10	5	4	1	2	5	6	10	5
Drift 2 (high)	10	-	6	2	4	6	1	14	4
Drift 2 (max)	6	8	5	5	16	5	0	8	4
Drift 3 (min)	3	-	5	8	-	6	2	0	3
Drift 3 (low)	7	2	2	4	4	5	14	4	2
Drift 3 (high)	47	8	5	8	4	4	4	3	3
Drift 3 (max)	11	-	5	12	-	4	16	-	**3**
Min.	0	1	2	1	2	4	0	0	2
Max.	12	8	6	12	16	6	16	14	8

- indicates values above the average ground level and omitted from the table.

3.4. Trafficked soil dry bulk density.

Mean dry bulk densities for both untrafficked and trafficked areas at each site (all depth increments) are presented in Figures 3.3a-3.3f (p. 69-71), and a threshold of 1.4 g cm^{-3}, considered potentially limiting to root/tree growth (chapter 1, section 1.3.2.1) is included (omitted from Figure 3.3b to maintain clarity). The sharp increase in bulk density at c. 30 cm was indicative of the transition from the peaty layer to the mineral layer (except for the deep peat at site 02N), and as a result of realignment of the peaty and mineral layers (chapter 2, section 2.5) represents the greatest depth of the peat layer measured at any sample point for that site.

Figure 3.3a. Mean soil dry bulk density - site 01K.

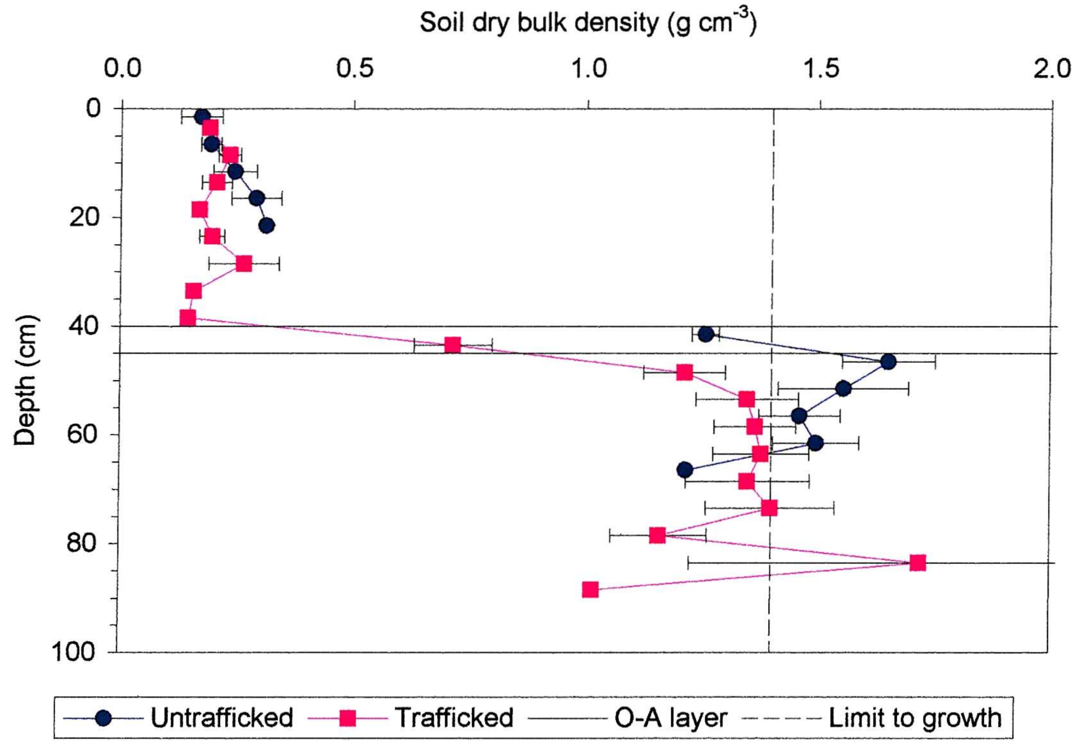
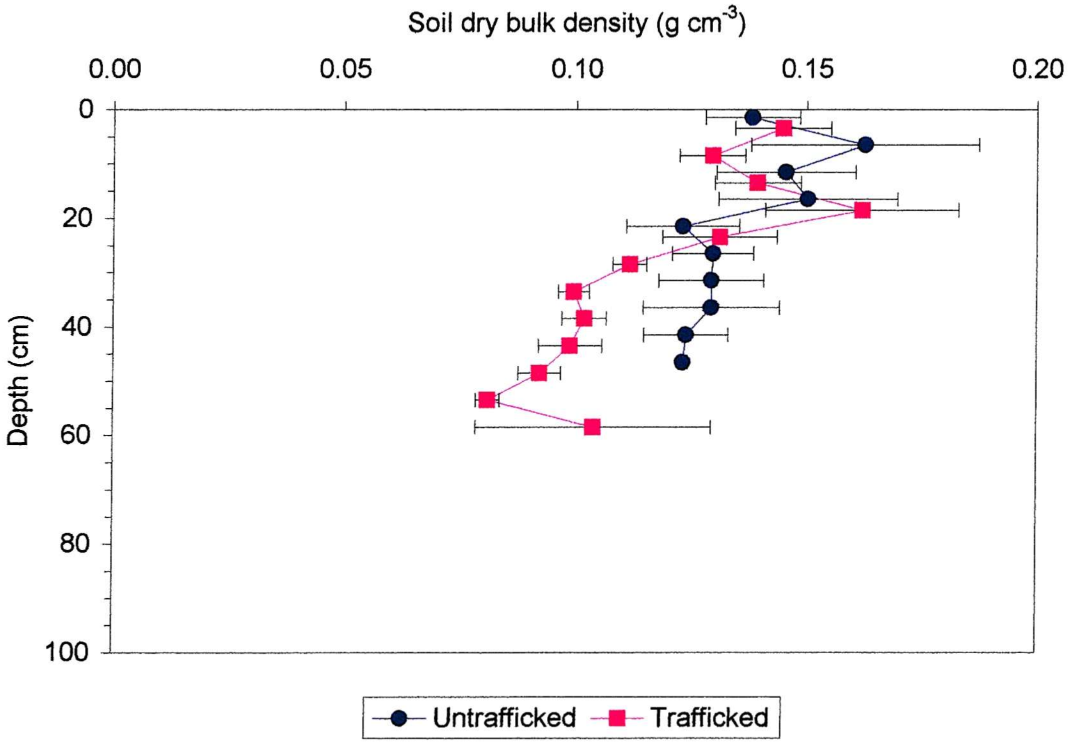


Figure 3.3b. Mean soil dry bulk density - site 02N.



Error bars represent ± 1 standard error. Figure 3.3b - limit to growth not shown, no O-A layer.

Figure 3.3c. Mean soil dry bulk density - site 03K.

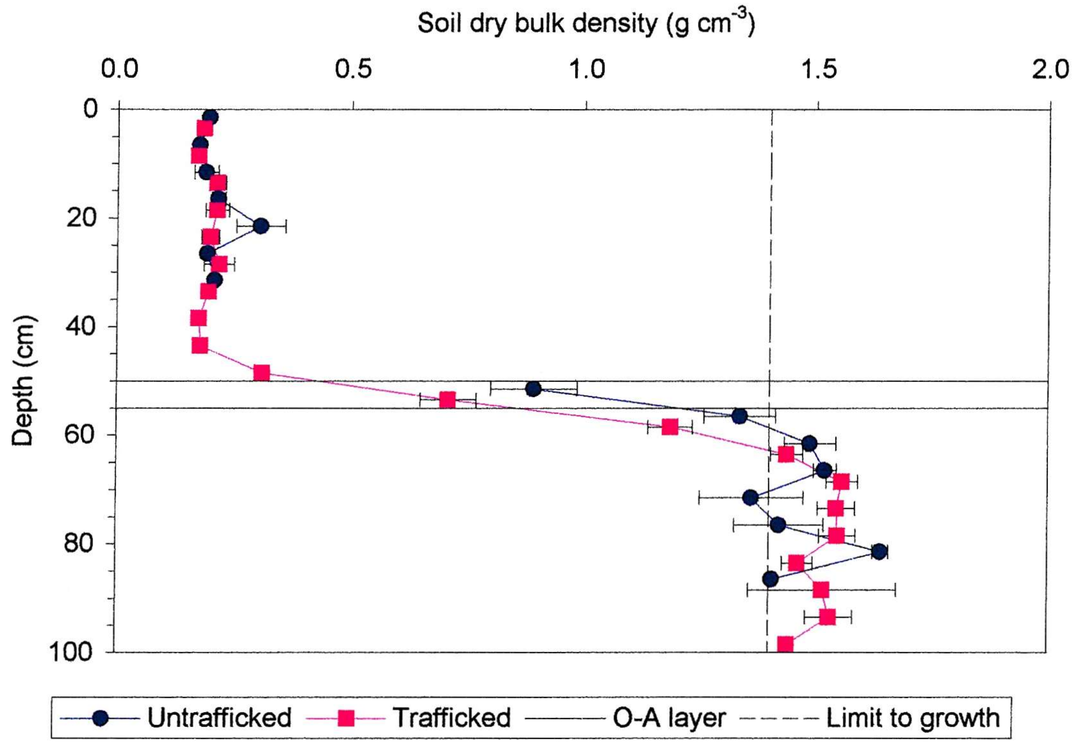
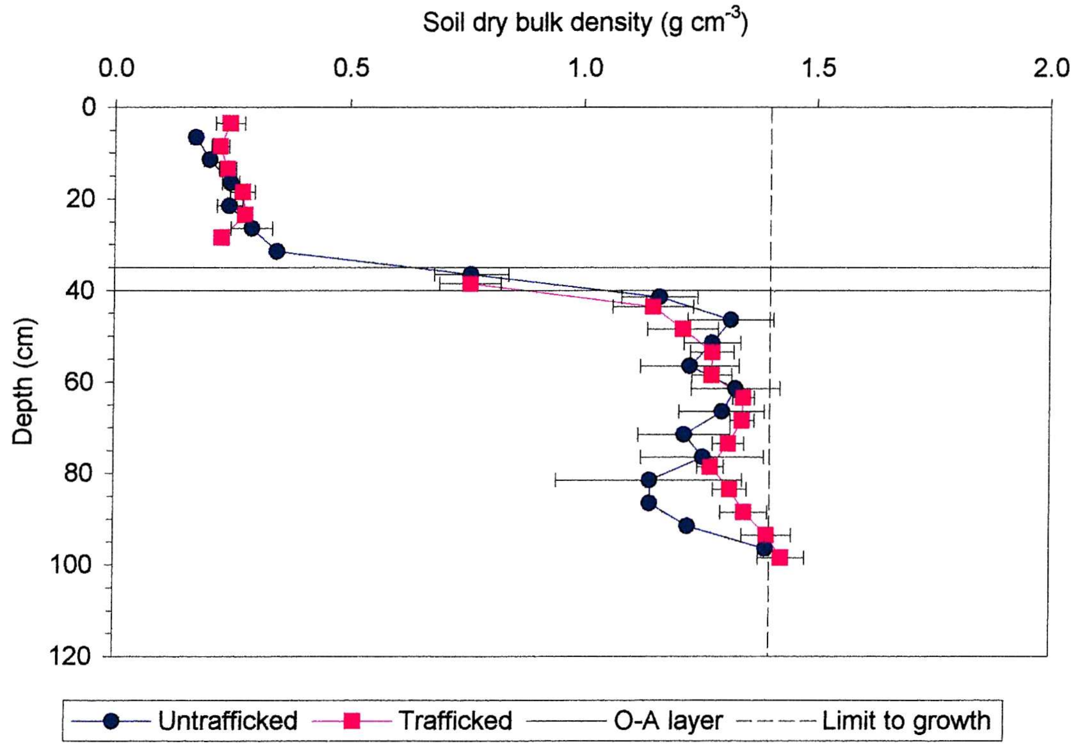


Figure 3.3d. Mean soil dry bulk density - site 04K.



Error bars represent ± 1 standard error.

Figure 3.3e. Mean soil dry bulk density - site 05K.

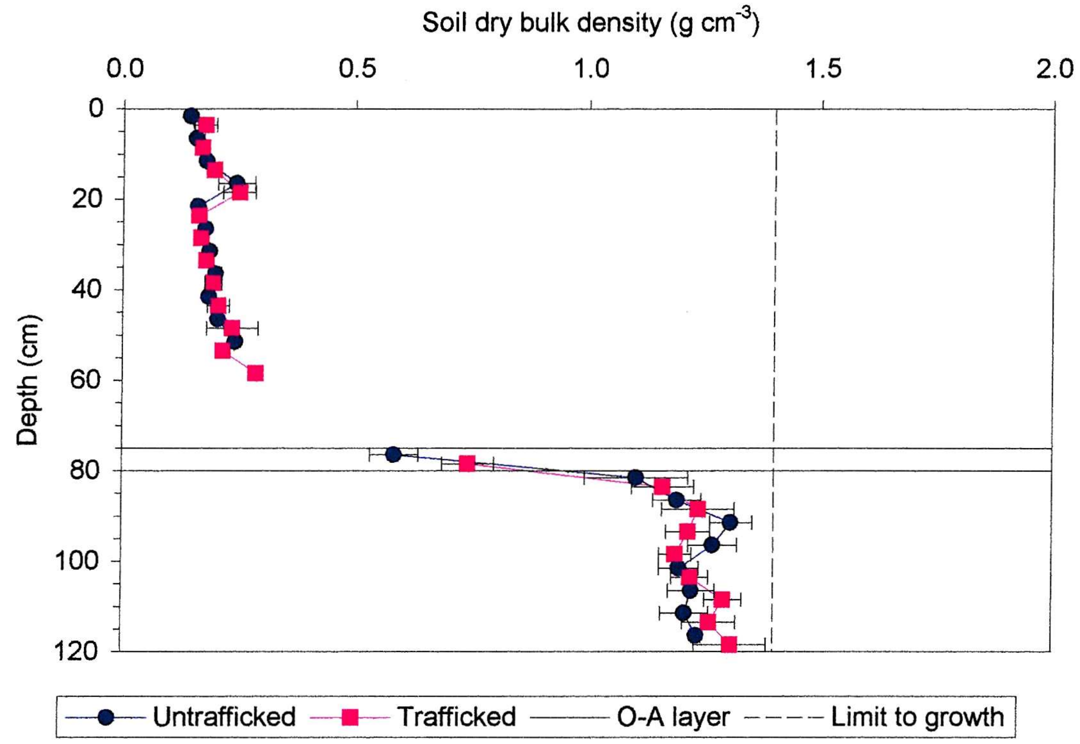
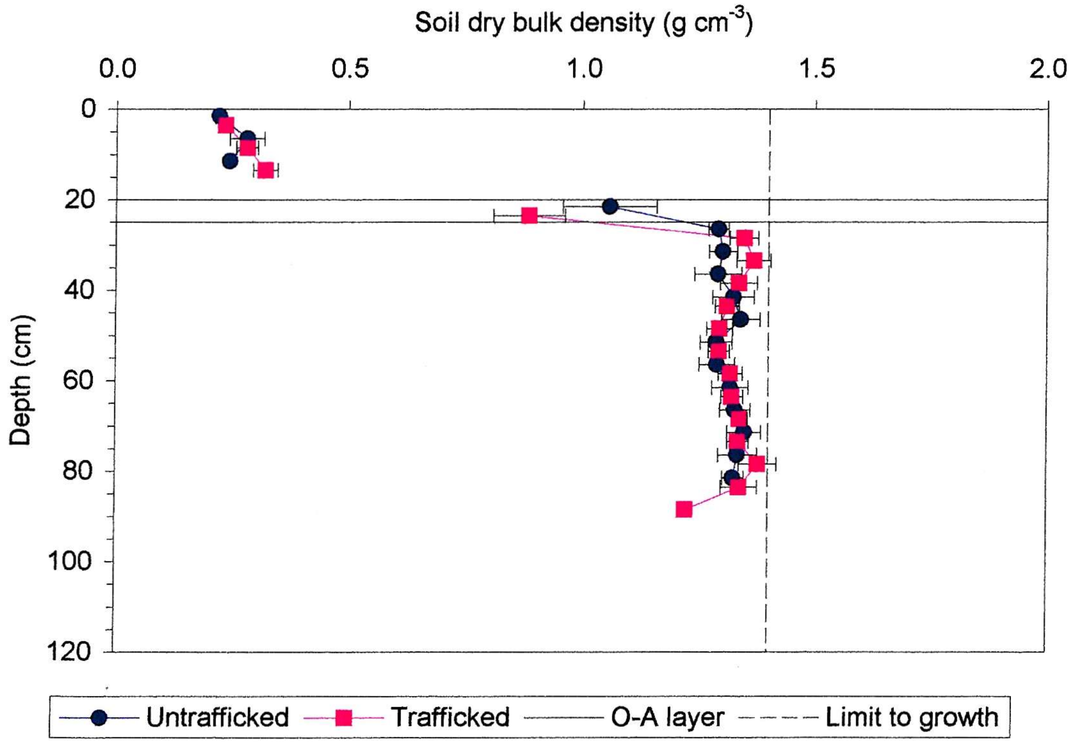


Figure 3.3f. Mean soil dry bulk density - site 06K.



Error bars represent ± 1 standard error.

Mean untrafficked (Tables 3.7a and 3.7b, p. 73-75) and trafficked (Tables 3.7c and 3.7d, p. 76-78) dry bulk density data for all depth increments at each site are summarised for the entire peat (O) layer (representing the effective rooting zone), the peat-mineral (O-A) layer and upper 30 cm portion of the mineral A-E layers (the latter representing the maximum depth of interest beyond which sample replication fell markedly). At all sites, mean untrafficked values throughout the O layer were below the potentially limiting value of 1.4 g cm^{-3}, and indicated the potential for increases in bulk density (assuming a maximum defined by the particle density of 1.4 g cm^{-3}, chapter 2, section 2.5). Throughout the O-A and A-E layers, mean untrafficked values approached 1.4 g cm^{-3}, and again indicated the potential for increases in bulk density assuming a maximum defined by the particle density of 2.65 g cm^{-3}, chapter 2, section 2.5), though these horizons did not constitute the effective rooting zone. Mean trafficked values of dry bulk density for all sites were either higher or lower than mean values from untrafficked areas, though in only a few cases were the differences found to be statistically significant (t-test assuming unequal variance, $p = 0.05$ or less).

Presented as percent differences from mean untrafficked values in Figures 3.4a-3.4b (p. 79) and following alignment at the peat-mineral (O-A) layer for clarity, the largest increases in dry bulk density were observed throughout the peaty (O) layer. At sites 01K and 03K, this was followed by a marked reduction in soil bulk density (similar to that observed at site 02N) becoming less marked with increasing depth beyond the O-A layer. At sites 04K, 05K and 06K the largest increases were observed throughout the O layer, large increases (05K) and decreases (04K and 06K) also took place at the O-A boundary, beyond which changes (either increases or decreases) in soil bulk density were minimal.

3.5. Trafficked soil penetration resistance.

The range of the Bush Recording Soil Penetrometer was 0-45 cm, much less than that of the coring apparatus, and as such best describes soil penetration resistance of the peat (O) layer and peat-mineral (O-A) layer. Hence, the depth reference for soil penetration resistance data was not re-defined as for soil

Table 3.7a. Summary of untrafficked soil dry bulk density (g cm^{-3}) - year 1 sites.

	Site																				
	01K							02N							03K						
Depth (cm)	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max
2.5	0.17	4	0.09	52	± 0.04	0.12	0.30	0.14	6	0.03	18	± 0.01	0.11	0.19	0.20	1				0.20	0.20
7.5	0.19	4	0.04	22	± 0.02	0.14	0.24	0.16	6	0.06	37	± 0.02	0.11	0.27	0.17	1				0.17	0.17
12.5	0.24	4	0.09	38	± 0.05	0.13	0.33	0.15	4	0.03	21	± 0.02	0.12	0.18	0.19	4	0.05	27	± 0.03	0.14	0.26
17.5	0.29	4	0.11	37	± 0.05	0.17	0.39	0.15	4	0.04	26	± 0.02	0.11	0.20	0.21	3	0.02	12	± 0.01	0.20	0.24
22.5	0.31	1				0.31	0.31	0.12	3	0.02	17	± 0.01	0.10	0.14	0.31	2	0.07	24	± 0.05	0.25	0.36
27.5								0.13	3	0.02	12	± 0.01	0.11	0.14	0.19	1				0.19	0.19
32.5								0.13	3	0.02	15	± 0.01	0.11	0.15	0.21	1				0.21	0.21
37.5								0.13	3	0.03	20	± 0.01	0.10	0.14							
42.5	**1.26**	**3**	**0.05**	**4**	**± 0.03**	**1.22**	**1.32**	0.12	3	0.02	13	± 0.01	0.11	0.14							
47.5	1.65	3	0.17	11	± 0.10	1.50	1.84	0.12	2	0.00	1	± 0.00	0.12	0.12							
52.5	1.56	3	0.24	16	± 0.14	1.33	1.81								**0.89**	**6**	**0.23**	**25**	**± 0.09**	**0.45**	**1.07**
57.5	1.46	3	0.15	10	± 0.09	1.29	1.56								1.34	5	0.17	13	± 0.08	1.21	1.62
62.5	1.50	3	0.16	11	± 0.09	1.31	1.61								1.49	6	0.14	9	± 0.06	1.33	1.64
67.5	1.22	1				1.22	1.22								1.52	6	0.06	4	± 0.02	1.46	1.61
72.5															1.36	6	0.27	20	± 0.11	0.86	1.64
77.5															1.42	3	0.17	12	± 0.10	1.24	1.57
82.5															1.64	2	0.02	1	± 0.02	1.62	1.66

N (number of samples), Std (standard deviation), Cv (coefficient of variation - %), Se (standard error), Min (minimum) and Max (maximum). Values in bold represent the O-A layer.

Table 3.7b. Summary of untrafficked soil dry bulk density (g cm^{-3}) - year 2 sites.

	Site																				
	04K							05K							06K						
Depth (cm)	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max
2.5								0.14	8	0.02	16	± 0.01	0.12	0.19	0.22	4	0.02	8	± 0.01	0.20	0.24
7.5	0.17	5	0.02	15	± 0.01	0.15	0.21	0.16	11	0.02	12	± 0.01	0.13	0.20	0.28	4	0.08	27	± 0.04	0.21	0.38
12.5	0.20	9	0.04	19	± 0.01	0.16	0.26	0.18	10	0.03	14	± 0.01	0.13	0.21	0.24	2	0.00	1	± 0.00	0.24	0.25
17.5	0.25	9	0.06	23	± 0.02	0.17	0.31	0.24	5	0.09	37	± 0.04	0.15	0.34							
22.5	0.24	2	0.04	16	± 0.03	0.22	0.27	0.16	2	0.01	4	± 0.00	0.16	0.17	**1.06**	**8**	**0.29**	**27**	**± 0.10**	**0.58**	**1.41**
27.5	0.29	2	0.06	21	± 0.04	0.25	0.34	0.18	2	0.01	5	± 0.01	0.17	0.18	1.29	10	0.07	5	± 0.02	1.14	1.37
32.5	0.35	1				0.35	0.35	0.19	2	0.00	2	± 0.00	0.18	0.19	1.30	12	0.11	8	± 0.03	1.14	1.50
37.5	**0.76**	**12**	**0.27**	**36**	**± 0.08**	**0.35**	**1.23**	0.20	2	0.02	9	± 0.01	0.19	0.21	1.29	9	0.15	12	± 0.05	1.11	1.61
42.5	1.16	12	0.28	24	± 0.08	0.45	1.40	0.19	1				0.19	0.19	1.33	11	0.15	11	± 0.04	1.06	1.62
47.5	1.32	11	0.31	23	± 0.09	0.48	1.58	0.20	1				0.20	0.20	1.34	11	0.14	10	± 0.04	1.21	1.61
52.5	1.28	10	0.19	15	± 0.06	0.80	1.45	0.24	1				0.24	0.24	1.29	11	0.11	9	± 0.03	1.11	1.43
57.5	1.23	10	0.33	27	± 0.11	0.35	1.51														
62.5	1.33	12	0.33	25	± 0.10	0.43	1.83														
67.5	1.30	11	0.31	24	± 0.09	0.43	1.62														
72.5																					
77.5								**0.59**	**9**	**0.16**	**27**	**± 0.05**	**0.32**	**0.76**							
82.5								1.10	10	0.35	32	± 0.11	0.40	1.47							
87.5								1.19	9	0.15	13	± 0.05	0.98	1.41							

N (number of samples), Std (standard deviation), Cv (coefficient of variation - %), Se (standard error), Min (minimum) and Max (maximum). Values in bold represent the O-A layer.

Table 3.7b. continued. Summary of untrafficked soil dry bulk density (g cm^{-3}) - year 2 sites.

	Site																				
	04K							05K							06K						
Depth (cm)	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max
92.5								1.31	9	0.14	10	± 0.05	1.16	1.54							
97.5								1.27	8	0.15	12	± 0.05	1.12	1.50							
102.5								1.20	8	0.12	10	± 0.04	1.02	1.34							
107.5								1.22	8	0.14	12	± 0.05	0.98	1.46							

N (number of samples), Std (standard deviation), Cv (coefficient of variation - %), Se (standard error), Min (minimum) and Max (maximum).

Table 3.7c. Summary of trafficked soil dry bulk density (g cm^{-3}) - year 1 sites.

	Site																				
	01K							02N							03K						
Depth (cm)	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max
2.5	0.19	18	0.06	32	± 0.01	0.10	0.33	0.14	9	0.03	21	± 0.01	0.09	0.19	0.18	1				0.18	0.18
7.5	0.23	15	0.09	40	± 0.02	0.11	0.49	0.13	12	0.02	19	± 0.01	0.10	0.19	0.17	8	0.03	19	± 0.01	0.13	0.23
12.5	0.21	8	0.09	45	± 0.03	0.12	0.39	0.14	14	0.03	25	± 0.01	0.10	0.21	0.21	16	0.07	33	± 0.02	0.14	0.36
17.5	0.17	4	0.02	13	± 0.01	0.14	0.19	0.16	14	0.08	48	± 0.02	0.09	0.33	0.21	12	0.09	41	± 0.03	0.15	0.43
22.5	0.20	3	0.05	24	± 0.03	0.16	0.25	0.13	11	0.04	31	± 0.01	0.10	0.21	0.20	8	0.05	27	± 0.02	0.15	0.30
27.5	0.27	2	0.11	40	± 0.08	0.19	0.34	0.11	9	0.01	10	± 0.00	0.10	0.13	0.22	7	0.09	40	± 0.03	0.15	0.39
32.5	0.16	1				0.16	0.16	0.10	8	0.01	10	± 0.00	0.09	0.12	0.19	5	0.04	19	± 0.02	0.17	0.26
37.5	0.15	1				0.15	0.15	0.10	5	0.01	10	± 0.00	0.08	0.11	0.17	2	0.01	7	± 0.01	0.17	0.18
42.5	__0.71**__	**15**	**0.32**	**45**	**± 0.08**	**0.34**	**1.54**	0.10	4	0.01	14	± 0.01	0.08	0.11	0.18	1				0.18	0.18
47.5	1.21**	15	0.34	28	± 0.09	0.75	1.79	0.1	2	0.01	7	± 0.00	0.09	0.10	0.31	1				0.31	0.31
52.5	1.35	13	0.40	29	± 0.11	0.81	2.22	0.1	2	0.00	4	± 0.00	0.08	0.08	**0.71**	**19**	**0.26**	**37**	**± 0.06**	**0.41**	**1.48**
57.5	1.37	13	0.32	23	± 0.09	0.84	2.00	0.10	2	0.04	35	± 0.03	0.08	0.13	1.19	19	0.21	18	± 0.05	0.79	1.53
62.5	1.38	11	0.34	25	± 0.10	0.85	2.02								1.44	15	0.14	10	± 0.04	1.19	1.61
67.5	1.35	9	0.40	30	± 0.13	0.95	1.95								1.56	12	0.12	7	± 0.03	1.29	1.70
72.5	1.40	9	0.42	30	± 0.14	1.06	2.17								1.55	13	0.14	9	± 0.04	1.35	1.83
77.5															1.55	11	0.13	8	± 0.04	1.34	1.73
82.5															1.46**	7	0.09	6	± 0.03	1.31	1.57

N (number of samples), Std (standard deviation), Cv (coefficient of variation - %), Se (standard error), Min (minimum) and Max (maximum). Values in bold represent the O-A layer. **mean trafficked soil bulk density significantly less than mean control soil bulk density (t-test assuming unequal variance, p = 0.05 or less).

Table 3.7d. Summary of trafficked soil dry bulk density (g cm^{-3}) - year 2 sites.

	Site																				
	04K							05K							06K						
Depth (cm)	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max
2.5	0.24	4	0.06	25	± 0.03	0.17	0.30	0.18	8	0.07	39	± 0.02	0.12	0.33	0.23	17	0.03	13	± 0.01	0.18	0.32
7.5	0.22*	11	0.06	28	± 0.02	0.15	0.36	0.17	13	0.05	28	± 0.01	0.12	0.28	0.28	9	0.07	25	± 0.02	0.18	0.42
12.5	0.24	13	0.07	28	± 0.02	0.16	0.39	0.20	13	0.06	29	± 0.02	0.15	0.35	0.32	3	0.05	14	± 0.03	0.27	0.35
17.5	0.27	7	0.07	26	± 0.03	0.19	0.40	0.25	10	0.11	45	± 0.04	0.14	0.48							
22.5	0.28	3	0.02	7	± 0.01	0.27	0.30	0.16	4	0.02	9	± 0.01	0.15	0.18	**0.89**	**16**	**0.31**	**35**	**± 0.08**	**0.43**	**1.38**
27.5	0.23	1				0.23	0.23	0.17	4	0.02	14	± 0.01	0.14	0.20	1.35	18	0.13	10	± 0.03	1.16	1.58
32.5								0.18	4	0.02	11	± 0.01	0.15	0.19	1.37	19	0.16	12	± 0.04	1.10	1.64
37.5	**0.76**	**22**	**0.31**	**40**	**± 0.07**	**0.33**	**1.39**	0.19	4	0.04	19	± 0.02	0.14	0.23	1.34	20	0.18	13	± 0.04	1.06	1.66
42.5	1.15	21	0.39	34	± 0.09	0.34	1.67	0.21	4	0.05	24	± 0.02	0.13	0.24	1.31	23	0.12	9	± 0.03	1.01	1.53
47.5	1.21	22	0.35	29	± 0.08	0.35	1.59	0.24	2	0.08	33	± 0.06	0.18	0.29	1.30	22	0.13	10	± 0.03	1.02	1.52
52.5	1.28	22	0.22	17	± 0.05	0.52	1.53	0.22	1				0.22	0.22	1.29	21	0.11	8	± 0.02	1.06	1.52
57.5	1.27	20	0.19	15	± 0.04	0.54	1.46	0.29	1				0.29	0.29							
62.5	1.34	21	0.11	8	± 0.02	1.16	1.64														
67.5	1.34	19	0.11	9	± 0.03	1.03	1.54														
72.5																					
77.5								**0.74**	**16**	**0.22**	**30**	**0.06**	**0.35**	**1.16**							
82.5								1.16	13	0.24	21	0.07	0.64	1.57							
87.5								1.24	16	0.31	25	0.08	0.38	1.65							

N (number of samples), Std (standard deviation), Cv (coefficient of variation - %), Se (standard error), Min (minimum) and Max (maximum). Values in bold represent the O-A layer. *mean trafficked soil bulk density significantly greater than mean control soil bulk density (t-test assuming unequal variance, p = 0.05 or less).

Table 3.7d. continued. Summary of trafficked soil dry bulk density (g cm^{-3}) - year 2 sites.

	Site																				
	04K							05K							06K						
Depth (cm)	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max
92.5								1.22	16	0.19	15	± 0.05	0.85	1.48							
97.5								1.19	14	0.13	11	± 0.03	0.94	1.34							
102.5								1.22	12	0.14	11	± 0.04	1.01	1.57							
107.5								1.29	9	0.12	9	± 0.04	1.08	1.53							

N (number of samples), Std (standard deviation), Cv (coefficient of variation - %), Se (standard error), Min (minimum) and Max (maximum).

Figure 3.4a. Percent difference between mean untrafficked and trafficked soil dry bulk density (g cm^{-3}) - year 1 sites.

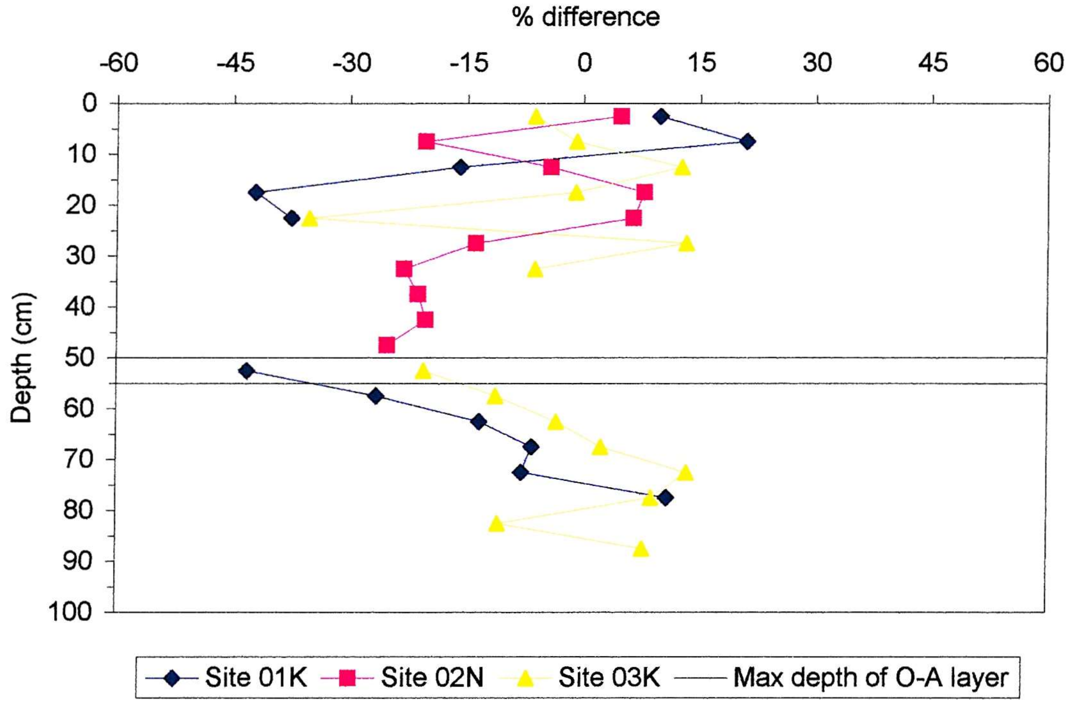
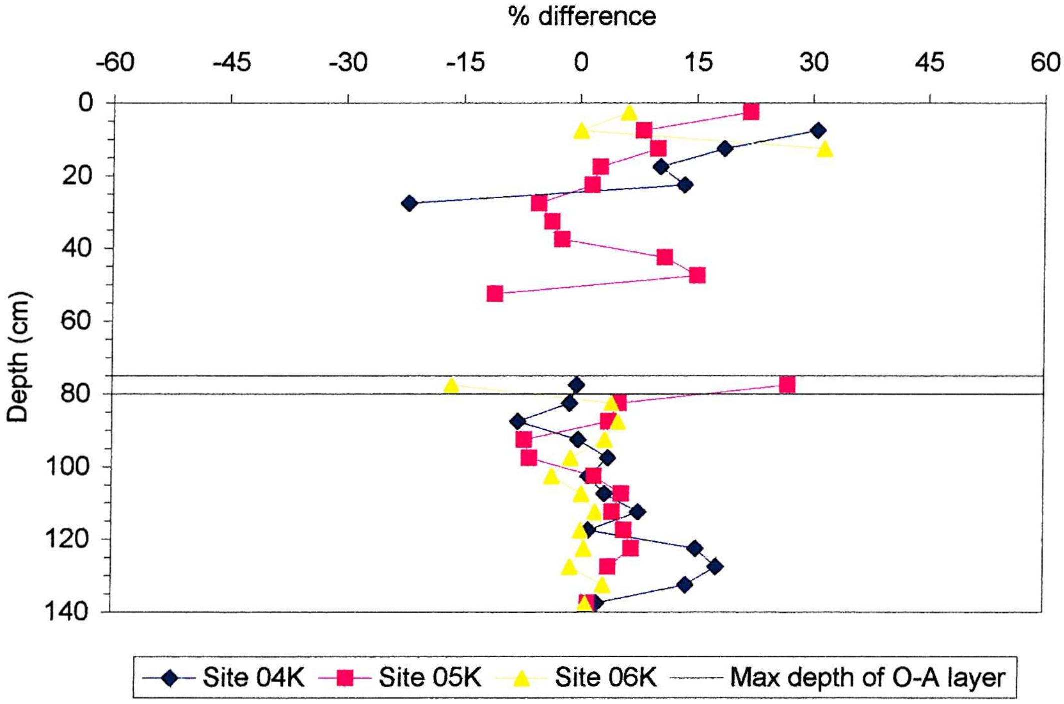


Figure 3.4b. Percent difference between mean trafficked and untrafficked soil dry bulk density (g cm^{-3}) - year 2 sites.



dry bulk density (chapter 2, section 2.5). Control data for soil penetration resistance at site 01K were collected from both an unfelled/untrafficked area of the operational stand and an adjacent untrafficked ride. Soil penetration resistance for the unfelled/untrafficked area of the operational stand was consistently higher than for the adjacent untrafficked ride, though differences between mean values were only significant between 0-12 cm (t-test assuming unequal variance, p = 0.05 or less). These differences were most likely due to the presence of the root mat and the compactive effect of the standing timber. Subsequent analysis of trafficked soil penetration resistance was carried out with reference to the unfelled/untrafficked forest control only, deemed more representative of background conditions.

For year 1 sites, mean untrafficked and trafficked values of soil penetration resistance (MPa) data at year 1 sites for all depth increments measured, are illustrated in Figures 3.5a-3.5c (p. 81-82), and summarised in Tables 3.8a and 3.8b (p. 83-84) for all depth increments up to and including 42-45 cm. A threshold of 2.5 MPa considered limiting to root/tree growth (chapter 1, section 1.3.2.1) is included for illustration. At site 01K, mean trafficked values were consistently lower than mean untrafficked values at all depths, and differences were found to be significant (t-test assuming unequal variance, p = 0.05 or less) at all depths except 21-27 cm. The opposite was observed at site 03K (except depths 36-39 cm), where mean trafficked values were often significantly higher than mean untrafficked values (t-test assuming unequal variance, p = 0.05 or less). At site 02N (the deep peat), mean trafficked values were higher than mean untrafficked values at all depths up to and including 24-27, and significant (t-test assuming unequal variance, p = 0.05 or less) at 0-3 cm and 9-18 cm. Beyond 25 cm, mean trafficked values were lower than means untrafficked values, though not significant (t-test assuming unequal variance, p = 0.05 or less). At each site, mean and maximum values for trafficked areas remained below the value of 2.5 MPa (chapter 1, section 1.3.2.1) where effects on root growth might be expected.

Figure 3.5a. Mean soil penetration resistance - site 01K.

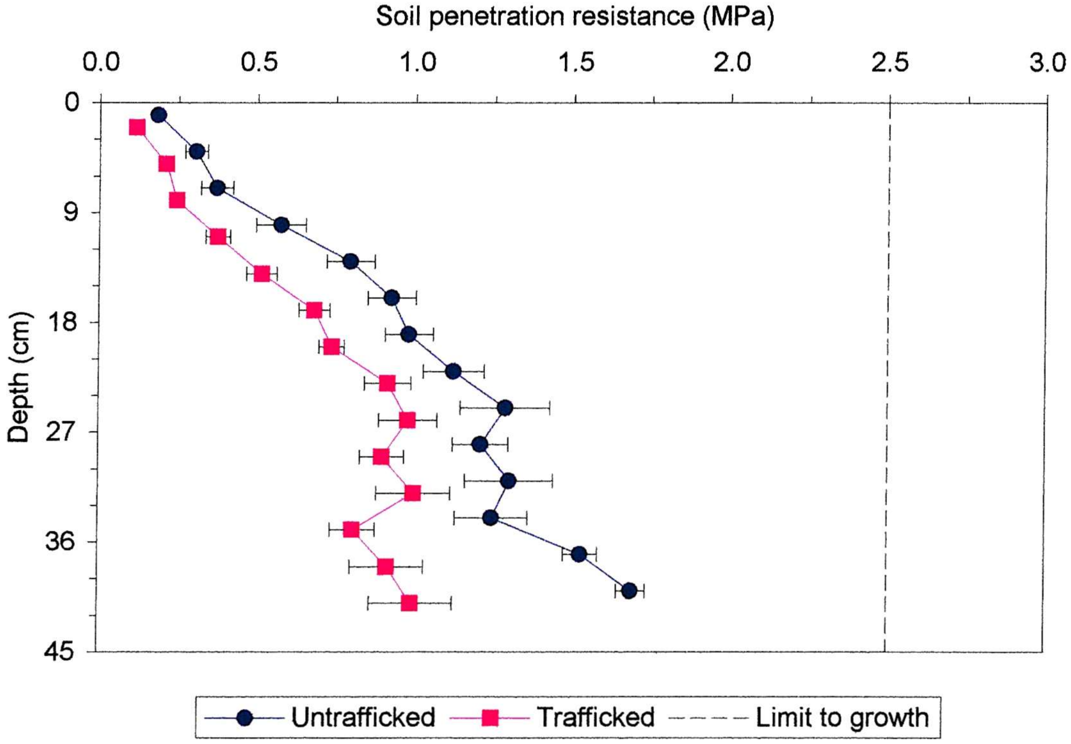
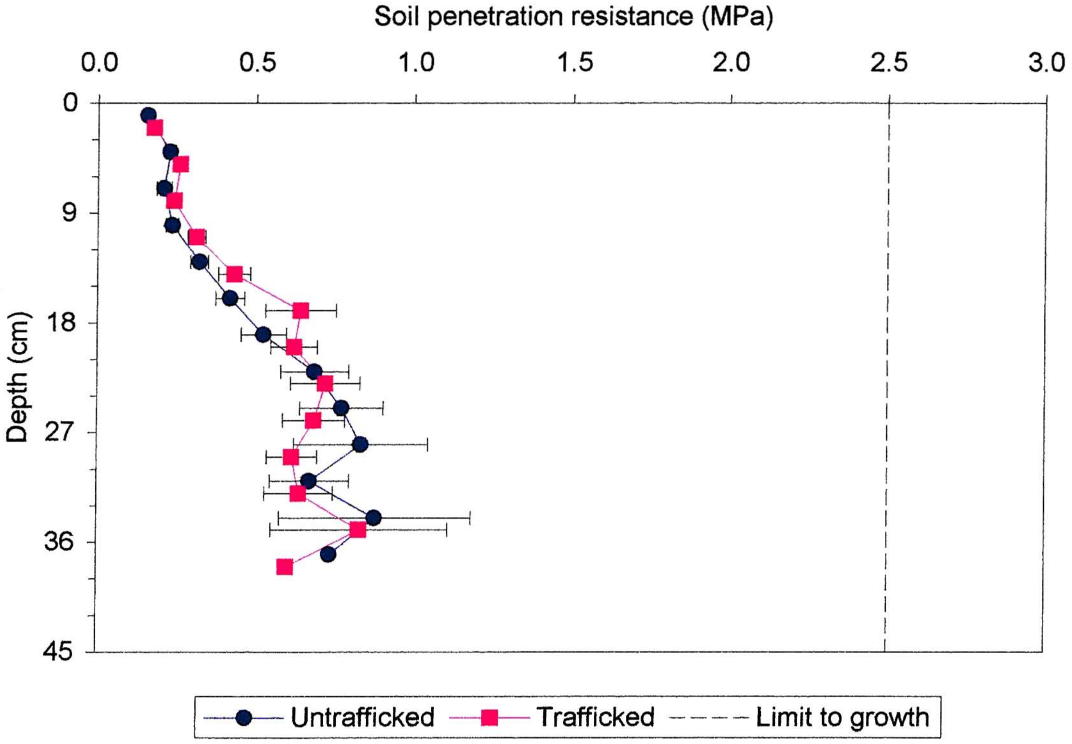
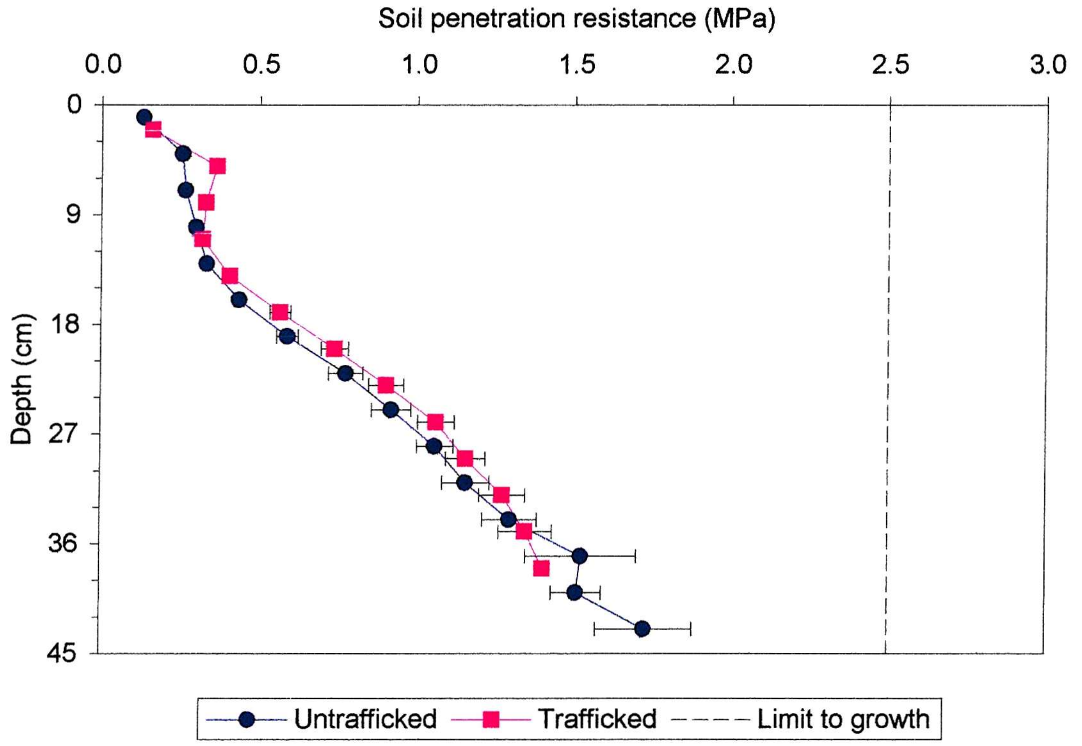


Figure 3.5b. Mean soil penetration resistance - site 02N.



Error bars represent ± 1 standard error.

Figure 3.5c. Mean soil penetration resistance - site 03K.



Error bars represent ± 1 standard error.

Table 3.8a. Mean untrafficked soil penetration resistance (MPa) - year 1 sites.

	Site																				
	01K							02N								03K					
Depth (cm)	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max
0-3	0.18	10	0.03	17	± 0.01	0.14	0.23	0.16	12	0.02	15	± 0.01	0.12	0.20	0.13	12	0.01	5	± 0.00	0.12	0.14
3-6	0.30	10	0.11	37	± 0.04	0.10	0.50	0.23	12	0.06	25	± 0.02	0.11	0.33	0.26	12	0.05	19	± 0.01	0.21	0.38
6-9	0.37	10	0.16	43	± 0.05	0.17	0.71	0.21	12	0.08	40	± 0.02	0.13	0.44	0.27	12	0.04	16	± 0.01	0.21	0.35
9-12	0.58	10	0.25	44	± 0.08	0.34	1.01	0.24	12	0.07	29	± 0.02	0.14	0.39	0.30	12	0.05	15	± 0.01	0.22	0.41
12-15	0.80	10	0.24	30	± 0.08	0.48	1.25	0.32	12	0.10	30	± 0.03	0.22	0.53	0.33	12	0.04	13	± 0.01	0.26	0.43
15-18	0.93	10	0.24	26	± 0.08	0.64	1.41	0.42	12	0.16	38	± 0.05	0.27	0.79	0.44	12	0.06	13	± 0.02	0.33	0.54
18-21	0.98	10	0.24	24	± 0.08	0.68	1.49	0.53	12	0.25	47	± 0.07	0.29	1.14	0.59	12	0.12	20	± 0.03	0.43	0.83
21-24	1.12	10	0.30	27	± 0.10	0.61	1.72	0.69	12	0.37	54	± 0.11	0.29	1.53	0.78	12	0.19	24	± 0.05	0.50	1.12
24-27	1.29	10	0.45	35	± 0.14	0.79	2.47	0.77	12	0.46	59	± 0.13	0.33	1.69	0.92	12	0.22	24	± 0.06	0.56	1.28
27-30	1.21	10	0.28	23	± 0.09	0.77	1.71	0.84	11	0.70	84	± 0.21	0.33	2.63	1.06	12	0.20	19	± 0.06	0.55	1.27
30-33	1.30	10	0.44	34	± 0.14	0.69	2.08	0.67	6	0.31	46	± 0.13	0.42	1.26	1.16	12	0.26	22	± 0.08	0.47	1.49
33-36	1.24	6	0.28	23	± 0.11	0.95	1.63	0.88	4	0.60	69	± 0.30	0.43	1.75	1.30	12	0.30	23	± 0.09	0.50	1.61
36-39	1.53	3	0.09	6	± 0.05	1.42	1.59	0.74	1				0.74	0.74	1.52	12	0.60	40	± 0.17	0.53	2.82
39-42	1.69	2	0.07	4	± 0.05	1.64	1.73								1.51	8	0.22	15	± 0.08	1.21	1.79
42-45															1.72	6	0.37	22	± 0.15	1.37	2.24

N (number of samples), Std (standard deviation), Cv (coefficient of variation - %), Se (standard error), Min (minimum) and Max (maximum).

Table 3.8b. Mean trafficked soil penetration resistance (MPa) - year 1 sites.

	Site																				
	01K							02N							03K						
Depth (cm)	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max
0-3	0.12**	20	0.04	35	±0.01	0.04	0.18	0.18*	22	0.03	18	±0.01	0.12	0.23	0.16*	24	0.03	19	±0.01	0.10	0.24
3-6	0.21**	20	0.07	32	±0.02	0.11	0.40	0.26	22	0.08	32	±0.02	0.11	0.47	0.36*	24	0.07	19	±0.01	0.22	0.49
6-9	0.24**	20	0.11	43	±0.02	0.15	0.52	0.24	22	0.09	38	±0.02	0.13	0.47	0.33*	24	0.08	23	±0.02	0.19	0.49
9-12	0.38**	20	0.18	47	±0.04	0.18	0.81	0.31*	22	0.13	42	±0.03	0.17	0.72	0.32	24	0.06	19	±0.01	0.23	0.48
12-15	0.52**	20	0.22	42	±0.05	0.29	1.20	0.43	22	0.24	55	±0.05	0.22	1.27	0.41*	24	0.09	23	±0.02	0.29	0.70
15-18	0.68**	20	0.22	32	±0.05	0.39	1.08	0.64	22	0.53	81	±0.11	0.26	2.51	0.57*	24	0.16	28	±0.03	0.40	1.09
18-21	0.74**	19	0.17	23	±0.04	0.56	1.05	0.62	21	0.34	55	±0.07	0.30	1.56	0.74*	24	0.21	29	±0.04	0.47	1.34
21-24	0.92	19	0.32	35	±0.07	0.60	1.65	0.72	20	0.49	68	±0.11	0.35	2.01	0.90	24	0.27	30	±0.06	0.55	1.76
24-27	0.98	18	0.39	39	±0.09	0.58	1.96	0.69	17	0.41	59	±0.10	0.36	1.62	1.06	24	0.29	27	±0.06	0.62	1.80
27-30	0.90**	17	0.29	32	±0.07	0.52	1.52	0.62	16	0.32	52	±0.08	0.36	1.46	1.16	24	0.31	27	±0.06	0.67	1.80
30-33	1.00	15	0.45	45	±0.12	0.48	2.00	0.64	13	0.39	61	±0.11	0.38	1.71	1.28	24	0.36	28	±0.07	0.64	1.93
33-36	0.81**	10	0.23	28	±0.07	0.51	1.13	0.83	8	0.79	95	±0.28	0.46	2.78	1.35	24	0.41	31	±0.08	0.70	2.09
36-39	0.92**	7	0.31	33	±0.12	0.58	1.27	0.60	1				0.60	0.60	1.40	22				0.70	2.46
39-42	0.99	2	0.19	19	±0.13	0.86	1.12														
42-45																					

N (number of samples), Std (standard deviation), Cv (coefficient of variation - %), Se (standard error), Min (minimum) and Max (maximum). *mean trafficked significantly greater than mean untrafficked (t-test assuming unequal variance, p = 0.05 or less), **mean trafficked soil penetration resistance significantly less than mean control soil penetration resistance (t-test assuming unequal variance, p = 0.05 or less).

For year 2 sites, mean untrafficked and trafficked values (not including central and adjacent areas of the extraction routes) of soil penetration resistance (MPa) data are illustrated in Figures 3.6a-3.6c (p. 86-87), for all depth increments (and for all ground treatments) up to and including 42-45 cm. A threshold of 2.5 MPa considered limiting to root/tree growth (chapter 1, section 1.3.2.1) is included for illustration. Mean values of untrafficked soil penetration resistance at year 2 sites are presented in Table 3.9a (p. 88). At sites 04K and 05K, mean trafficked values beneath the wheel tracks were often significantly higher than mean untrafficked values (t-test assuming unequal variance, p = 0.05 or less) at depths up to c. 30 cm (Tables 3.9b and 3.9c, p. 89-90). At site 06K, mean trafficked values were higher mean untrafficked values between 0-21 cm depth, and lower than mean untrafficked values between 21-45 cm depth. In each case, the statistical significance (t-test assuming unequal variance, p = 0.05 or less) of trafficked values at site 06K (Table 3.9d, p. 91) was less marked than those of sites 04K and 05K. Only at site 06K (at depths of c. 21-30 cm) did mean trafficked values approach the threshold of 2.5 MPa considered potentially limiting to root growth. However, this is a likely result of the shallow peat layer at this site with higher values indicative of the upper A-E layer.

Mean trafficked values of soil penetration resistance (MPa) are shown as percent differences from mean untrafficked values in Figures 3.7a, p. 92 (year 1 sites) and Figures 3.7b-3.7d, p.92-93 (year 2 sites). At site 01K, differences in soil penetration resistance showed no strong pattern with depth, at sites 02N and 03K the largest increases took place c. 15-18 cm (sites 02N) and c. 3-6 cm (site 03K), and became less marked with depth. At all year 2 sites, the largest increases took place under the wheel tracks, followed by those measured centrally (between the wheel tracks) and then laterally (adjacent to the wheel tracks) except at site 06K where the opposite occurred. At sites 04K, 05K and 06K, initially large increases at c. 6-9 cm, reflecting compression of the upper peat (O) layer, were followed by a marked reduction in response (increases or decreases) at c. 9-12 cm, beyond which differences in soil penetration resistance (increases or decreases) became less marked with depth.

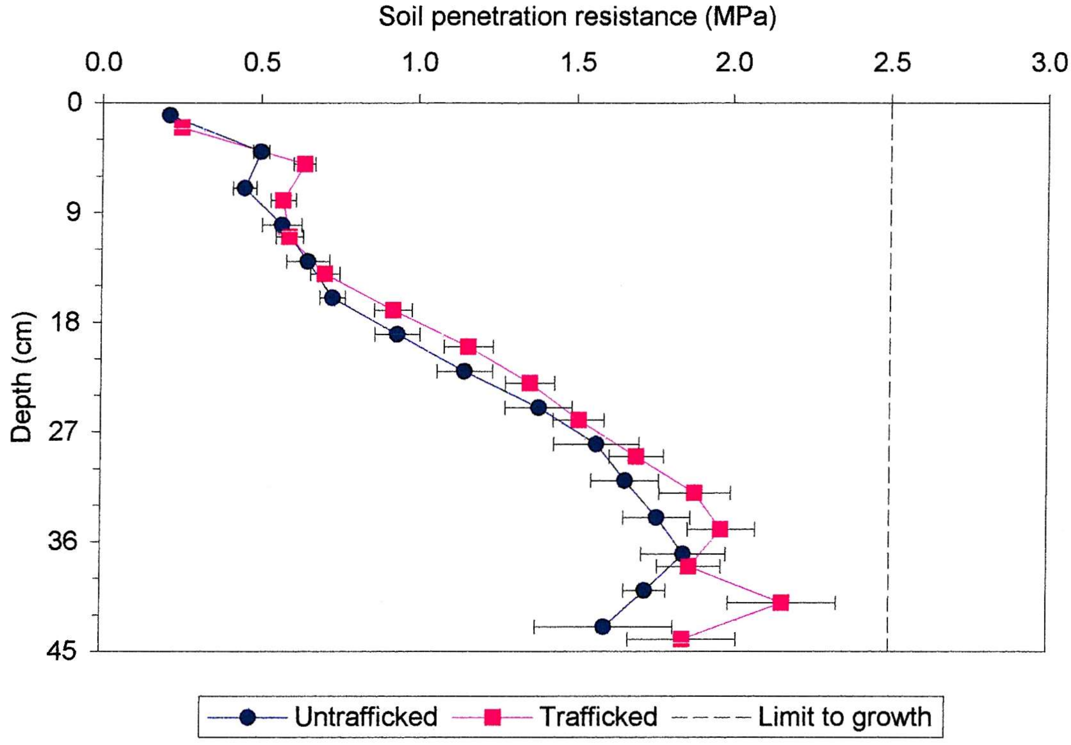


Figure 3.6a. Mean soil penetration resistance - site 04K.

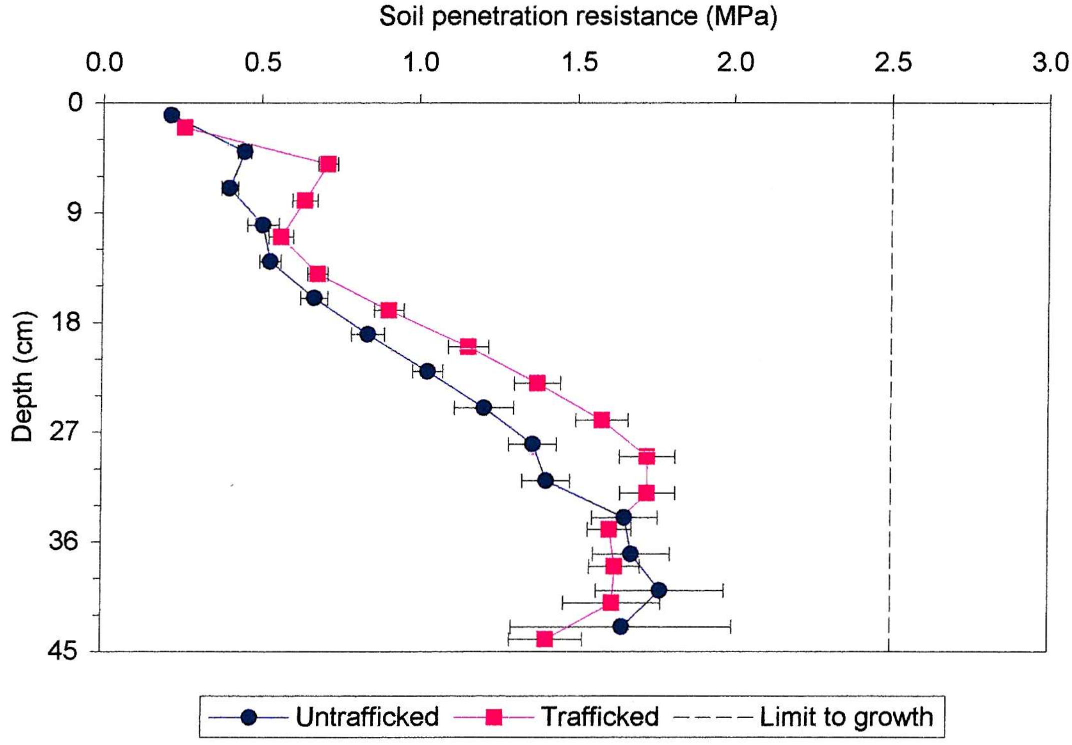
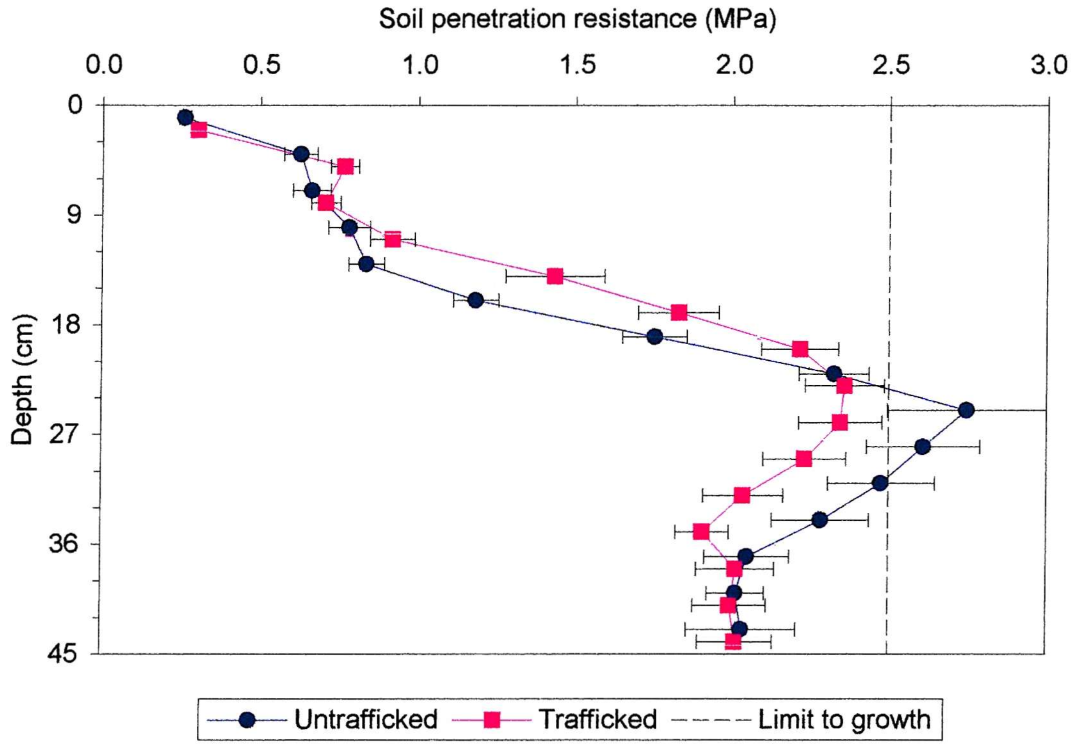


Figure 3.6b. Mean soil penetration resistance - site 05K.

Error bars represent ± 1 standard error.

Figure 3.6c. Mean soil penetration resistance - site 06K.



Error bars represent ± 1 standard error.

Table 3.9a. Mean untrafficked soil penetration resistance (MPa) - year 2 sites.

	Site																				
	04K							05K							06K						
Depth (cm)	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max
0-3	0.21	12	0.03	15	± 0.01	0.14	0.27	0.21	12	0.04	17	± 0.01	0.15	0.29	0.26	12	0.06	25	± 0.02	0.17	0.39
3-6	0.50	12	0.09	18	± 0.03	0.36	0.66	0.45	12	0.08	17	± 0.02	0.30	0.55	0.63	12	0.18	29	± 0.05	0.36	1.03
6-9	0.45	12	0.13	29	± 0.04	0.28	0.75	0.40	12	0.09	23	± 0.03	0.23	0.56	0.66	12	0.20	31	± 0.06	0.40	0.95
9-12	0.57	12	0.22	38	± 0.06	0.30	0.97	0.51	12	0.18	35	± 0.05	0.26	0.97	0.78	12	0.23	29	± 0.07	0.45	1.17
12-15	0.65	12	0.24	37	± 0.07	0.38	1.25	0.53	12	0.12	23	± 0.03	0.36	0.84	0.84	12	0.20	24	± 0.06	0.56	1.26
15-18	0.73	12	0.14	19	± 0.04	0.51	0.94	0.67	12	0.15	22	± 0.04	0.46	1.03	1.19	12	0.25	21	± 0.07	0.94	1.90
18-21	0.94	12	0.25	26	± 0.07	0.54	1.43	0.84	12	0.18	22	± 0.05	0.49	1.17	1.75	12	0.35	20	± 0.10	1.14	2.45
21-24	1.15	12	0.30	26	± 0.09	0.72	1.77	1.03	12	0.17	16	± 0.05	0.78	1.25	2.33	12	0.39	17	± 0.11	1.55	2.85
24-27	1.38	12	0.37	26	± 0.11	0.97	2.04	1.21	12	0.32	27	± 0.09	0.72	1.77	2.75	12	0.87	32	± 0.25	1.56	5.00
27-30	1.57	12	0.47	30	± 0.14	1.05	2.37	1.36	12	0.26	19	± 0.08	0.96	1.85	2.61	11	0.60	23	± 0.18	1.85	3.56
30-33	1.66	12	0.37	23	± 0.11	1.10	2.36	1.41	12	0.26	19	± 0.08	1.02	1.81	2.48	11	0.57	23	± 0.17	1.89	3.32
33-36	1.76	12	0.37	21	± 0.11	1.18	2.29	1.66	12	0.36	22	± 0.10	1.08	2.09	2.28	11	0.52	23	± 0.16	1.75	3.41
36-39	1.85	12	0.47	25	± 0.14	1.14	2.56	1.68	12	0.42	25	± 0.12	0.99	2.43	2.05	11	0.45	22	± 0.13	1.51	2.81
39-42	1.72	11	0.22	13	± 0.07	1.37	2.04	1.77	9	0.61	34	± 0.20	1.23	3.18	2.01	11	0.30	15	± 0.09	1.69	2.78
42-45	1.60	5	0.49	31	± 0.22	0.93	2.30	1.65	4	0.70	43	± 0.35	1.11	2.59	2.03	7	0.46	23	± 0.17	1.67	3.02

N (number of samples), Std (standard deviation), CV (coefficient of variation - %), SE (standard error), Min (minimum) and Max (maximum).

Table 3.9b. Mean trafficked soil penetration resistance (MPa) - site 04K.

	Location																				
	Tracks							Central area								Adjacent area						
Depth (cm)	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max
0-3	0.25*	24	0.06	23	± 0.01	0.14	0.38	0.20	12	0.06	30	± 0.02	0.08	0.32	0.22	24	0.05	21	± 0.01	0.14	0.31
3-6	0.64*	24	0.17	27	± 0.03	0.29	0.97	0.49	12	0.09	18	± 0.03	0.29	0.62	0.50	24	0.11	22	± 0.02	0.33	0.76
6-9	0.57*	24	0.20	34	± 0.04	0.29	1.11	0.45	12	0.11	25	± 0.03	0.30	0.60	0.45	24	0.14	32	± 0.03	0.27	0.92
9-12	0.59	24	0.21	35	± 0.04	0.31	0.98	0.54	12	0.10	18	± 0.03	0.34	0.66	0.50	24	0.13	25	± 0.03	0.29	0.88
12-15	0.71	24	0.23	33	± 0.05	0.41	1.16	0.65	12	0.16	24	± 0.04	0.44	0.91	0.57	24	0.11	19	± 0.02	0.37	0.82
15-18	0.92*	24	0.29	32	± 0.06	0.49	1.51	0.87	12	0.31	36	± 0.09	0.57	1.51	0.73	24	0.17	24	± 0.04	0.46	1.26
18-21	1.16	24	0.38	33	± 0.08	0.65	2.18	1.11	12	0.40	36	± 0.12	0.70	1.92	0.95	24	0.29	31	± 0.06	0.58	2.03
21-24	1.36	24	0.38	28	± 0.08	0.75	2.10	1.38	12	0.51	37	± 0.15	0.91	2.35	1.21	24	0.53	44	± 0.11	0.71	3.45
24-27	1.51	24	0.39	26	± 0.08	0.88	2.33	1.51	12	0.46	30	± 0.13	1.00	2.39	1.41	24	0.38	27	± 0.08	0.88	2.63
27-30	1.70	24	0.42	25	± 0.09	1.06	2.60	1.66	12	0.44	27	± 0.13	1.14	2.52	1.57	24	0.38	24	± 0.08	1.02	2.67
30-33	1.88	24	0.56	30	± 0.11	1.14	3.40	1.84	12	0.52	29	± 0.15	1.16	2.97	1.70	24	0.36	21	± 0.07	1.14	2.43
33-36	1.97	24	0.53	27	± 0.11	1.23	2.99	1.81	12	0.53	29	± 0.15	1.22	3.04	1.83	23	0.45	24	± 0.09	1.19	2.71
36-39	1.87	23	0.49	26	± 0.10	1.16	2.83	2.06	12	0.73	35	± 0.21	1.26	3.79	2.04	22	0.56	28	± 0.12	1.34	3.13
39-42	2.16	19	0.75	35	± 0.17	1.31	3.39	1.82	8	0.41	22	± 0.14	1.20	2.45	2.03	16	0.63	31	± 0.16	1.39	3.15
42-45	1.84	10	0.54	30	± 0.17	1.33	3.01	1.73	6	0.37	21	± 0.15	1.24	2.14	2.19	11	0.80	36	± 0.24	1.38	3.75

N (number of samples), Std (standard deviation), Cv (coefficient of variation - %), Se (standard error), Min (minimum) and Max (maximum). *mean trafficked soil penetration resistance significantly greater than mean untrafficked soil penetration resistance (t-test assuming unequal variance, p = 0.05 or less).

Table 3.9c. Mean trafficked soil penetration resistance (MPa) - site 05K.

	Location																				
	Tracks							Central area							Adjacent area						
Depth (cm)	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max
0-3	0.26*	24	0.05	18	± 0.01	0.17	0.38	0.24	12	0.05	20	± 0.01	0.15	0.31	0.22	24	0.04	18	± 0.01	0.16	0.28
3-6	0.71*	24	0.15	21	± 0.03	0.47	1.06	0.55	12	0.16	30	± 0.05	0.38	0.89	0.49	24	0.15	31	± 0.03	0.31	1.01
6-9	0.64*	24	0.20	31	± 0.04	0.31	1.20	0.49*	12	0.11	23	± 0.03	0.35	0.63	0.45	24	0.14	32	± 0.03	0.28	0.90
9-12	0.56	24	0.19	34	± 0.04	0.35	1.18	0.55	12	0.17	31	± 0.05	0.35	0.90	0.46	24	0.11	23	± 0.02	0.27	0.65
12-15	0.68*	24	0.16	23	± 0.03	0.45	1.07	0.72	12	0.42	59	± 0.12	0.39	1.97	0.50	24	0.09	18	± 0.02	0.32	0.74
15-18	0.91*	24	0.23	25	± 0.05	0.61	1.47	0.77	12	0.22	29	± 0.06	0.46	1.30	0.62	24	0.10	16	± 0.02	0.40	0.82
18-21	1.16*	24	0.31	27	± 0.06	0.69	2.12	0.92	12	0.18	19	± 0.05	0.62	1.32	0.82	24	0.18	21	± 0.04	0.50	1.29
21-24	1.38*	24	0.36	26	± 0.07	0.82	2.54	1.11	12	0.17	15	± 0.05	0.85	1.38	0.99	24	0.16	16	± 0.03	0.62	1.21
24-27	1.58*	24	0.41	26	± 0.08	0.91	2.43	1.41	12	0.31	22	± 0.09	0.93	1.97	1.19	24	0.22	18	± 0.04	0.72	1.60
27-30	1.73*	24	0.43	25	± 0.09	0.98	2.70	1.47	12	0.37	25	± 0.11	1.01	2.22	1.46	24	0.36	25	± 0.07	0.80	2.15
30-33	1.73*	24	0.43	25	± 0.09	1.08	2.74	1.59	12	0.42	27	± 0.12	1.03	2.54	1.57	24	0.49	31	± 0.10	0.84	3.26
33-36	1.61	24	0.34	21	± 0.07	0.95	2.20	1.59	12	0.41	26	± 0.12	1.10	2.66	1.66	23	0.51	31	± 0.11	0.99	3.48
36-39	1.62	22	0.38	23	± 0.08	1.16	2.70	1.93	10	0.83	43	± 0.26	0.89	3.46	1.69	22	0.53	31	± 0.11	1.05	3.38
39-42	1.62	14	0.58	36	± 0.15	0.90	3.19	1.41	5	0.82	58	± 0.36	0.11	2.21	1.66	17	0.56	34	± 0.13	1.07	2.89
42-45	1.41	2	0.16	12	± 0.12	1.29	1.52	0.23	1				0.23	0.23	2.08	10	1.07	51	± 0.34	1.18	4.32

N (number of samples), Std (standard deviation), Cv (coefficient of variation - %), Se (standard error), Min (minimum) and Max (maximum). *mean trafficked soil penetration resistance significantly greater than mean untrafficked soil penetration resistance (t-test assuming unequal variance, p = 0.05 or less).

Table 3.9d. Mean trafficked soil penetration resistance (MPa) - site 06K.

	Location																				
	Tracks							Central area							Adjacent area						
Depth (cm)	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max	Mean	N	Std	Cv	Se	Min	Max
0-3	0.30	24	0.08	28	± 0.02	0.19	0.47	0.31	12	0.07	22	± 0.02	0.18	0.40	0.28	24	0.07	26	± 0.01	0.19	0.49
3-6	0.77	24	0.22	29	± 0.04	0.41	1.23	0.62	12	0.09	15	± 0.03	0.43	0.77	0.61	24	0.11	18	± 0.02	0.44	0.86
6-9	0.71	24	0.23	32	± 0.05	0.35	1.12	0.61	12	0.11	18	± 0.03	0.38	0.79	0.63	24	0.21	33	± 0.04	0.37	1.28
9-12	0.92	24	0.35	38	± 0.07	0.42	1.92	0.64	12	0.16	25	± 0.05	0.37	0.84	0.72	24	0.25	35	± 0.05	0.38	1.29
12-15	1.44*	24	0.77	53	± 0.16	0.73	4.04	0.91	12	0.29	32	± 0.08	0.52	1.43	0.96	24	0.31	32	± 0.06	0.57	1.73
15-18	1.83*	24	0.63	34	± 0.13	1.01	3.16	1.18	12	0.42	36	± 0.12	0.63	2.02	1.27	24	0.46	36	± 0.09	0.66	2.51
18-21	2.22*	24	0.60	27	± 0.12	0.96	3.08	1.57	12	0.61	39	± 0.18	0.83	2.70	1.67	24	0.54	33	± 0.11	0.97	3.08
21-24	2.36	24	0.62	26	± 0.13	1.11	3.74	1.99	12	0.56	28	± 0.16	1.23	2.79	2.12	24	0.61	29	± 0.12	1.32	4.00
24-27	2.35	24	0.65	28	± 0.13	1.17	3.48	2.25	12	0.49	22	± 0.14	1.72	2.82	2.43	24	0.64	26	± 0.13	1.79	4.41
27-30	2.23	24	0.65	29	± 0.13	1.27	3.64	2.44	12	0.56	23	± 0.16	1.77	3.40	2.56	24	0.86	33	± 0.17	1.53	5.52
30-33	2.04	24	0.63	31	± 0.13	0.91	3.43	2.36	12	0.47	20	± 0.13	1.81	3.08	2.35	24	0.64	27	± 0.13	1.38	4.19
33-36	1.91	24	0.42	22	± 0.09	1.23	2.65	2.12	12	0.51	24	± 0.15	1.42	2.88	2.17	24	0.52	24	± 0.11	1.18	3.37
36-39	2.01	22	0.58	29	± 0.12	1.23	3.00	1.94	12	0.61	32	± 0.18	1.24	3.36	2.03	24	0.51	25	± 0.10	1.11	3.37
39-42	1.99	21	0.54	27	± 0.12	1.27	3.00	1.95	10	0.51	26	± 0.16	1.37	3.02	2.03	22	0.53	26	± 0.11	1.44	3.94
42-45	2.01	13	0.43	21	± 0.12	1.44	2.71	1.58**	7	0.24	15	± 0.09	1.20	1.82	1.94	15	0.56	29	± 0.14	1.30	3.01

N (number of samples), Std (standard deviation), Cv (coefficient of variation - %), Se (standard error), Min (minimum) and Max (maximum). *mean disturbed > mean control (t-test assuming unequal variance, p = 0.05 or less), **mean trafficked soil penetration resistance less than mean untrafficked soil penetration resistance (t-test assuming unequal variance, p = 0.05 or less).

Figure 3.7a. Percent difference between mean untrafficked and trafficked soil penetration resistance (MPa) - year 1 sites.

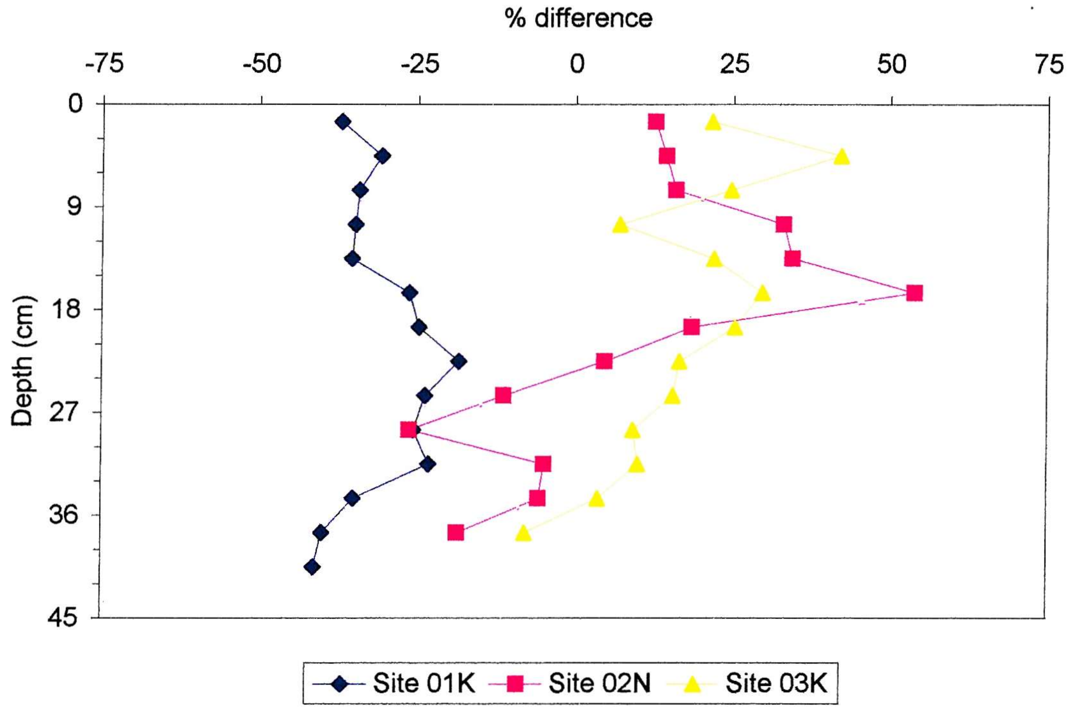


Figure 3.7b. Percent difference between mean untrafficked and trafficked soil penetration resistance (MPa) - site 04K.

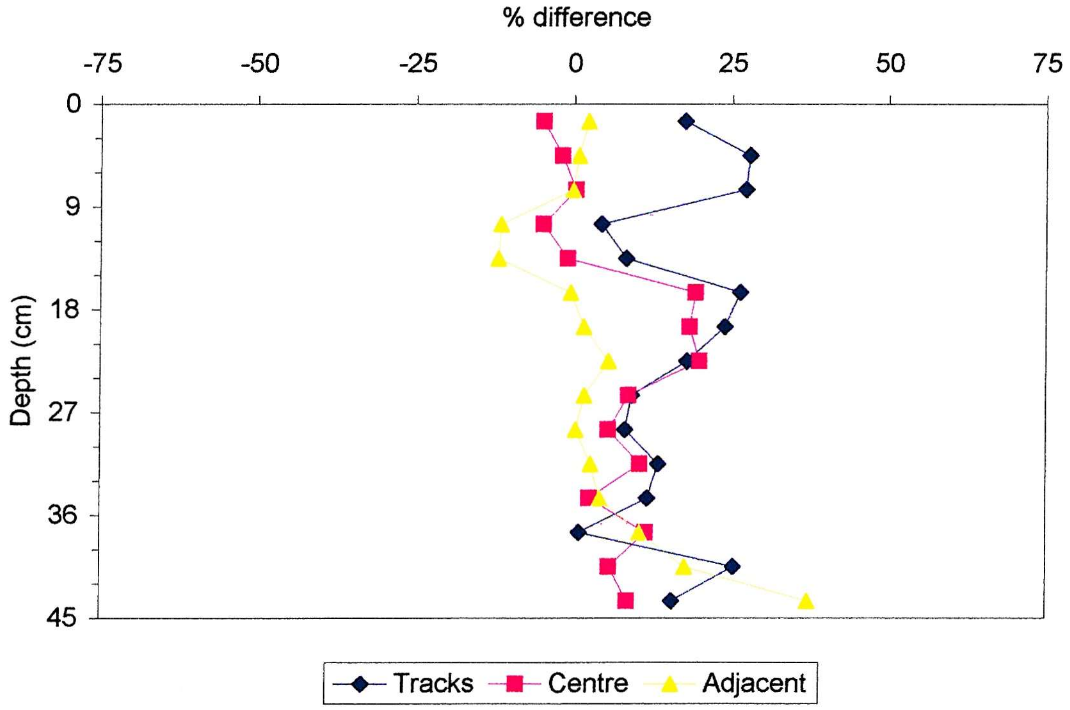


Figure 3.7c. Percent difference between mean untrafficked and trafficked soil penetration resistance (MPa) - site 05K.

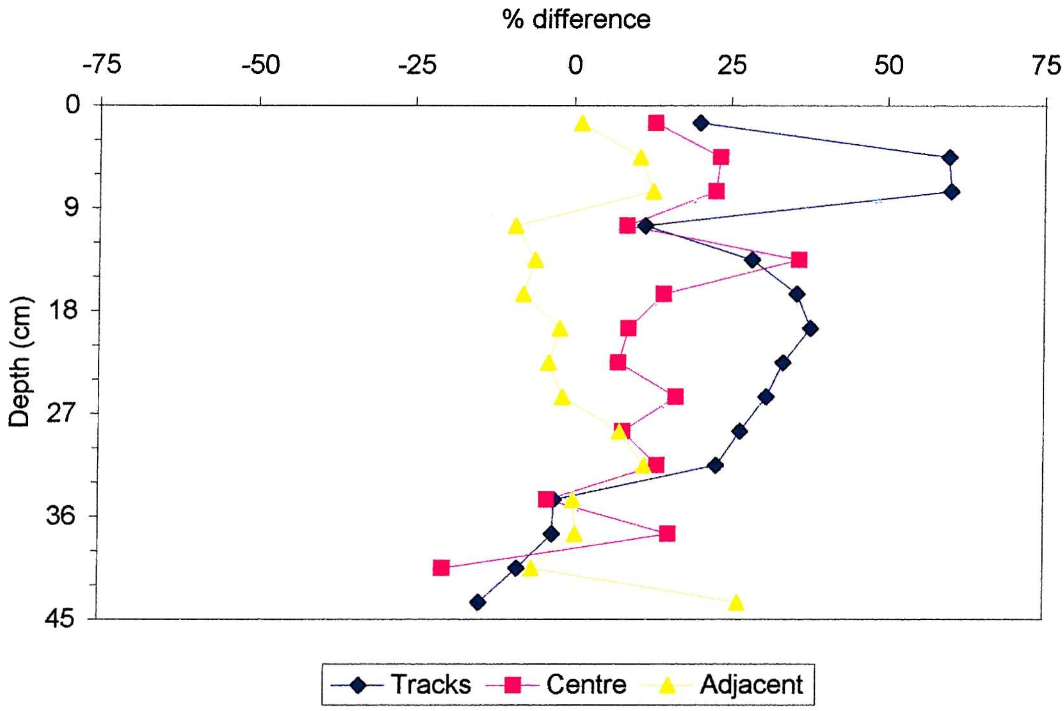
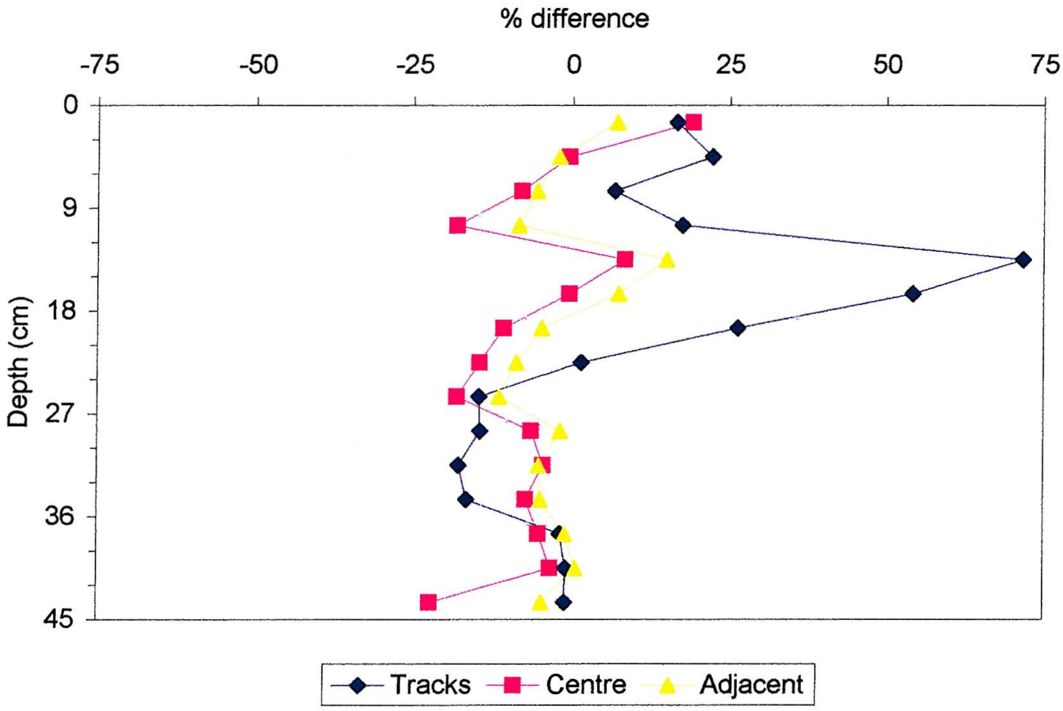


Figure 3.7d. Percent difference between mean untrafficked and trafficked soil penetration resistance (MPa) - site 06K.



The profiles of mean trafficked soil penetration resistance at year 2 sites are presented in Figures 3.8a - 3.8c (p. 95-96). Mean trafficked values at 0-45 cm depths (under the right and left wheel tracks, between the wheel tracks, and to the right and left of the wheel tracks) were either higher or lower than mean untrafficked values. The pattern of soil response across the profile at each depth increment did not suggest that there was a loading effect (e.g. a bias towards larger increases under the right wheel tracks) due to the position of cut timber (always on the right hand side during loading). Changes in soil penetration resistance between and adjacent to the wheel tracks were rarely significant (t-test assuming unequal variance, $p = 0.05$ or less, Tables 3.9b-3.9d, p. 89-91).

3.6. Trafficked soil total porosity and saturated hydraulic conductivity.

Mean untrafficked and trafficked values of total porosity derived at each site for the entire peat (O) layer, considered to represent the effective rooting zone (chapter 2, section 2.1), are presented in Table 3.10 (p. 97). As total porosity is a derivative of soil bulk density and particle density, the significance of any changes in total porosity, and size of associated errors, was assumed to be reflected by the values of bulk density presented above (section 3.4). As such, total porosity was considered to show very little change for either the O layer or deeper mineral (A-E) layers (not shown).

At sites 05K and 06K, the mean value of trafficked saturated hydraulic conductivity (K_S) for the upper mineral (A) layer was smaller than the mean untrafficked value (Figure 3.9, p. 98). Mean values for the untrafficked areas at both sites (Table 3.11, p.97) were comparable ($1.4\text{x}10^{-2}$ and $1.6\text{x}10^{-2}$ mm s^{-1} at sites 05K and 06K respectively) and typical for a silty soil of low permeability (e.g., 10^{-2} - 10^{-4} mm s^{-1} ~ Carter and Bentley, 1991). Mean trafficked values at site 05K showed an overall reduction in saturated hydraulic conductivity of approximately 35% though at site 06K a reduction of approximately 75% was observed. However, as a result of the high levels of variance, neither was found to be statistically significant (t-test assuming unequal variance, $p = 0.05$ or less).

Figure 3.8a. Profile of mean soil penetration resistance - site 04K.

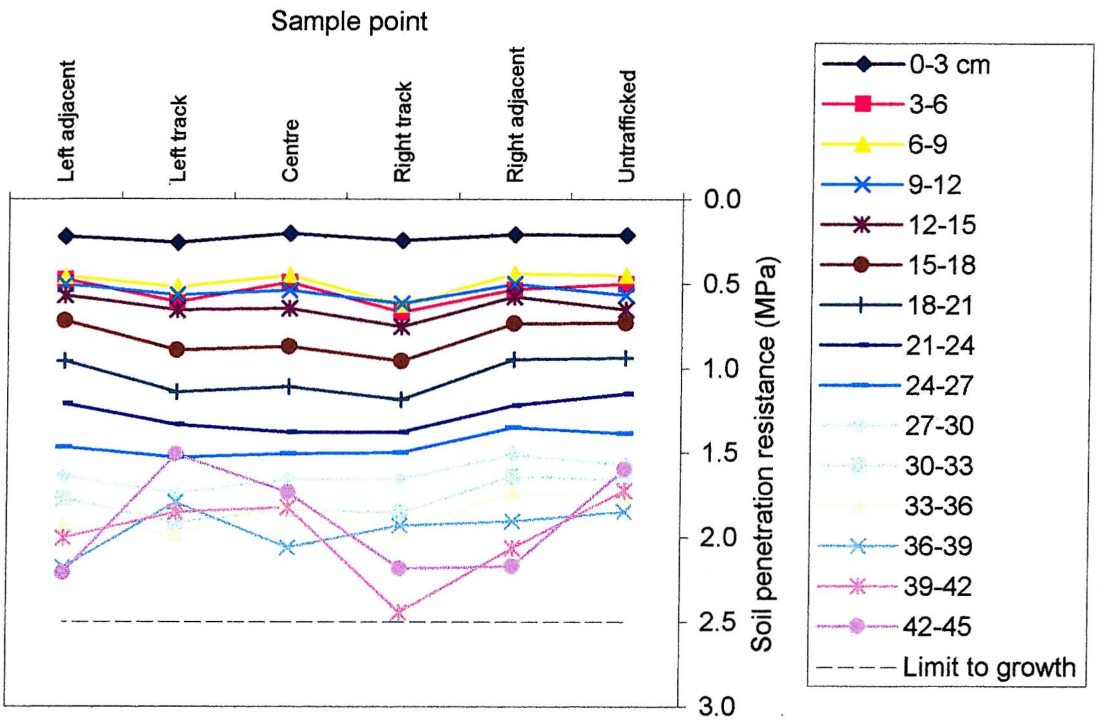


Figure 3.8b. Profile of mean soil penetration resistance - site 05K.

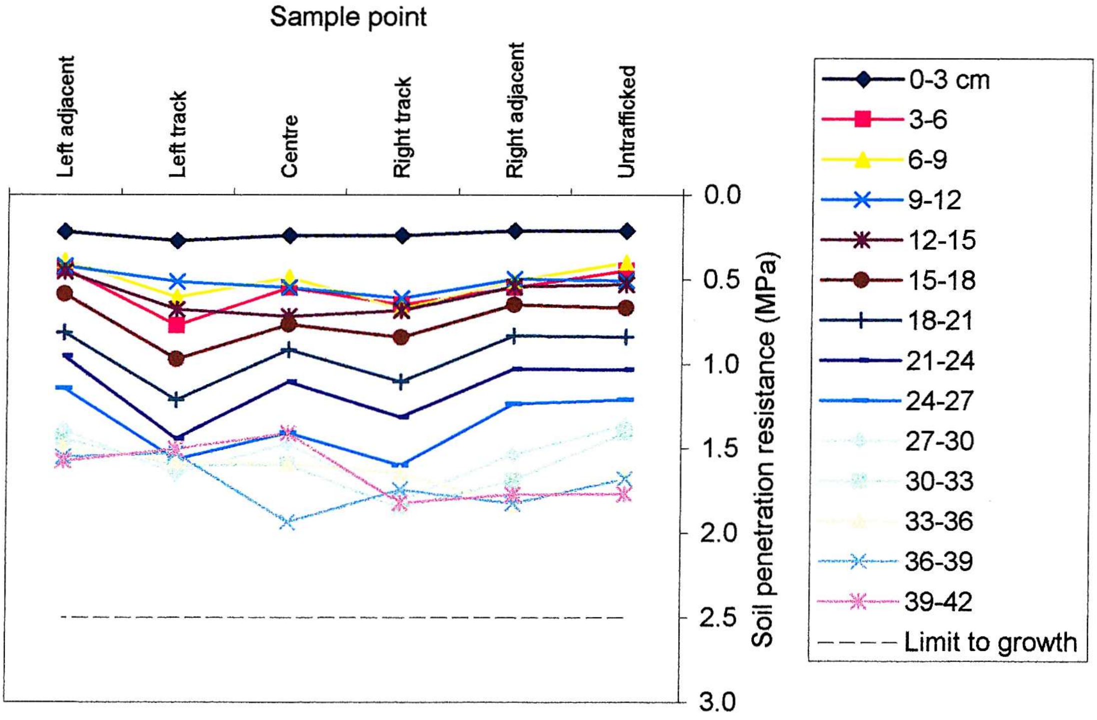


Figure 3.8c. Profile of mean soil penetration resistance - site 06K.

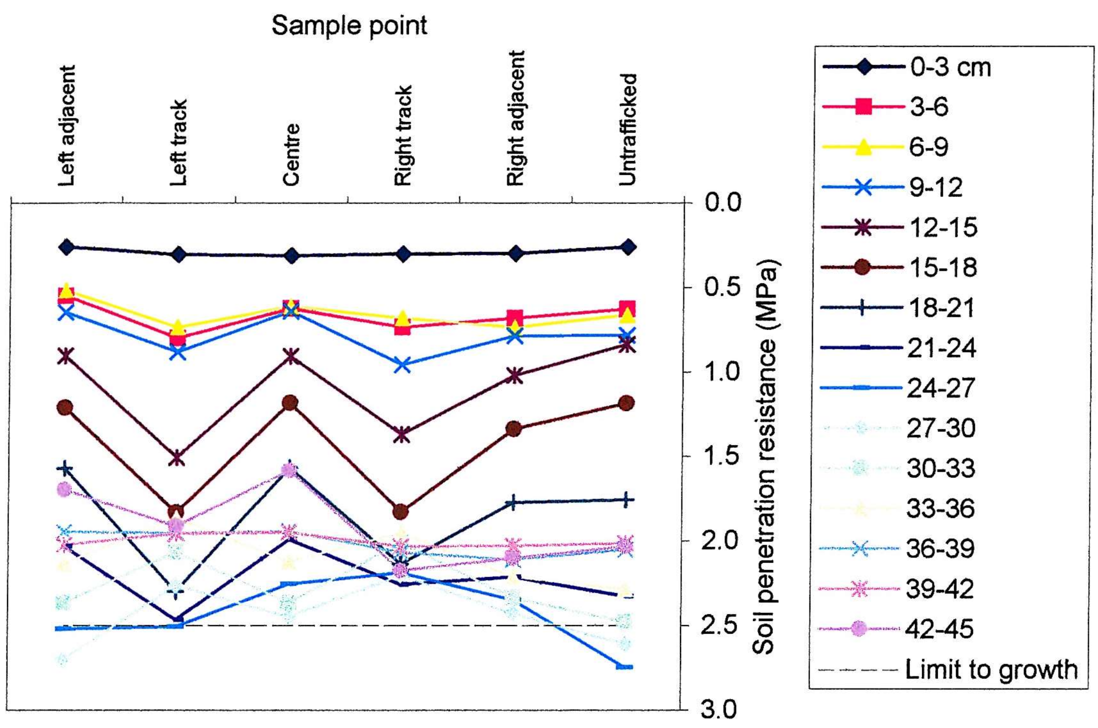


Table 3.10. Mean soil total porosity (percent total soil volume) for the entire peat (O) layer - year 1 and year 2 sites.

		Soil total porosity (%)						
Site	Treatment	Mean	N	Std	Cv	Se	Min	Min
01K	Untrafficked	84	17	6.52	8	1.58	72	92
	Trafficked	85	52	5.40	6	0.75	65	93
02N	Untrafficked	90	37	2.37	3	0.39	80	93
	Trafficked	91	92	3.14	3	0.33	76	94
03K	Untrafficked	85	13	3.95	5	1.09	74	90
	Trafficked	85	61	4.70	6	0.60	69	90
04K	Untrafficked	84	28	4.15	5	0.78	75	90
	Trafficked	83	39	4.46	5	0.71	72	89
05K	Untrafficked	87	45	3.20	4	0.48	75	92
	Trafficked	86	68	4.73	5	0.57	66	91
06K	Untrafficked	82	10	3.79	5	1.20	73	85
	Trafficked	82	29	3.92	5	0.73	70	87

N (number of samples), Std (standard deviation), Cv (coefficient of variation - %), Se (standard error), Min (minimum) and Max (maximum).

Table 3.11. Mean saturated hydraulic conductivity (mm s^{-1}) at sites 05K and 06K.

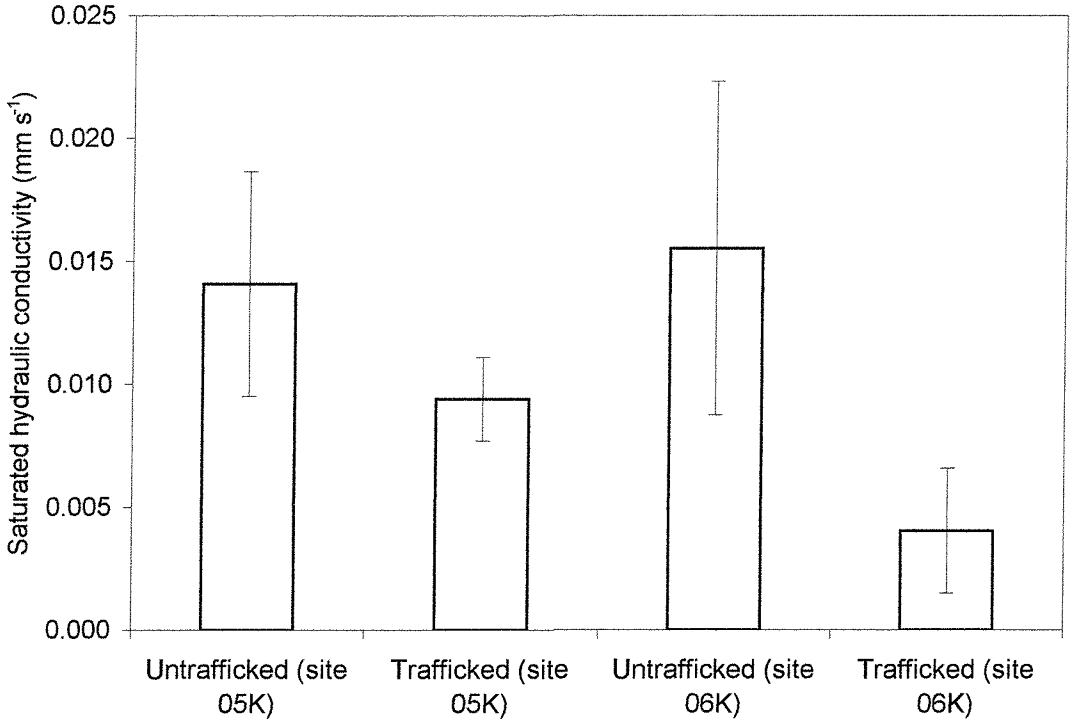
	K_s (mm s^{-1})						
Site/treatment	Mean	N	Std	Cv	Se	Min	Max
05K - Untrafficked	0.014	8	0.013	92	0.005	0.003	0.031
05K - Trafficked	0.009	17	0.007	74	0.002	0.0*	0.024
06K - Untrafficked	0.016	9	0.020	131	0.007	0.0*	0.053
06K - Trafficked	0.004	24	0.012	308	0.003	0.0*	0.061

N (number of samples), Std (standard deviation), Cv (coefficient of variation - %), Se (standard error), Min (minimum) and Max (maximum). * where no infiltration was measured.

3.7. The effect of multiple machine passes on soli response.

The relationship between trafficked soil dry bulk density and the number of machine passes was highly variable (Figures 3.10a-3.10f, p. 99-101), and mean values for each treatment (number of machine passes) were either higher or lower than mean untrafficked values irrespective of the number of machine passes.

Figure 3.9. Mean saturated hydraulic conductivity - sites 05K and 06K.



Error bars represent ± 1 standard error.

Figure 3.10a. Mean soil dry bulk density for each ground treatment - site 01K.

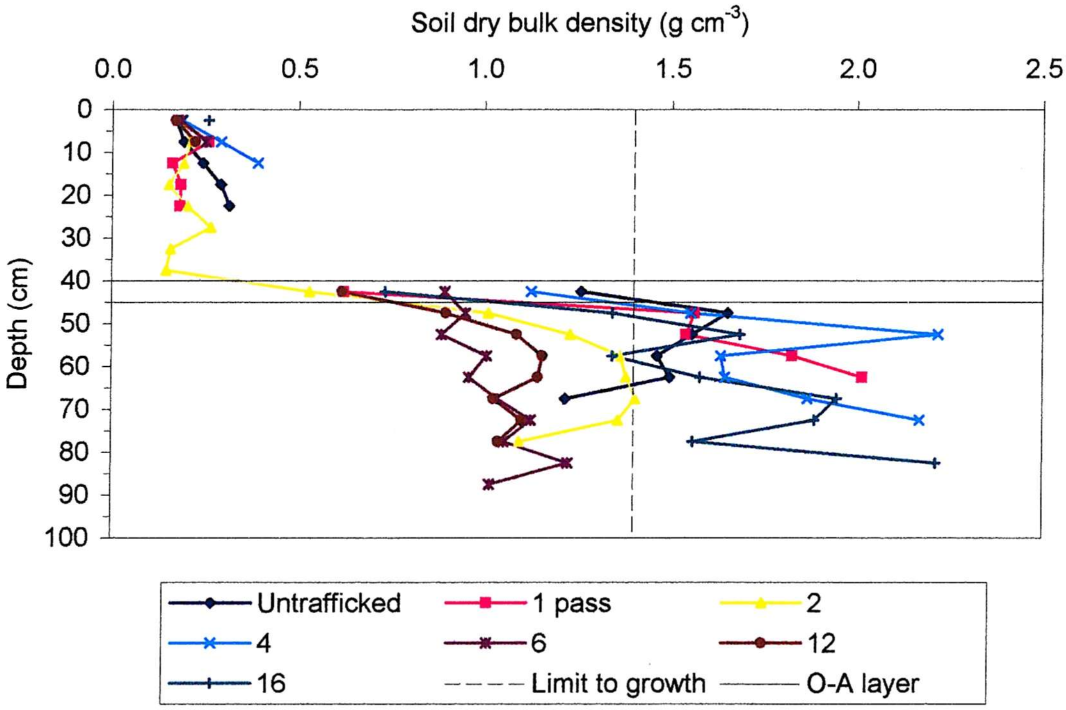


Figure 3.10b. Mean soil dry bulk density for each ground treatment - site 02N.

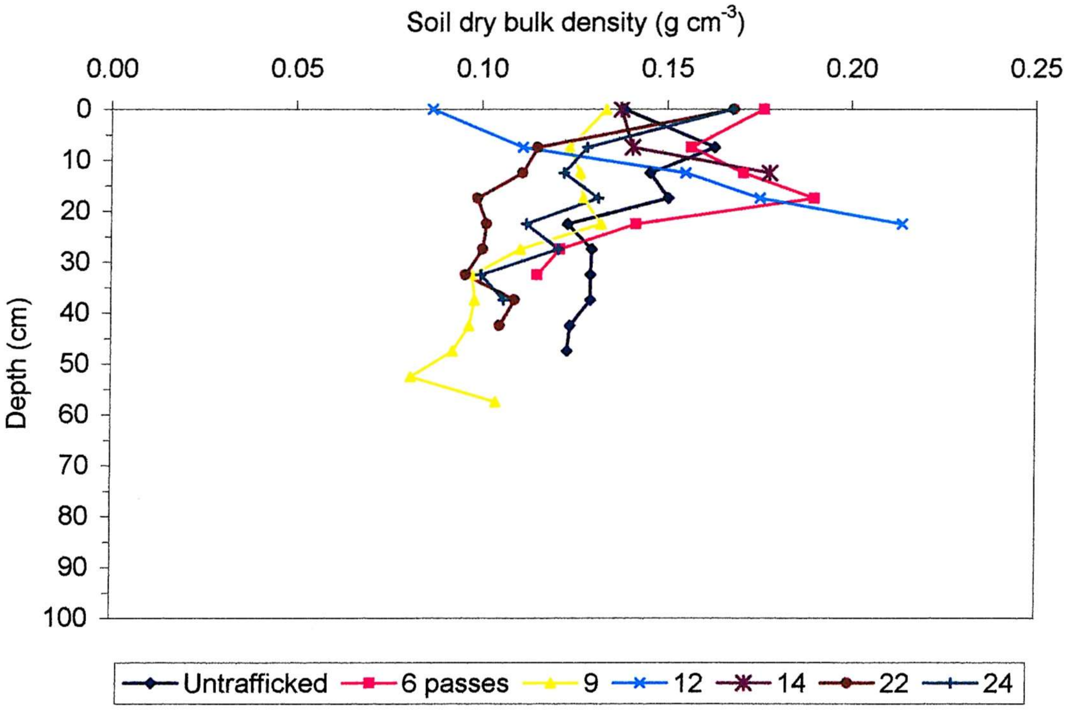


Figure 3.10c. Mean soil dry bulk density for each ground treatment - site 03K.

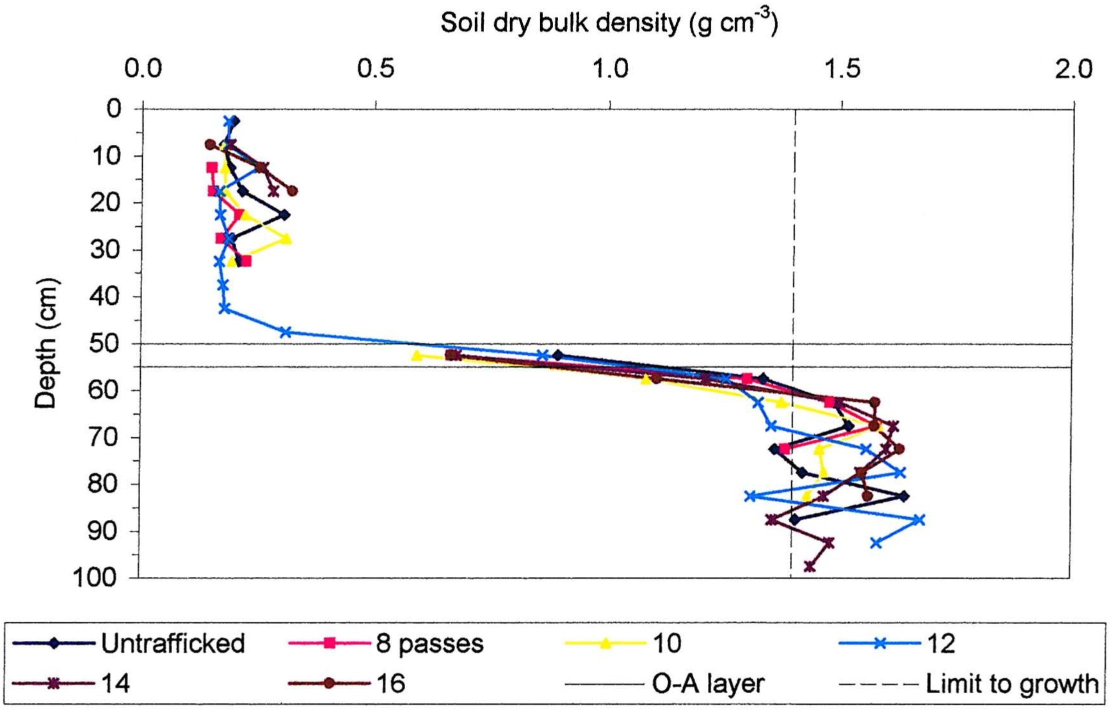


Figure 3.10d. Mean soil dry bulk density for each ground treatment - site 04K.

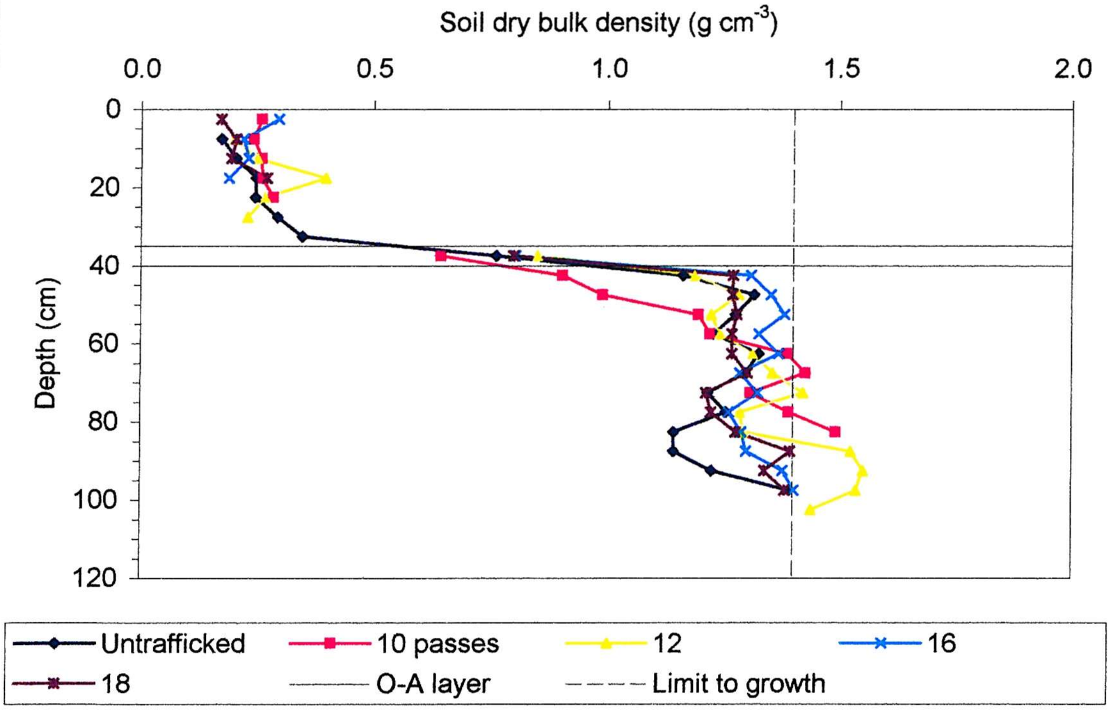


Figure 3.10e. Mean soil dry bulk density for each ground treatment - site 05K.

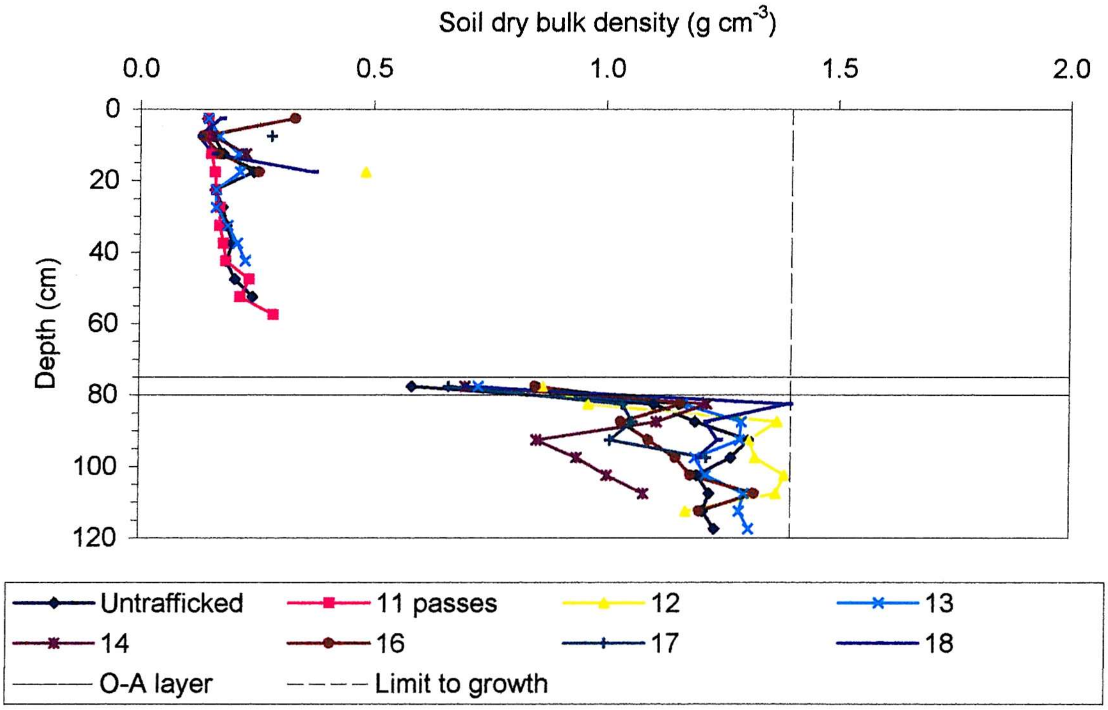
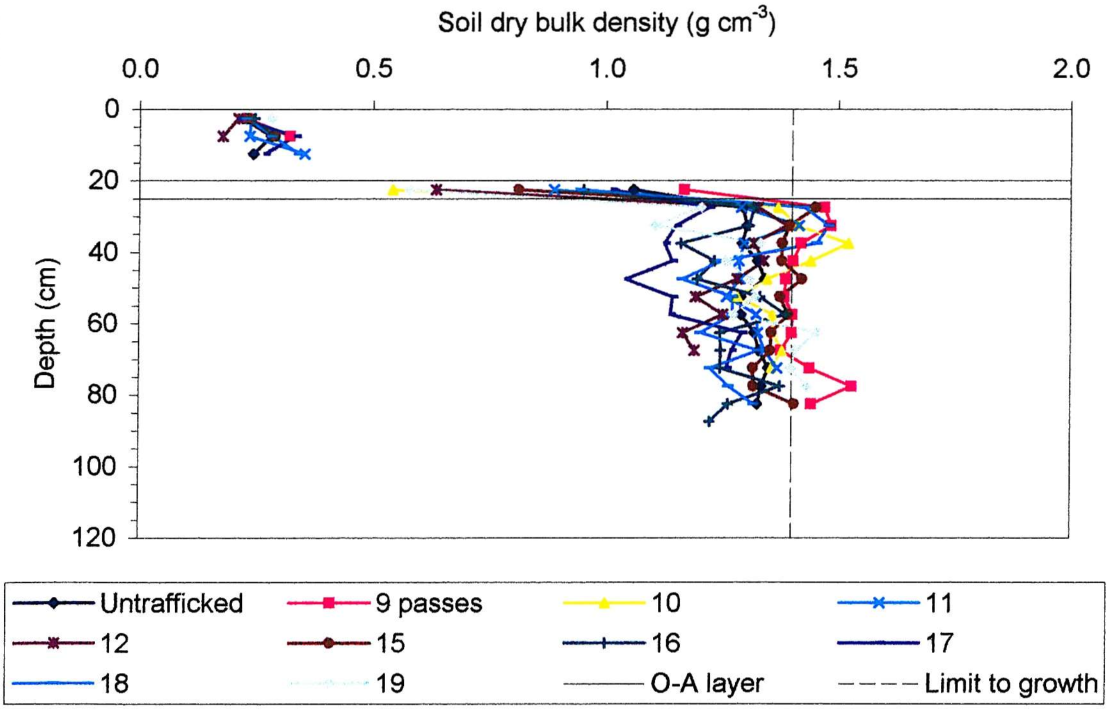


Figure 3.10f. Mean soil dry bulk density for each ground treatment - site 06K.



Mean trafficked values of saturated hydraulic conductivity for each ground treatment were lower than the mean untrafficked value in all but one case (after 17 machine passes at site 05K), but no pattern of response according to the number of machine passes was observed (Figures 3.11a and 3.11b, p. 103).

Mean values of trafficked soil penetration resistance for each ground treatment are illustrated in Figures 3.12a-f (p. 104-106). At sites 03K, 04K, 05K and 06K where the number of machine passes within each disturbance class was well replicated, soil penetration resistance showed a consistent pattern of response to varying levels of traffic intensity. In each case, following the smallest number of machine passes ranging between eight, ten, 11 and up to 12 (sites 03K, 04K, 05K and 06K respectively), soil penetration resistance was generally lower than mean untrafficked values at the majority of depths. For trafficking intensities of ten, 12, 12 and 15 machine passes (sites 03K, 04K, 05K and 06K respectively) and beyond, values were higher than mean untrafficked values at the majority of depths. At site 01K, mean trafficked values were lower than mean untrafficked values following one, two, four, six and including 12 machine passes) for the same soil type, while intermittent increases in soil penetration resistance were found following 16 machine passes. No traffic related pattern of soil penetration resistance at site 02N was observed.

Figure 3.11a. Mean saturated hydraulic conductivity for each ground treatment - site 05K.

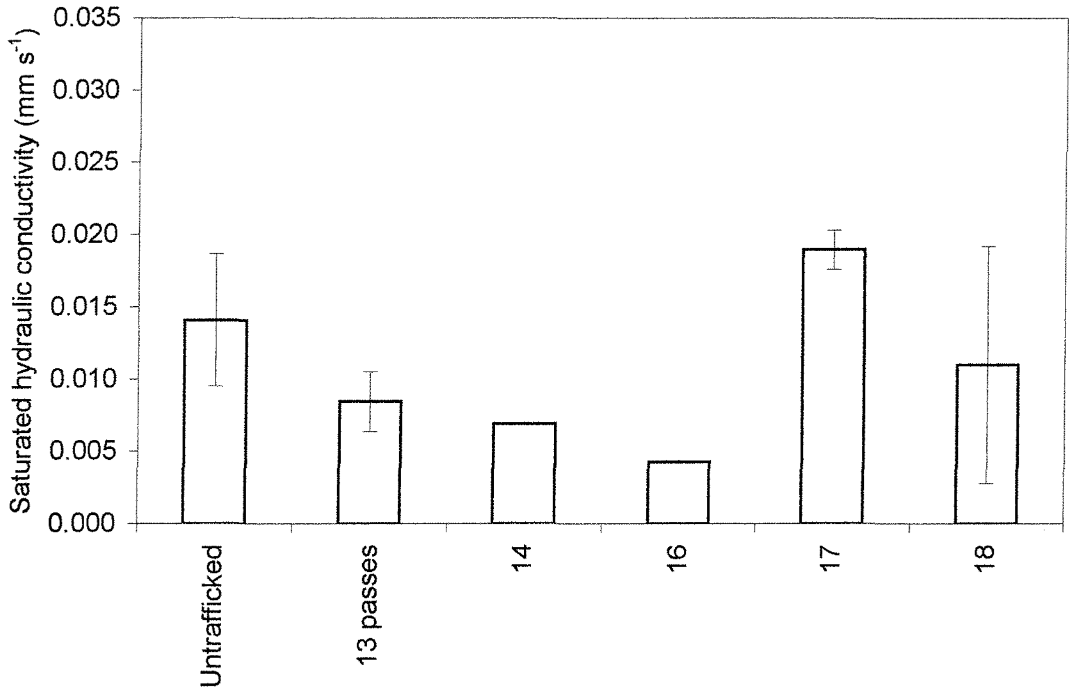
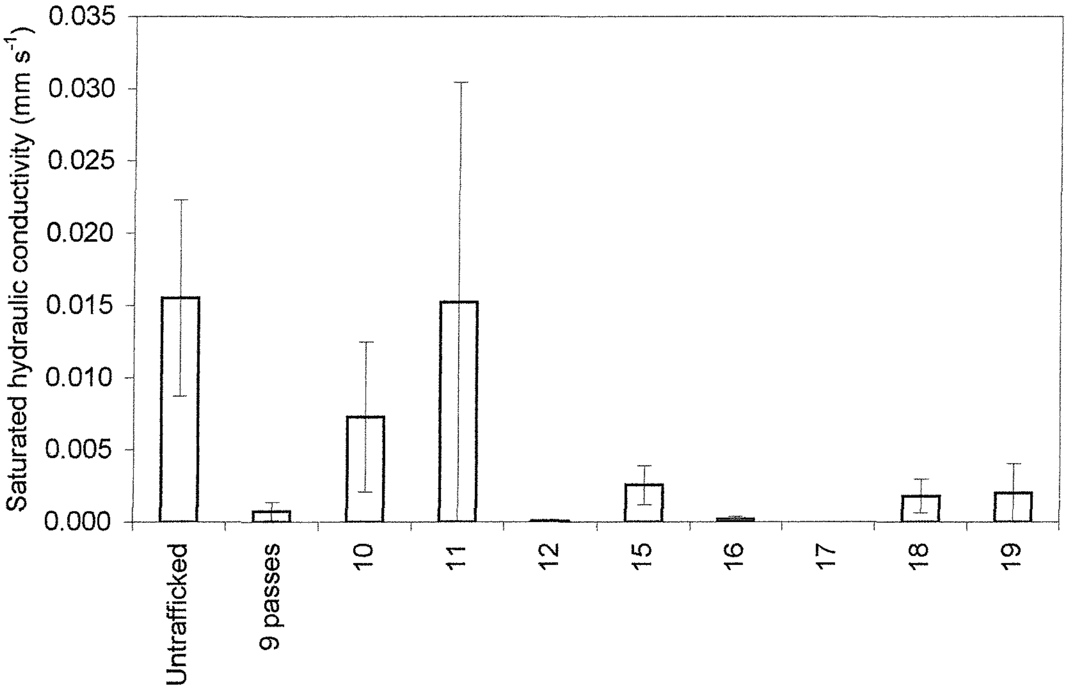


Figure 3.11b. Mean saturated hydraulic conductivity for each ground treatment - site 06K.



Error bars represent ± 1 standard error.

Figure 3.12a. Mean soil penetration resistance for each traffic treatment - site 01K.

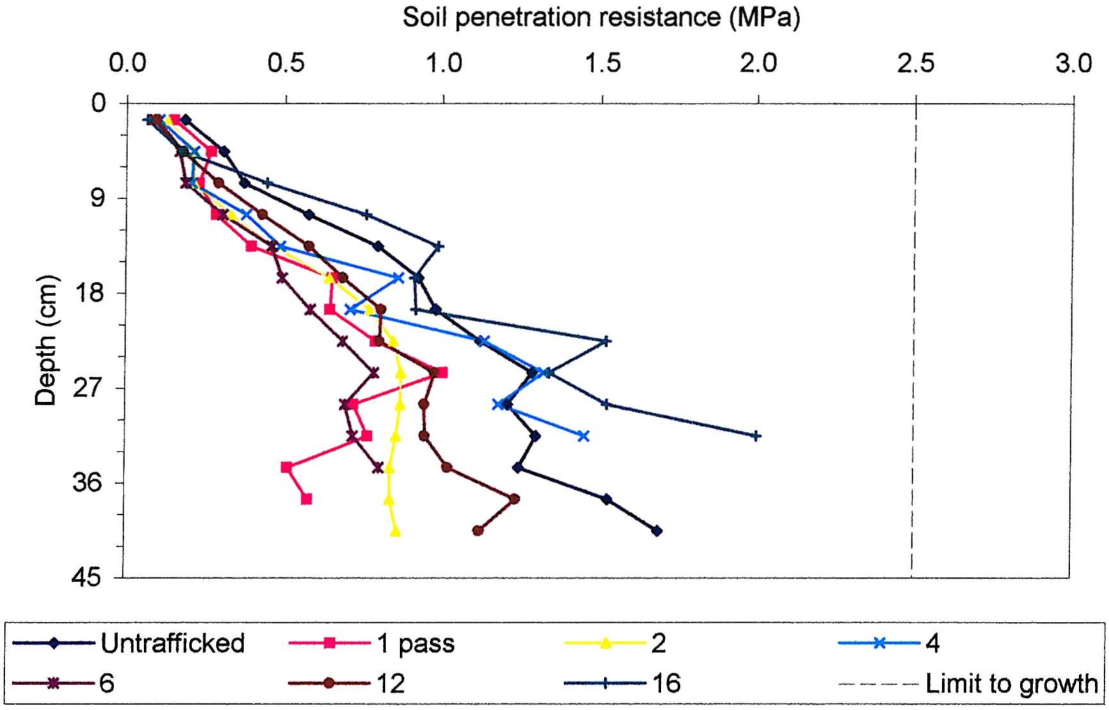


Figure 3.12b. Mean soil penetration resistance for each traffic treatment - site 02N.

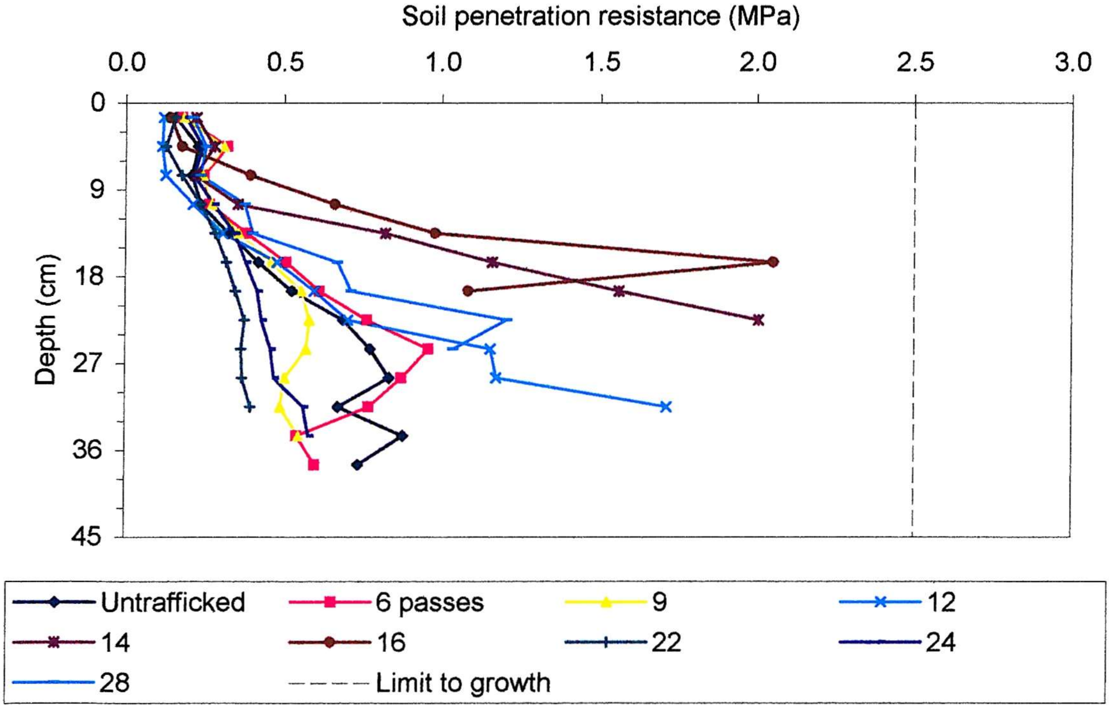


Figure 3.12c. Mean soil penetration resistance for each traffic treatment - site 03K.

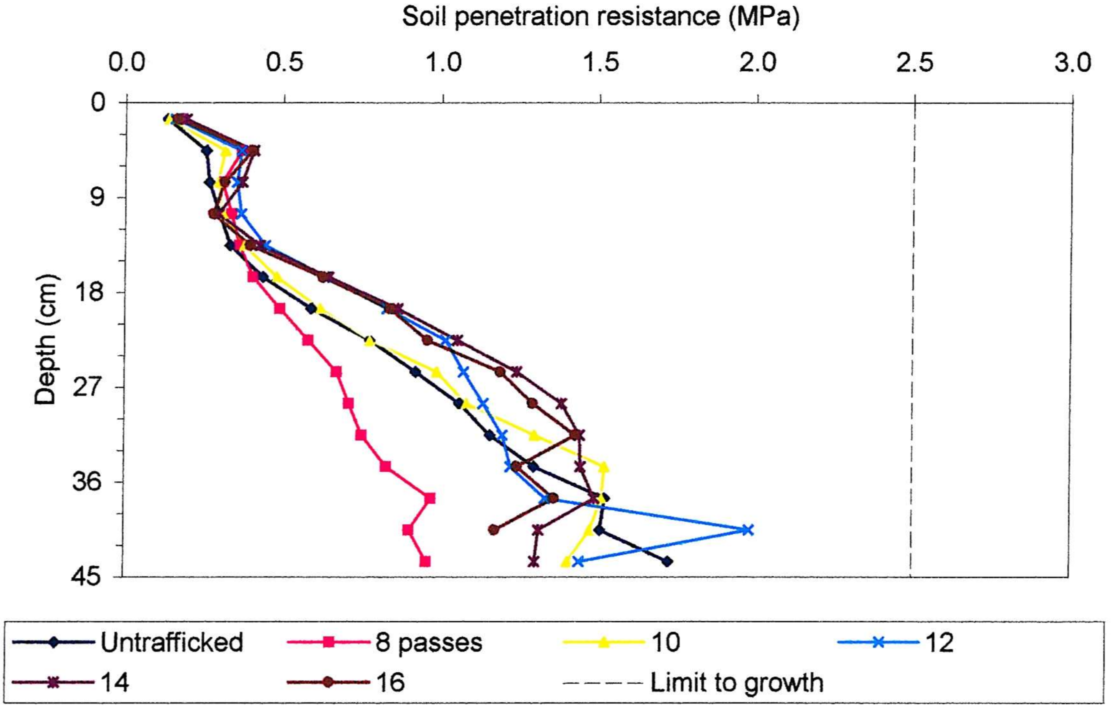


Figure 3.12d. Mean soil penetration resistance for each traffic treatment - site 04K.

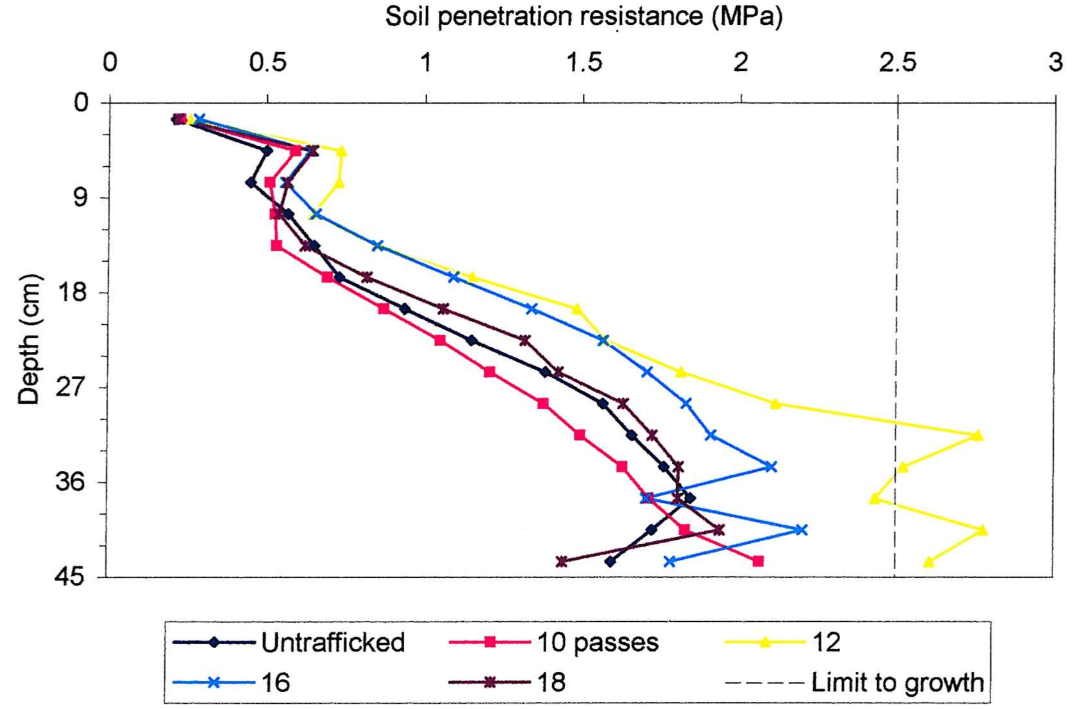


Figure 3.12e. Mean soil penetration resistance for each traffic treatment - site 05K.

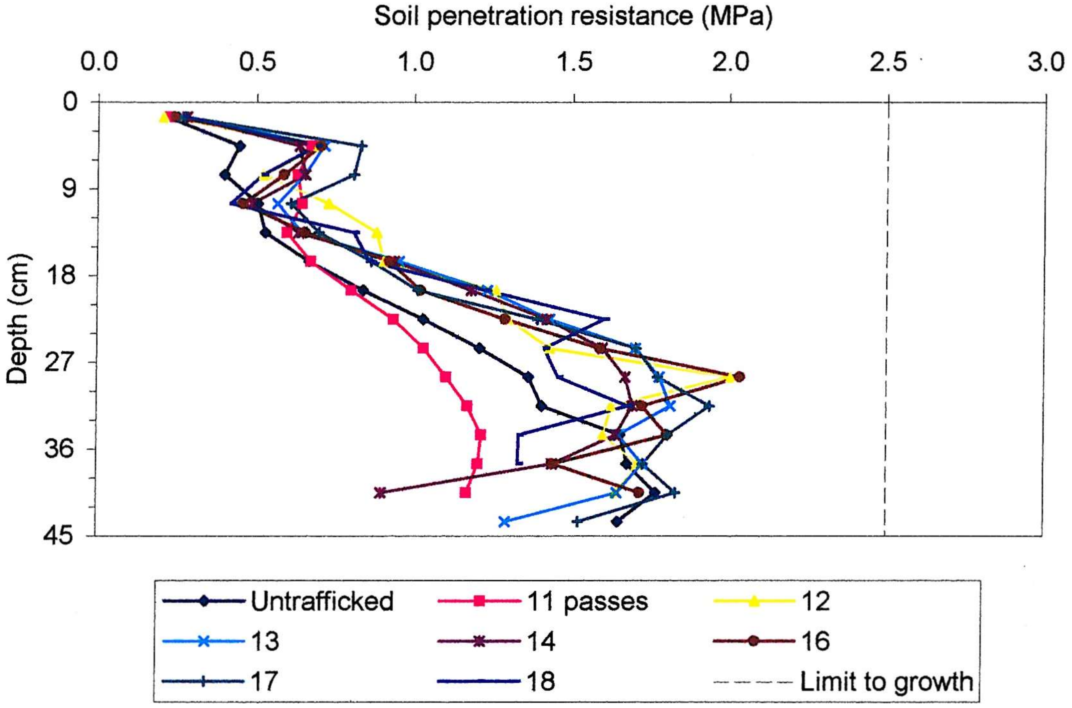
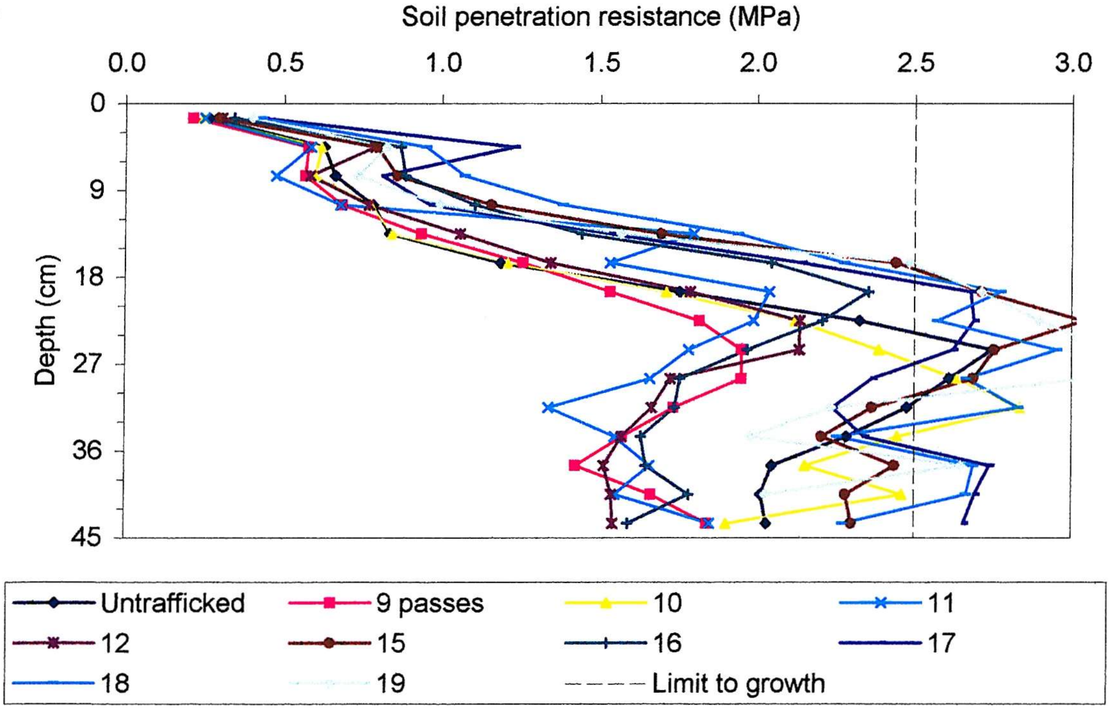


Figure 3.12f. Mean soil penetration resistance for each traffic treatment - site 06K.



Chapter 4 - Interpretation and discussion.

This chapter uses theoretical soil mechanics to explain the trafficked soil conditions measured during this study. The relationships between untrafficked soil conditions, traffic intensity and soil response are further considered, and trafficked soil conditions are examined in relation to soil thresholds limiting to root and tree growth. Factors affecting the efficacy of brash mats under operational conditions are also described.

4.1. Introduction.

In the context of this study, external loads applied by forest machinery were considered a combination of both static loading (machine stationary during timber loading) and dynamic loading (machine travelling). The period of machine loading during either was relatively short, and up to a maximum of c. 60 seconds (based on random timings made during year 1 and year 2 trials).

4.1.1. The response of the mineral (A-E) layers.

Given the saturated nature of the upper (A) and lower (E) mineral layers encountered during year 1 and year 2 trials (chapter 3, section 3.1) and their confinement during machine loading as a result of the overlying peat (O) and surface litter layers, volumetric changes (increases or decreases in soil dry bulk density) of the mineral soil were considered to be possible only by the process of consolidation. The application of consolidation theory in any situation relies on a number of assumptions (Hillel, 1982) these include;

- that the soil is fully saturated and homogeneous,
- the soil particles and surrounding water are incompressible,
- water flow and consolidation occur in one dimension (vertical),
- Darcy's law of water flow applies, and hydraulic conductivity remains constant,

- loading is instantaneous and remains constant, and the rate of consolidation during compression is a function of hydraulic conductivity,
- there is a linear relationship between the effective stress acting on the soil matrix and the observed volume change.

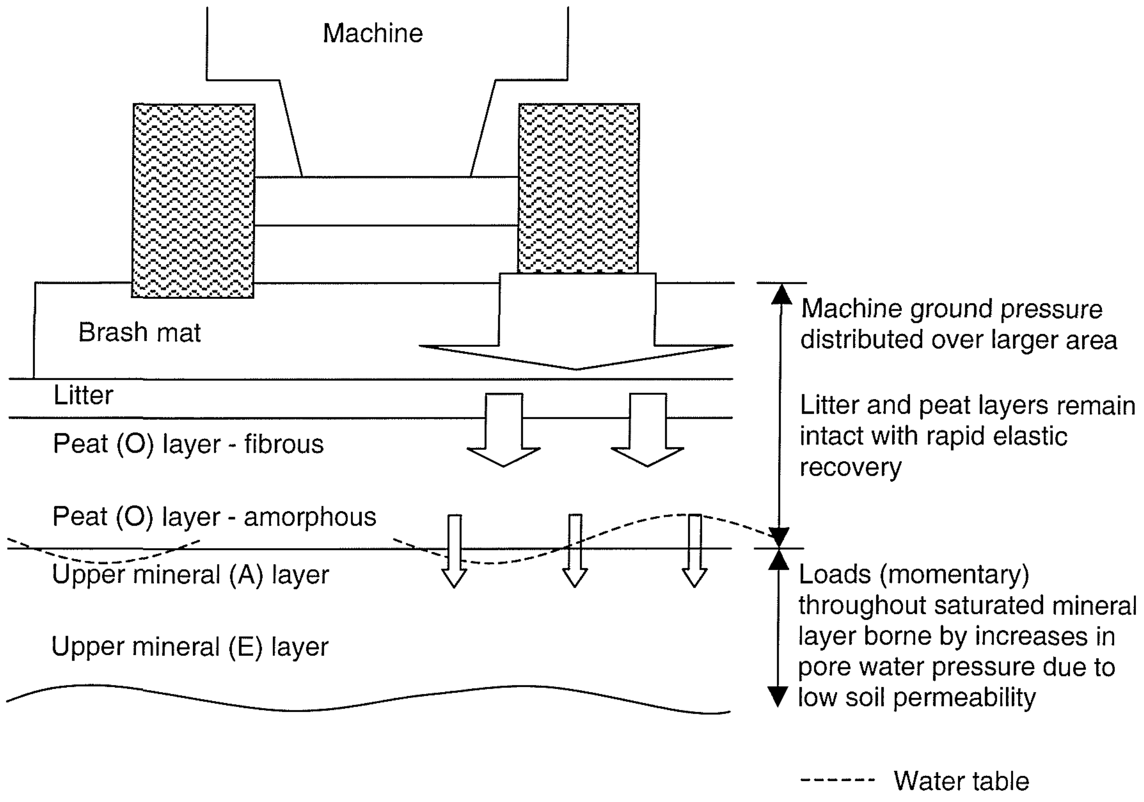
For increases in soil density to take place under these conditions, large time scales are involved as loads are borne initially by increases in pore water pressure, and consolidation can only take place where drainage of pore fluids and therefore excess (compressive) pressures are released. As such, the application of consolidation theory in studies of mobility and trafficability can be inappropriate due to the very short periods of loading associated with the passage of machinery (Karafiath and Nowatzki, 1978). This is particularly true of fine-grained soils such as silts or clays upon which so many problems relating to trafficability and mobility occur. Conversely, the permeability of coarse grained soils is often several orders of magnitude greater than that of silt or clay soils, and as such, consolidation may occur more rapidly.

In this study, all the soil structural requirements for consolidation were satisfied throughout the mineral (A-E) layers, however the period of loading was insufficient (above, this section) for any consistent increases in soil density to occur. Plastic deformation was eliminated due to confinement by the overlying peat (O) and litter layers, while changes in soil dry bulk density were minimal. The latter was ascribed to a combination of factors including only momentary loading by machinery and the fact that the rate of compressibility for fine textured silty clay soils with low rates of permeability in a confined state is very low (above, this section and Figure 4.1, p. 109).

4.1.2. The response of the peat (O) layer.

While the response of the mineral (A-E) layers may be described with reference to the process of consolidation, it could not be applied satisfactorily to the overlying peat (O) layer as the assumptions described above (section 4.1.1) were not fully satisfied.

Figure 4.1. Soil response of the peat (O) and mineral (A-E) layers.



Summarised by Hobbs (1986) there are a number of specific reasons why this is so:

- The applied boundary conditions are not valid for peat soils due to large axial strains, hence Darcy's law must be expressed in terms of relative velocity between a moving fluid and moving fibrous matrix.
- The rate and extent of reductions in permeability upon loading are extremely high causing a marked decrease in drainage.
- Volume changes are not linear with pressure.
- Gasses are held within the soil water and hence it must be assumed that the water is to some extent compressible.

Despite high water contents, Hobbs (1986) noted that the engineering properties of peat soils were similar in all but strength to those of normally consolidated clays, where the tensile strength of peat was high in relation to bulk density as a result of its fibrosity. In addition, and notwithstanding the high compressibility of peat soil in an otherwise unconfined state (Whitlow, 1995), the lack of significant changes in soil dry bulk density measured throughout the peat (O) layer during year 1 and year 2 trials were ascribed to (a) the retention *in situ* of the peat layer in a confined state (Figure 4.1, p. 109), (b), the inherent elasticity of the upper fibrous peat layer and (c), the low permeability of the lower amorphous peat layers - c. 3×10^{-2} - 6×10^{-3} mm s^{-1} (based on a Scottish raised bog and Russian fen respectively; Ingram, 1983).

4.1.3. The relationship between untrafficked soil properties, the number of machine passes and soil response for the peat (O), peat-mineral (O-A) and mineral (A-E) layers.

The relative importance of key soil properties and the number of machine passes in determining soil response (changes in soil dry bulk density) at year 2 sites was investigated using Stepwise Multiple Regression. Given the drop in sample replication with depth for both the peat (O) and mineral (A-E) layers, the first 0-20 cm of the O layer, the O-A layer and 7.5 cm, 17.5 cm and 27.5 cm depths of the A-E layer were considered. Data were organised such that for each sample unit, control bulk soil properties (soil dry bulk density, soil water and organic matter content) determined from the single undisturbed soil core were used to describe the untrafficked soil properties under both the right and left wheel tracks (data for soil particle size distribution were insufficient for inclusion in the analysis). Values of trafficked soil dry bulk density were then grouped according to whether they were above or below their respective control irrespective of statistical significance. Results are presented in Table 4.1 (p. 111).

The Stepwise Multiple Regression showed that no single factor was consistently responsible for trafficked values of soil dry bulk density measured either above or below the control. Importantly, untrafficked soil conditions could be more significant than the number of machine passes in determining soil response under the conditions investigated in this study. At all sites throughout the peaty (O) layer and, where applicable, the peat-mineral (O-A) layer, trafficked soil penetration resistance was less than the control following up to c. 12 machine passes, beyond which consistent increases in soil penetration resistance were measured (chapter 3, section 3.7), though seldom exceeding the limiting threshold (2.5 MPa).

Table 4.1. Results of the Stepwise Multiple Regression analysis.

		Trafficked soil dry bulk density > control				Trafficked soil dry bulk density < control			
Layer	Depth (cm)	N. machine passes	Bulk Density (g cm^{-3})	Soil water (%)	Organic matter (%)	N. machine passes	Bulk density (g cm^{-3})	Soil water (%)	Organic matter (%)
O	2.5	-	-	-	-	na	na	na	na
	7.5	-	-	-	-	na	na	na	na
	12.5	-	-	-	-	na	na	na	na
	17.5	Na	na	na	na	na	na	na	na
O-A	2.5	-	-	-	(20) *	-	(22) *	-	(22)
A-E	7.5	(27)	-	(27)	-	(20)	-	-	-
	17.5	-	-	-	-	(23)	-	-	-
	27.5	-	-	(6)	-	(12) *	-	-	-

Not enough data (na), no response (-), values in parentheses indicate number of samples and *significance ($p < 0.05$ or less).

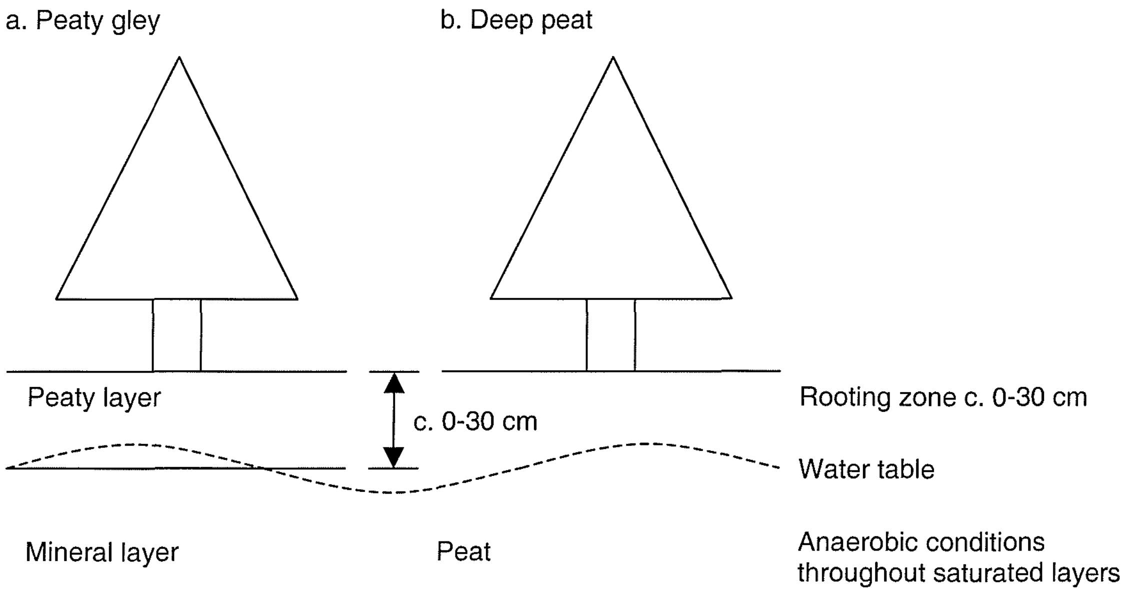
Penetrometer soil strength has been shown to increase exponentially with increases in bulk density (Sands *et al.,* 1979), and may explain why soil penetration resistance appeared far more sensitive to harvesting machinery when compared to only minor changes in soil dry bulk density. Unfortunately, soil penetration resistance data and soil dry bulk density data collected in this study could not be directly compared given the differing depth resolutions at which each were collected.

4.2. Trafficked soil conditions and site productivity.

Data which describe the ideal physical soil conditions for root/tree growth and limiting thresholds are few. In considering the implications of trafficked soil conditions for future productivity measured in this study, reference is made to previously described thresholds (chapter 1, section 1.3.2.1). Despite variations according to species and soil type, soil dry bulk densities of c. 1.4 g cm^{-3} and soil strengths (soil penetration resistance) of 2.5 MPa, have been frequently cited in previous studies as being potentially limiting to tree root growth, and for illustration are considered a suitable benchmark against which potential impacts on productivity may be assessed.

It is also important to define the rooting zone within which soil impacts are most likely to have a direct effect on root growth. At all the sites visited in this study, the effective rooting zone was confined to the peaty (O) layer for the saturated peaty gley soils investigated, whilst at site 02N (the deep peat), rooting was confined to the upper 30 cm of the soil (based on observations made during soil core extraction). In each case, this was ascribed to the position of the water table (chapter 3, section 3.1, and Figure 4.2) and subsequent anaerobic conditions throughout the saturated lower peat horizons (deep peat soil) and mineral horizons (peaty gley soils), as opposed to mechanical impedance (for the mineral soils at all year 2 sites, the mean untrafficked soil dry bulk density never exceeded the potentially limiting value of 1.4 g cm^{-3}).

Figure 4.2. The rooting zone - year 1 and year 2 sites.



Trafficked soil dry bulk densities throughout the peat (O) layer at all sites remained well below the limiting threshold of 1.4 g cm^{-3}, while the highest values recorded for the peat layer at any site was 0.49 g cm^{-3} (site 01K), c. 65% below the limiting value of 1.4 g cm^{-3}. Trafficked soil penetration resistance data at all depth increments in relation to the limiting threshold of 2.5 MPa are summarised in Table 4.2.

Table 4.2. Summary of soil penetration resistance in relation to growth limiting thresholds.

		Soil penetration resistance (MPa)							
Site	Treatment	Mean	N	Std	Se	Cv	Min	Max	N > 2.5 MPa*
01K	Untrafficked	0.81	623	0.55	0.02	68	0.05	3.58	8 (1.3)
	Trafficked	0.53	1085	0.42	0.01	78	0.01	3.13	2 (0.2)
02N	Untrafficked	0.35	963	0.30	0.01	84	0.05	2.63	1 (0.1)
	Trafficked	0.38	1748	0.31	0.01	80	0.02	2.78	3 (0.2)
03K	Untrafficked	0.61	1285	0.49	0.01	80	0.05	3.10	4 (0.3)
	Trafficked	0.68	2547	0.50	0.01	73	0.01	3.06	15 (0.6)
04K	Untrafficked	0.96	1362	0.68	0.02	71	0.02	4.59	39 (2.9)
	Adjacent	0.98	4094	0.70	0.01	71	0.04	5.05	149 (3.6)
	Trafficked	1.07	2706	0.72	0.01	67	0.03	5.43	115 (4.2)
05K	Untrafficked	0.83	1324	0.57	0.02	68	0.01	4.32	18 (1.4)
	Adjacent	0.86	3950	0.65	0.01	75	0.00	14.89	83 (2.1)
	Trafficked	1.01	2536	0.67	0.01	66	0.00	5.01	94 (3.7)
06K	Untrafficked	1.39	1239	0.98	0.03	70	0.05	5.12	168 (13.6)
	Adjacent	1.36	3864	0.95	0.02	70	0.04	6.44	486 (12.6)
	Trafficked	1.48	2531	0.96	0.02	65	0.05	5.69	388 (15.3)

N (number of samples), Std (standard deviation), Cv (coefficient of variation - %), Se (standard error), Min (minimum) and Max (maximum). Data for adjacent areas includes area between and either side of wheel tracks. Values in parentheses indicate percent of total observations. *value potentially limiting to root growth (chapter 1, section 1.3.2.1).

Mean soil penetration resistance generally remained well below the limiting threshold (2.5 MPa), and only at site 06K was there a marked difference in the proportion of measured values (for all treatments) in excess of this threshold Notwithstanding only minor changes in soil penetration resistance, it is worth noting that previous studies have reported decreases in soil strength following machine harvesting on mineral soils (e.g. Jakobsen and Greacen, 1985; Braunack, 1986; Jansson and Johansson, 1998; Hutchings *et al.,* In press). Jakobsen and Greacen (1985) suggested that this may have resulted from either a loss of thixotropic soil strength or an increase in soil moisture content to near saturation creating the conditions rendering the soil column incompressible. However, such a response may be temporary given the phenomenon of age hardening (Dexter *et al.,* (1988). For example, measurements taken 14 months after initial harvesting trials by Jakobsen and Greacen (1985) found further statistically significant increases in soil penetration resistance for many previously trafficked areas. Therefore, soil penetration resistance measured at all sites in this study may not represent the final trafficked soil condition, and in due course further strength increases throughout the peat (O) layer may take place over as much as 50% of the site area (based on the area of the brash mat, chapter 3, section 3.2.2). Unfortunately, additional trials to investigate this phenomenon could not be undertaken as each experimental plot underwent further (though unquantified) trafficking during the period following initial collection of soil data.

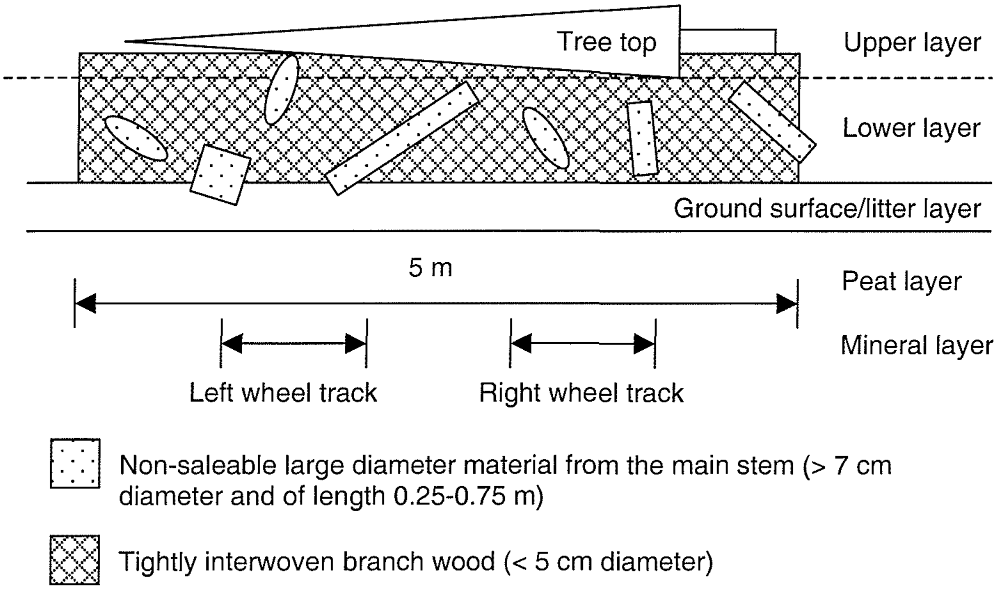
In addition, the peat (O) layer determines infiltration and water storage, both of which may be significantly reduced following machine harvesting operations (Wingate-Hill and Jakobsen, 1982). Given the retention *in situ* of the O layer, erosion of mineral soil is unlikely. However reductions in saturated hydraulic conductivity throughout the peat layer, potentially of a similar order of magnitude to those measured directly below for the upper mineral (A) layer, may affect soil quality. For example, Hobbs (1986) noted that permeability of peat is highly sensitive to changes in void ratio, where a reduction in the latter of half an order of magnitude can result in a reduction in permeability of up to three orders of magnitude. As such, permeabilities in the order of 3×10^{-5} - 6×10^{-7} mm s^{-1} (based on the examples given above (Ingram, 1983) might be expected throughout the O layer subsequent to trafficking, with consequences for drainage and water availability.

Irrespective of tillage and notwithstanding the trafficked soil conditions measured in this study, it is important to note that root growth will generally follow the line of least resistance (Greacen and Sands, 1980) along zones of low soil strength and/or structural weakness. Investigating the role of re-stock tillage in ameliorating soil damage was beyond the scope of this study, though uncertainty regarding the overall efficacy of tillage treatments (chapter 1, section 1.3.3.3) suggests that such treatments may prove unnecessary and in some cases detrimental to site productivity. In addition, the ability of tree species to develop adaptive responses to conditions such as water logging (Coutts and Philipson, 1987) must be considered. Hence, regardless of potential changes in root symmetry with implications for tree stability, and notwithstanding reductions in timber quality and the associated economic implications (Wronski and Murphy, 1994), tree growth and long-term site productivity *per se* may not be significantly affected where water, air and nutrients remain in plentiful supply (Greacen and Sands, 1980; Wronski and Murphy, 1994).

4.3. The efficacy of the brash mats.

The thickness of the brash mats varied considerably both from one site to the next, and across each site individually. Typically trafficked thickness' of c. 75-100 cm for primary routes and c. 25-50 cm along secondary routes were measured, the former demonstrating the much larger volumes of branch wood associated with trees along the forest edges. The composition of the brash mat in terms of the distribution of specific types of logging residues was far more consistent (Figure 4.3).

Figure 4.3. Composition of the brash mat (not to scale).



Looking from the back of each extraction route (see Figures 2.1, p. 41 and 2.2, p. 45, chapter 2), the main body of the brash mat comprised a lower layer of tightly interwoven branch wood (< 5 cm diameter) armoured by an upper layer of larger diameter tree tops (stem diameter < 7 cm) placed perpendicular to the direction of travel. In addition, non-saleable large diameter material from the main stem (> 7 cm diameter and of length 0.25-0.75 m) such as butt off-cuts, forks (where the main stem splits into two separate stems) and stops (a portion of the stem exhibiting a rapid change in diameter) were located randomly throughout the brash mat. This latter material had the potential to amplify machine loads at the ground surface (where the applied load is concentrated over an area less that that of the footprint area (Murgatroyd, 1997a). However, based on the cross-sectional profiles of soil resistance to penetration (chapter 3, section 3.5), there was no suggestion of this phenomenon occurring throughout either the upper mineral (A) layer or entire peat (O) layer. This suggests that machine loads are rapidly attenuated with depth due to the presence of the brash mat and the elastic properties of the overlying O layer (section 4.1.2). Localised failure of the brash mat during repeated trafficking was observed to be dependent largely on the presence of large diameter material (described above, this section), along with terrain features and specific vehicle manoeuvres (described below) rather than the overall thickness of the brash mat.

Primary extraction routes were generally located along forest edges where a larger volume of material was available for the construction of brash mats (above, this section). Representing a much smaller area of the entire clearfell than secondary routes, they remained largely intact at all sites irrespective of specific ground features, and despite much higher levels of traffic. However, emulsification of the peat (O) layers and mixing of peat soil with brash material often took place along wetter areas. In addition, and despite larger volumes of logging waste, failure of the brash mat at turning points from primary to secondary routes (often at right angles) was noted at all sites where the brash mat was observed to 'shear', resulting in rapid displacement, deep rutting and exposure of the mineral (A-E) layers (where present). On the deep peat soil, deep rutting was instantaneous and to axle depth during a single pass.

Isolated failures of the brash mat along secondary extraction routes were associated with terrain features, notably drains and, to a lesser extent, tree stumps. The latter often threw the vehicle off-line which in some instances resulted in machines running momentarily off the brash mat. The presence of an extensive drainage network (obstacles of 40 cm at 1.5 to 5 m spacing) constituting ground roughness class 3 (Forestry Commission, 1996) presented considerable problems at site 04K. Where extraction routes crossed drain channels the surrounding area became water logged, and failure of the brash mat was rapid resulting in deep rutting and loss of machine traction. This necessitated replenishment of the brash mat (using logging wastes from areas where the timber had already been removed) before extraction could continue. At this site, the pattern of felling and extraction over the experimental plot did not comply with the current Forests and Water Guidelines (Forestry Commission, 2000), serving to illustrate both the efficacy of these guidelines and difficulties in ensuring that in all cases they are adhered to. At site 01K, the distribution of material within the brash mats affected their overall efficacy in providing both ground protection and machine traction along the steep (12-14^{o}) secondary extraction routes constituting slope class 3 (Forestry Commission, 1996). Here, the large diameter (<7 cm) portion of the non-saleable stem was quickly deflected as the machinery struggled to maintain traction. This resulted in deep rutting, exposure of the mineral horizons and soil erosion (unquantified).

Chapter 5 - Application.

This chapter presents operational guidelines, based on the observations made during year 1 and year 2 trials, for the design of minimal impact harvesting systems. In doing so, a provisional pre-harvest soil sensitivity analysis is developed along with a methodology for optimising the efficacy of brash mats, the former based upon fundamental soil mechanical relationships, the latter based upon forest and terrain character, and machine specification.

5.1. Introduction.

Throughout the following discussion, emphasis is placed on maximising soil protection while maintaining efficient transportation of timber to road side. Attention is given to protection of the soil resource under the shortwood system, broader application is considered where appropriate.

5.2. Assessment of pre-harvest site conditions.

Careful planning of harvesting operations based upon pre-existing knowledge of site conditions and soil response represents a major opportunity to maintain or enhance both the sustainable rate of timber production and biodiversity of the forest, while avoiding the need for ameliorative measures which can prove both costly and, in some cases, ineffective.

5.2.1. Pre-harvest assessment of soil sensitivity.

Prior to the commencement of harvesting operations, the harvesting system should be designed in accordance with topographical (terrain) and pedological (soil) constraints. In doing so, the pattern of extraction, and application of existing measures (discussed below) aimed at further protecting the soil may be maximised.

Previously the upper soil horizons comprising either wet peaty material over seasonally saturated mineral horizons, or deep peats (>45 cm), were considered to be of a low bearing capacity, and in the absence of brash mats, subject to rapid displacement, ponding of surface water, and under certain conditions, erosion of mineral material (Forestry Commission, 1998). However, this study has demonstrated that the presence of a well maintained brash mat practically eliminated the incidence of ponding, soil displacement and erosion along wheel tracks. In addition, soil densification as a result of consolidation of the mineral layers (unlikely due to only momentary soil loading by machinery) or compaction of the peat layers (more likely where soil air only is expelled), was minimal.

A provisional semi-quantitative soil disturbance hazard assessment procedure is presented in Table 5.1 (p. 120), which assumes the use of brash mats. Classification is based upon soil response to varying intensities of trafficking observed during year 1 and 2 trials, and previously reported soil response under a range of scenarios where soil response is determined largely by soil water content and soil texture. For example, the rate and extent of increases in soil density of saturated soils are reduced in fine textured soils due to low permeability and associated increases in soil pore water pressures during loading (chapter 4, section 4.1.1). By contrast, increases in density of unsaturated soils are more sensitive to the number of machine passes rather than the degree of loading where up to 50% of volume changes may occur in the first few machine passes (chapter 1, section 1.3.1) due to the speed with which air is squeezed from the soil voids. The use of the pre-harvest soil sensitivity analysis allows decisions to be made regarding the timing of operations, the spatial distribution of, and intensity of traffic upon, extraction routes.

5.2.1.1. The timing of harvesting operations.

Despite evidence for increased bearing capacity on frozen soils, in the UK such conditions do not occur with sufficient duration or predictability to warrant planning based on such extremes. Similarly, given the inherent variability in water content

Table 5.1. Provisional semi-quantitative soil disturbance hazard assessment*.

	Soil texture**					
	FINE		MEDIUM		COARSE	
	Clayey to fine silty		Coarse silty to fine loamy		Coarse loamy to sandy	
% sand (S), % silt (Z) and % clay (C)	S (< 65) Z (< 65) C (36-60)	S (< 15) Z (50-83) C (18-35)	S (< 15) Z (> 68) C (< 18)	S (> 15) Z (< 68) C (18-35)	S (> 15) Z (< 85) C (< 18)	S (> 70) Z (< 30) C (< 15)
Soil moisture status	Saturated	Unsaturated	Saturated	Unsaturated	Saturated	Unsaturated
<30 passes (e.g., secondary extraction routes <150 m)	L***	**M-H**	**L**	**H**	**L-M**	**H**
>30 passes (e.g., primary extraction routes >150 m)	**L**	**M-H**	**L-M**	**H**	**M**	**H**

*assumes the presence of a well maintained brash mat, **soil texture (Pyatt, 1970) - S (% sand), Z (% silt) and C (% clay). For peat assume (a) coarse texture/high compressibility with rapid elastic recovery where fibrous and (b) fine texture (low permeability)/high compressibility where amorphous. ***based on traffic intensity over experimental plots (extraction routes 150 m length) during year 1 and year 2 trials. Risk categories in bold type are provisional and based on the theoretical rate and extent of increases in density for saturated and unsaturated soils, and assume that the rate of soil density increases (L-low, M-medium and H-high) under the same levels of trafficking for either saturated soils of greater permeability (consolidation) or lower water contents (compaction) would be greater than those measured during this study.

(both seasonally and spatially) Froelich and McNabb (1984) suggested that limiting harvesting operations based on soil water content may prove disruptive and therefore costly.

However, it has been demonstrated in this study that the trafficability of saturated fine textured mineral soils and wet (i.e., beyond field capacity) peat soils is greatly improved where brash mats are used. This is due to the elimination of plastic deformation, and based on the presented theory (chapter 4, section 4.1.1 and 4.1.2), a likely result of increases in soil pore water pressures associated with the process of consolidation. Given the low rate at which soil volume changes occur under saturated conditions, and the fact that upland soils are at or beyond field capacity for much of the year, it may be prudent to limit harvesting of coarse textured soils to periods of greater rainfall (and therefore soil water content) when the rate of volume changes may be significantly reduced due to increased pore water pressures under loading, and the incidence of compaction (more rapid than consolidation) minimised.

5.2.1.2. The location and construction of brash mats.

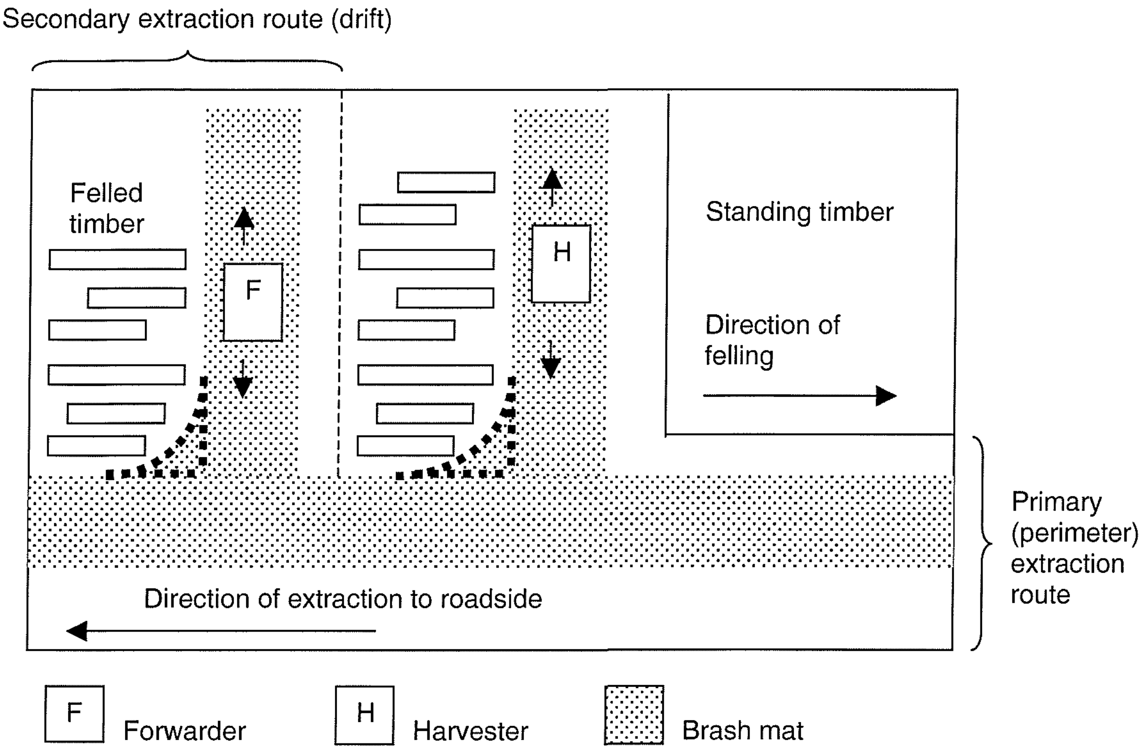
Restricting machinery to designated routes represents the most direct means of reducing the areal extent of soil impacts where associated losses in operational efficiency (leading of timber to roadside) have been estimated at less than 10% (Froehlich and McNabb, 1984), though costs during planning may be incurred (Wronski and Murphy, 1994). The spatial extent of designated extraction routes under the shortwood system and therefore the area of soil potentially at risk from machine impacts (estimated in this study to range between c. 30-50% of the site area), is dictated largely by machine specification (the reach of the harvesting head) and the volume/mix of saleable timber products (for example, where extraction routes are kept narrow to avoid unmanageable quantities of cut timber). As a result, it is unlikely that this could be manipulated without significant disruption and therefore cost to the harvesting operation. However, attention to the 'form' and location of key extraction routes, particularly where difficult ground conditions are localised, offers an opportunity to further limit ground impacts, and the following recommendations are made:

- Avoid crossing of drains and water courses wherever possible;
- Where secondary extraction routes join primary extraction routes (identified as key areas of brash failure), the entry point should be widened (Figure 5.1, p. 123) to minimise the incidence of brash deflection and deep rutting.
- For slope class 3 or greater (>11°), circular routes are advocated where a heavily brashed primary (perimeter) route (chapter 4, section 4.3) carries the majority of traffic upslope, thus limiting brash deflection on secondary routes associated with multiple machine passes and poor tractive efficiency when travelling up-slope (Figure 5.2, p. 123).
- Tree tops (stem diameter <7 cm) should be placed to enhance the structural integrity of the brash mat during repeated downhill trafficking (Figure 5.2, p. 123). This concept is considered in greater detail below in section 5.3.

5.2.1.3. Controlling the number of machine passes.

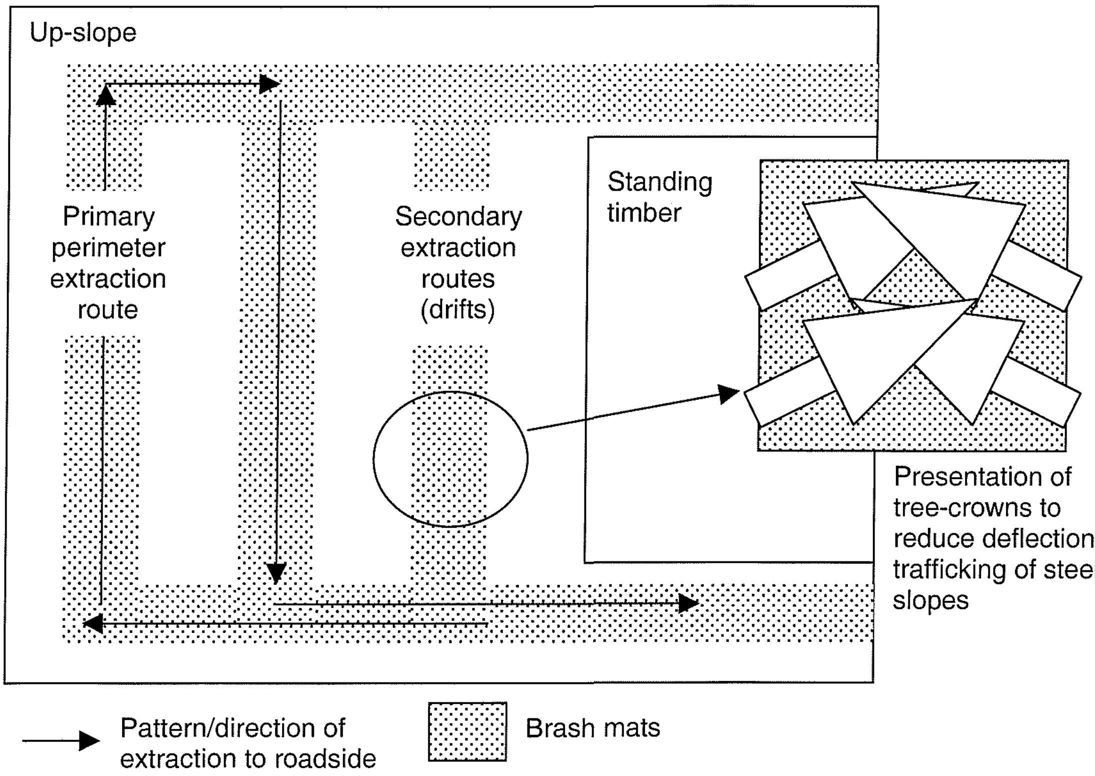
An obvious theoretical approach to reducing soil disturbance, would be to limit the number of machine passes at any given area based upon knowledge of the disturbance curve (i.e., change in soil structural properties as a function of increasing numbers of machine passes). Unfortunately the success of such an approach may be limited given that the majority of soil changes occur during the first few machine passes (chapter 1, section 1.3.1). In addition, it has been demonstrated that under the shortwood system, management decisions aimed at limiting soil disturbance must assume a high number of machine passes across the entire site, and based on the results of this study, a minimum of 8-10 machine passes. However, significant increases in soil density and soil penetration resistance were not found at high levels of trafficking, and soil disturbance (deep rutting and exposure of mineral layers) over much of the site (comprising secondary extraction routes) was related instead to the longevity of the brash mat (chapter 4, section 4.3).

Figure 5.1. Reducing brash deflection at turning points.



Heavily dashed lines indicate reshaping of junctions, and increased area of brash mat

Figure 5.2. Design of circular extraction routes for slope class 3 or greater (>11°).



5.3. Optimising the longevity of brash mats.

Brash mats have been demonstrated in this study to provide a highly effective means of limiting soil impacts, provided the brash mat remains intact. The longevity of the brash mat during repeated trafficking, and the occurrence of localised failure of the brash mat (deflection of logging residues and expose of the ground surface), was ascribed to a number of key internal and external factors rather than brash mat thickness or the number of machine passes (chapter 4, section 4.3), these included:

- Specific vehicle manoeuvres and trafficking intensity in relation to terrain factors (section 5.2.1.2 and below, section 5.3.1).
- Composition of the brash mat (below, sections 5.3.1 and 5.3.2).

Brash volume may also be important, especially on sensitive soils where the inherent volume and/or strength/bearing capacity of logging residues is low (a function of species, stand condition, stocking regime, previous thinning operations and harvesting system). This is considered below (section 5.3.2).

5.3.1. Terrain and composition.

Based on the observations during year 1 and year 2 trials, a simple semi-quantitative guide to assessing the potential scale of brash mat failure is presented in Table 5.2 (p. 125). The risk of failure is increased where ground conditions deteriorate, and/or where ground roughness and/or slope increases. In addition, the structural integrity and machine load applied to the ground surface is affected by the volume and distribution of large diameter logging residues (chapter 4, section 4.3). For example, a firm mineral soil (class 2) of intermediate ground roughness (class 2) and slope 6-11° (class 2), and fine composition (proportion of large diameter material >7 cm diameter of length 0.25-0.75 m), has a low-medium (L-M) failure risk. In contrast, a dry peaty gley (class 4) of intermediate ground roughness (class 4) and slope 27°+ (class 5), and medium

Table 5.2. Brash mat failure hazard assessment based on terrain and composition.

	Ground conditions and/or ground roughness and/or ground slope*				
	1	2	3	4	5
	Dry sands and gravels	Firm mineral soils	Soft mineral/ironpan soils (dry)	Peaty gleys (dry), soft mineral soils (wet)	Peaty gleys (wet), deep peats
	Obstacles** small/widely spaced	Intermediate	Obstacles of 40 cm at 1.5-5 m spacing	Intermediate	Obstacles of 60 cm at 1.5-5 m spacing
Composition***	0-10% (0-6°)	0-20% (6-11°)	20-33% (11-18°)	33-50% (18-27°)	50%+ (27°+)
Fine	L	L-M	M	M-H	H
Medium	M	M	M	M-H	H
Coarse	H	H	H	H	H

*UK Forestry Commission terrain classification, **boulders, plough furrows etc. ***proportion of material >7 cm diameter and of length 0.25-0.75 m. Low (L), medium (M) and high (H) risk of brash mat failure and machine down time associated with re-brashing.

composition (proportion of large diameter material >7 cm diameter of length 0.25-0.75 m), has a high (H) failure risk.

The bearing capacity of the logging residues (e.g., brittleness, flexibility etc) as determined by species will also affect the longevity of the brash mat, though little is known regarding the engineering properties of this material. For example, the branch wood of Sitka spruce is highly flexible and able to withstand repeated trafficking, while that of Norway spruce is generally quite brittle and often subject to rapid breakage (based upon anecdotal evidence from machine operators).

The engineering properties of saleable timber in the UK are described in a number of ways (Cahalan, 1987). The *modulus of rupture* (a measure of bending strength) represents the stress throughout the extreme fibres at the point of failure. The *modulus of elasticity* expresses the relationship between stress and strain, and reflects the extent to which a timber sample will bend before failure. The *shear strength* (measured parallel to the grain) represents the load a sample can withstand prior to shear failure. Nominal specific gravity (the ratio of weight of the sample to an equal volume of water) and density at a given water content) are additional factors affecting those described above, and in general, an increase in either/or both will increase the overall timber strength.

Assuming that the engineering properties of logging residues may be described in a similar way, a brash mat failure hazard assessment is presented in Table 5.3. For example, where the flexibility and/or strength of logging residues is low the risk of high is high (H).

Table 5.3. Brash mat failure hazard assessment based on the engineering properties of logging residues.

	Strength of logging residues		
Flexibility of logging residues	High	Med	Low
High	L	M	H
Medium	M	M	H
Low	H	H	H

Low (L), medium (M) and high (H) risk of failure.

5.3.2. The volume of logging residues.

A means of carrying out pre-harvest volume estimates of logging residues was developed during this study such that minimum recommended volumes for effective ground protection could be presented. Based upon provisional allometric functions (Robert Matthews, 2000; personal communication)[1] and readily available yield information (Edwards and Christie, 1981), the methodology accounts for variations according to; (1) soil type (2) species, (3) age (4) stocking density and (5) previous thinning operations. The two major components of the logging residues are defined as; (1) branch wood (V_{branch}) comprising the main stem of <7 cm diameter and all other woody branch material not part of the main stem (including root volume) and (2), non-saleable components of the main saleable stem (>7 cm diameter and generally of length 0.25-0.75 m) lost during conversion (V_{loptop}) comprising off-cut tops (>7 cm diameter), forks (where the main stem splits into two separate stems) and some stops (a portion of the main stem exhibiting a rapid change in diameter) but not including massive butts and very large diameter off-cuts (too large to provide effective floatation). Total tree volume can be calculated from:

$$V_{total} = V_{stem} \times f(t) \qquad \text{[Eqn. 5.1]}$$

where V_{stem} ($m^3\ ha^{-1}$) is the volume of saleable timber (Edwards and Christie, 1981) and $f(t)$ is an inflation factor obtained using either:

$$f(t) = \alpha + \frac{\beta}{(1+\gamma.t)} \quad \text{where } t > t_{min}; \qquad \text{[Eqn. 5.2]}$$

or;

$$f(t) = f(t_{min}) \quad \text{where } t \leq t_{min}; \qquad \text{[Eqn. 5.3]}$$

---

[1] Robert Matthews, Forest Research, Alice Holt Lodge, Farnham, Surrey, UK.

where t is stand age (yrs) and t_{min}, α, β and γ are parameters given in Table 5.4.

Table 5.4. Parameters for Eqns. 5.2 and 5.3 (after Matthews, 2000).

	Parameters			
Species group	t_{min} (yrs)	α	β	γ
Spruces *	22	1.441	-0.720	-0.067
Pines	20	1.194	-2.785	-0.117
Firs **	16	1.022	-1.211	-0.093
Oak and beech	25	1.609	-0.636	-0.063
Other broadleaves	19	1.309	-0.387	-0.070

*(inc. Hemlock, Cedar, Cypress). **(inc. other conifers not listed).

Based on a rearrangement and modification of Eqn 5.1 (p. 127), the first component of the brash mat V_{branch} is assumed to be given by:

$$V_{branch} = V_{stem} \times r \times (f(t) - 1) \qquad \text{[Eqn. 5.4]}$$

where r (0.85) is the correction factor to remove root volume (estimated at 15% of V_{total} - V_{stem}). The second component V_{loptop} is assumed to be given by:

$$V_{loptop} = g \times V_{stem} \qquad \text{[Eqn. 5.5]}$$

where g (0.06) is the stem volume potentially saleable but lost during conversion, based on an estimated range of 0.05% to 0.07% (R. Matthews, 2000; personal communication). Finally the total volume of brash material (the total volume of saleable and non-saleable material lost during conversion) V_{brash} is given by:

$$V_{brash} = V_{branch} + V_{loptop} \qquad \text{[Eqn. 5.6]}$$

5.3.2.1. Silvicultural factors affecting the volume of logging residues.

In the following example, the effects of yield class, spacing, thinning regime and species on volume estimates of V_{branch} and V_{loptop} are considered. Silvicultural treatments common to UK upland forestry have been chosen (Roger Coppock, 2000; personal communication)[2], though the methodology described above may be applied throughout the UK where existing yield models (Edwards and Christie, 1981) are applicable. Tree species considered include Sitka spruce, Norway spruce, Scots pine, Lodgepole pine and Japanese larch which dominate the coniferous upland plantations of Scotland and Northern England. The trend towards wider spacing is reflected (before 1970 at c. 1.7 m, after 1970 at c. 2.0 m., Roger Coppock, 2000; personal communication)[3]. However, recent studies suggest the engineering properties of Sitka spruce timber may be impaired beyond c. 2.0 m spacing (Hibberd, 1990), and for illustration this is used as an upper limit. All examples are based on $t > t_{min}$ (Eqn. 5.2, p. 127) which is considered to represent economic viability (main stem > 7 cm diameter) for which yield models are available.

Differences in V_{brash} according to species are shown in Figure 5.3 (p. 130). Examples are based upon an average yield class and a spacing of 2.0 m for all but Japanese larch (data for unthinned stand only available at 1.7 m spacing). As the stands mature, differences in V_{brash} between the five species (spruce, pine and larch) become apparent. At clearfell (typically 50-61 years for the pine species and 44 years for the larch), V_{brash} is approximately 50% and 30% respectively of that for the spruce species (typically clearfelled at 50-55 years). Beyond the average age of felling, the volume of V_{brash} continues to rise for the spruce species while stabilising for the pines, but for larch, V_{brash} falls steadily from c. 35 years. Figure 5.4 (p. 130) illustrates the effect of yield class and spacing on V_{brash} for Sitka spruce. There is a marked increase in V_{brash} with greater yield class (YC: 6, 12, 18 and 24), but the effect of spacing (at either 1.7 m or 2.0 m) within each yield class has no appreciable effect (on V_{brash}). The effect of thinning treatments on V_{brash} for Sitka spruce at 1.7 m spacing (YC: 6, 12 and 24) is demonstrated in Figure 5.5 (p. 131). For each yield class, the effect of both line thinning (no delay) and crown thinning (no delay) is to reduce V_{brash} at clearfell (typically 40-60 years)

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[2] Roger Coppock. Forestry Commission, Forest Planning, Edinburgh, UK.
[3] As above

Figure 5.3. Differences in V_{brash} according to species.

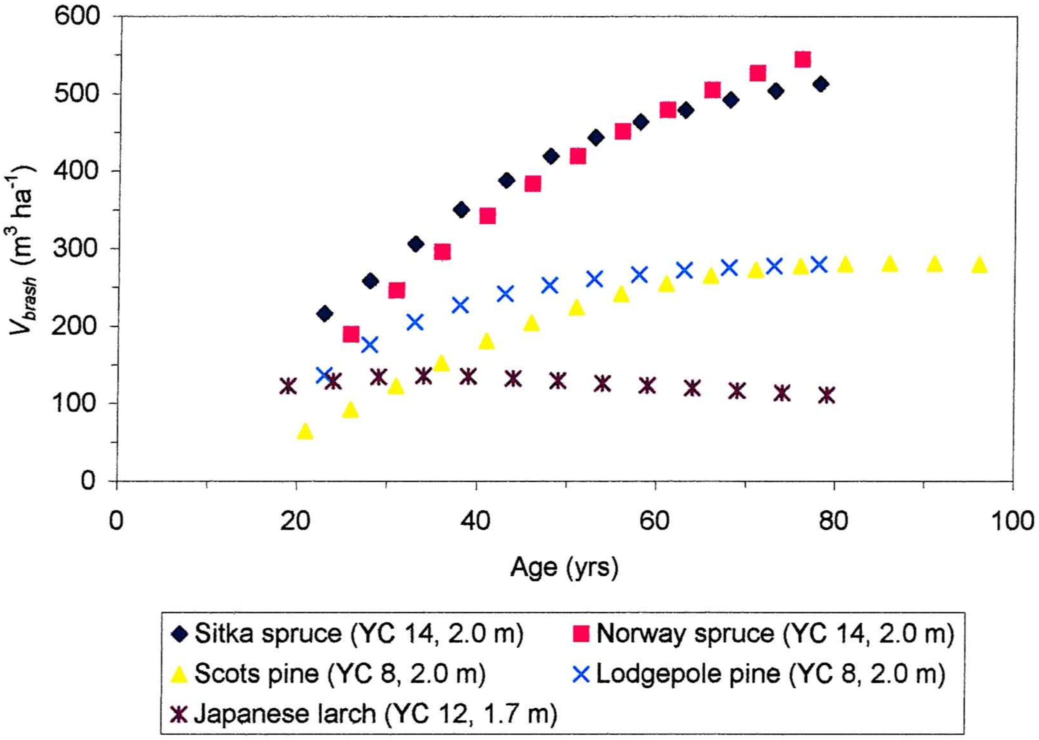


Figure 5.4. The effect of yield class (YC) and spacing (m) on V_{brash} for Sitka spruce.

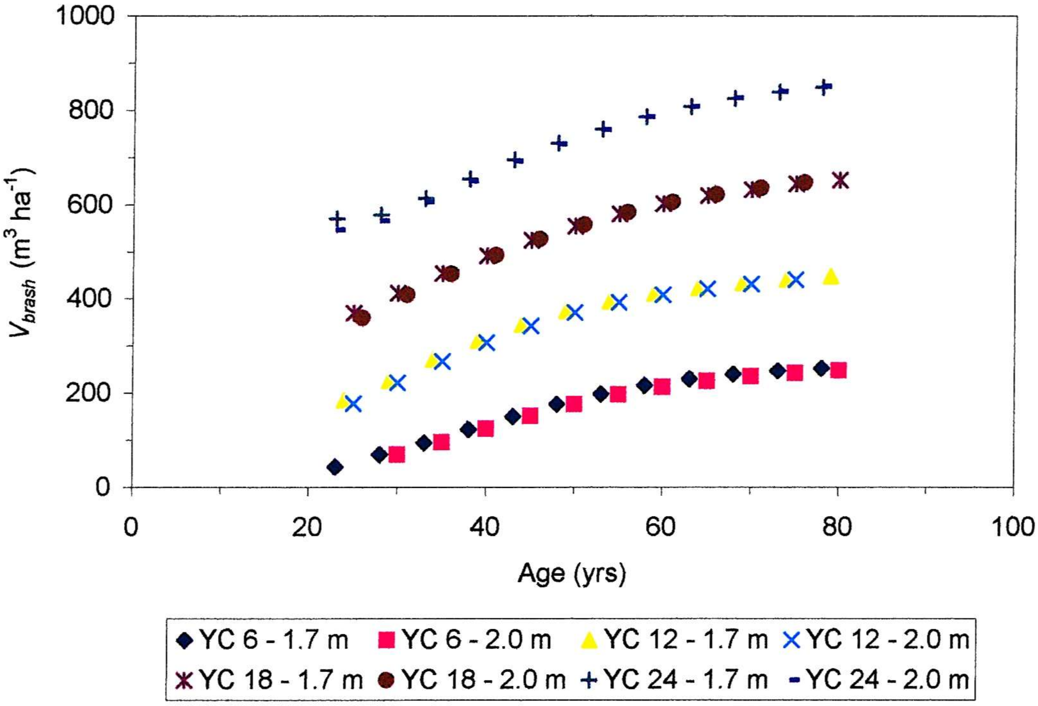
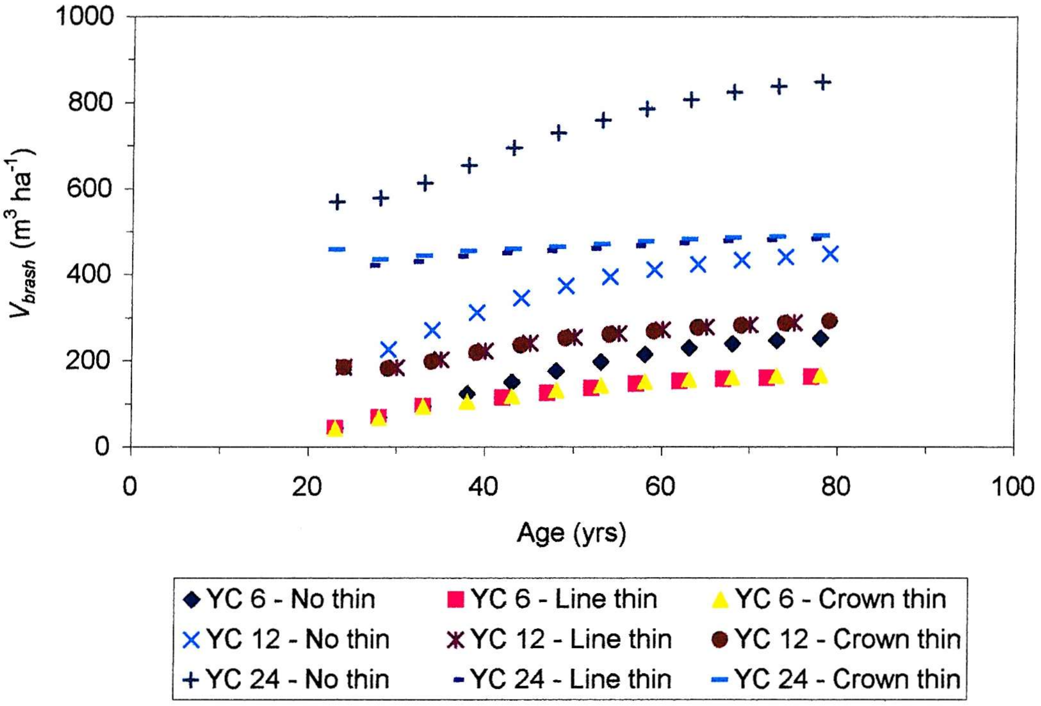


Figure 5.5. The effect of different thinning treatments on V_{brash} for Sitka spruce.



to around 60% of an unthinned stand. The difference in V_{brash} between line-thinning (no delay) and crown thinning (no delay) within each yield class is negligible.

In addition, the overall composition of V_{brash} in terms of both V_{branch} and V_{loptop} is important as the former provides soil protection and vehicle traction while the latter has been shown in this study to result structural weakness (chapter 4, section 4.3) within the brash mat. The relative proportions of V_{branch} and V_{loptop} around the typical and maximum rotation length according to species are summarised below in Table 5.5.

Table 5.5. Typical volume estimates (m^3 ha^{-1}) of V_{stem}, V_{branch}, V_{loptop} and V_{brash}.

Species	Age*	V_{stem}	V_{branch}	V_{loptop}	V_{brash}	V_{loptop} (% total)
SS (YC 14, 2.0 m)	48	591	384	35	419	8
	78	886	460	53	513	10
NS (YC 14, 2.0 m)	56	688	410	41	451	9
	76	933	489	56	545	10
SP (YC 8, 2.0 m)	61	417	230	25	255	10
	101	624	239	37	277	14
LP (YC 8, 2.0 m)	48	343	233	21	253	8
	78	542	247	33	280	12
JL (YC 8, 1.7 m)	44	322	114	19	133	15
	79	462	84	28	111	25

* For each species, lowest values indicates typical age and highest value represents maximum age (rotation length) at time of clearfell.

The proportion of V_{loptop} at clearfell is typically between 8% and 14% of V_{brash} based on the silvicultural conditions in this example, however for Japanese larch V_{loptop} approaches c. 25% of V_{brash} at the maximum rotation length. In practice, the inclusion of V_{loptop} during the construction of the brash mat is random and difficult to predict. In addition, given the effect of V_{loptop} on the longevity of the brash mat and distribution of machine loads at the ground surface (chapter 4, section 4.3), it is recommended that the inclusion of V_{loptop} in the brash mat is avoided as far as possible.

5.3.2.2. Estimating the volume of logging residues - year 1 and year 2 sites.

The following guidelines assume V_{brash} comprises V_{branch} only (section 5.3.2., Eqn. 5.4, p. 128). Volume estimates and subsequent recommendations apply to secondary extraction routes (constituting the largest area of the site). For primary extraction routes, volume estimates may be 2 to 3 times greater (based on observations of crown density along forest edges). An approximation of V_{branch} (m^3 ha^{-1}) available for an entire compartment (V_{comp}) is given by:

$$V_{comp} = V_{branch} \times A \qquad \text{[Eqn. 5.7]}$$

where A is the total area (ha) of the felling coupe. In practice, the volume/thickness of the brash mat at any point on the clear-fell is a function of V_{comp} (m^3) and the areal extent of extraction routes EX_{tot} (ha), the latter a function of machine specification which may be predicted for a range of scenarios using:

$$EX_{tot} = \frac{A}{(D_{width} / B_{width})} \qquad \text{[Eqn. 5.8]}$$

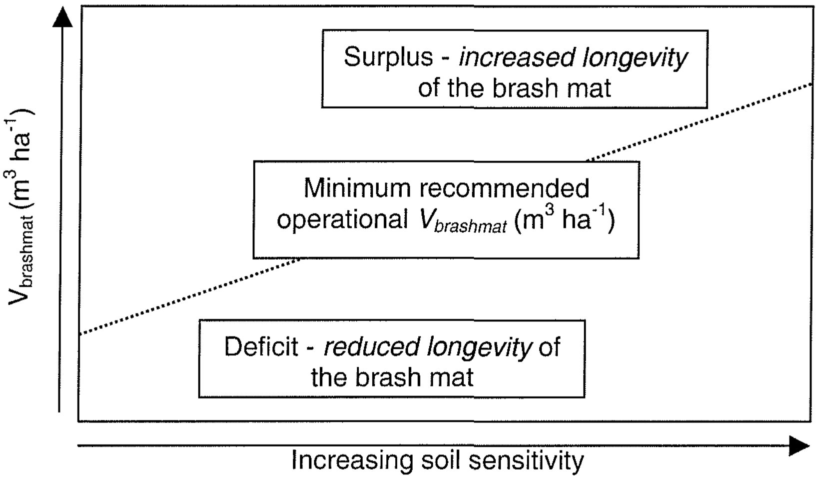
where D_{width} (m) is the drift width (determined by the boom reach of the harvester) and B_{width} (m) the width of the brashed extraction route. For the purpose of illustration, the latter is considered constant ($B_{width} = 5$ m) based upon observations during year 1 and year 2 trials. However, in practice this may be modified where smaller machines are used (e.g., during thinning operations). Effective ground protection defined by $V_{brashmat}$ (m^3 ha^{-1}) is then given by:

$$V_{brashmat} = \frac{V_{comp}}{EX_{tot}} \qquad \text{[Eqn. 5.9]}$$

Application of the process described above is demonstrated theoretically in Figure 5.6 (p. 134). Under certain conditions, stand character and/or machine specification (harvester boom reach) may not allow the generation of sufficient

V_{branch} resulting in a 'deficit', hence machinery with a greater reach must be considered to ensure an 'operational' $V_{brashmat}$. However, in some cases where the bearing capacity of the branch wood is low, soil bearing capacity particularly low or the scale of the clear fell such that the total area of primary extraction routes is high, the use of harvesting machinery with the greatest boom reach is advisable to ensure a 'surplus' of branch wood.

Figure 5.6. A theoretical guide to optimising the longevity of the brash mat based on soil sensitivity to disturbance.



5.3.2.3. Defining an optimal volume of logging residues.

In order to calibrate the theoretical model described above, yield model scenarios applied during forecasts by Forest Enterprise (Dave Woodhouse, 2000; personal communication)[4], and data regarding machine specification, plot dimensions and stand information were applied (Table 5.6, p. 135) to sites 01K and 03K-06K (data for sites 02N and 03K were unavailable). Maximum boom reach is that of the harvester upon which maximum drift width is based, actual boom reach is based on the actual (average) drift width at year 1 and 2 sites. Maximum boom reach assumes full utilisation of the boom therefore the spatial distribution of extraction routes is minimised and hence $V_{brashmat}$ is maximised, though this was never

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[4] Dave Woodhouse (Harvesting Manager). Forest Enterprise, Kielder Forest District, Northumberland, UK.

achieved at any site studied (discussed below, this section). Volume estimates of $V_{brashmat}$ (year 1 and 2 sites) are presented in Table 5.7.

Table 5.6. Yield model scenarios, machine specification, plot dimensions and stand information applied during calculation of $V_{brashmat}$ - year 1 and year 2 sites.

Site	Max boom reach (m)*	Max drift width (m)	Actual boom reach (m)	Actual drift width (m)**	Brash mat width (m)	Species	Yield class	Age (yrs)	Area (ha)	Thining	Spacing (m)	V_{stem} (m^3 ha^{-1})
01K	8.85	17.7	8	16	5	SS	12	47	70	No	1.7	533
02N	8.85	17.7	8	16	5	SS	Na	Na	Na	Na	na	na
03K	8.8	17.6	6	12	5	SS	Na	Na	Na	Na	na	na
04K	8.8	17.6	6	12	5	SS	12	51	8.0	No	1.7	533
05K	9.5	19.0	5	10	5	SS	10	48	42.5	No	1.7	408
06K	8.8	17.6	7.5	15	5	SS	14	48	12.5	No	1.7	585

*chapter 2, Table 2.2. **chapter 2, Table 2.1.

Table 5.7. Estimates of $V_{brashmat}$ - year 1 and year 2 sites.

Site	V_{total} (m^3 ha^{-1})	V_{branch} (m^3 ha^{-1})	V_{comp} (m^3)	EX_{tot} (ha)	$V_{brashmat}$ (m^3 ha^{-1})	Efficiency (%)*
01K	946	351	24558	21.9	1123	90
02N	Na	Na	Na	Na	Na	90**
03K	Na	Na	Na	Na	Na	68**
04K	926	334	2673	3.3	802	68
05K	720	265	11265	21.3	530	53
06K	1032	380	4751	4.2	1140	85

*% of maximum attainable $V_{brashmat}$ assuming full boom reach is utilised, ** values for sites 02N and 03K are based on plot dimensions (chapter 2, Table 2.1).

At each site, $V_{brashmat}$ was 53-90% of maximum attainable $V_{brashmat}$. In any situation this may reflect terrain factors and machine stability, or product mix (for example where drifts are kept narrow to ensure products can be stacked for efficient removal). Based on these volume estimates and the observed response of the brash mat at year 1 and year 2 sites along secondary extraction routes, a critical $V_{brashmat}$ of c. 500-1000 m^3 ha^{-1} is recommended where terrain factors (ground condition, surface roughness and slope of class 1-2) do not influence the longevity of the brash mat (Table 5.2, p. 125). At site 01K, a $V_{brashmat}$ of c. 1123 m^3 ha^{-1} was insufficient to prevent widespread (though unquantified) deflection of brash material on steep ground (slope class 3), at site 04K, a $V_{brashmat}$ of c. 800 m^3 ha^{-1} was insufficient to avoid localised failures associated with a drainage network (ground roughness class 3). Where terrain factors are such that re-brashing may be a requirement (ground conditions, surface roughness or slope of class 3 or greater), $V_{brashmat}$ should be maximised (below, section 5.3.3.1) to ensure an adequate supply of branch wood, whilst the omission of V_{loptop} may serve to increase the longevity of the brash mat further still.

5.3.3. Machine choice and specification.

The importance of machine choice and specification is considered to relate to (1); maximising $V_{brashmat}$ based on harvester boom reach and (2), maintaining machine traction without compromising the efficiency of the brash mat.

5.3.3.1. Utilisation of harvester boom reach.

Based on the maximum attainable and measured drift widths (based on specified boom reach) for all sites during year 1 and year 2 trials presented above (Table 5.6, p. 135), it can be seen that between 53-90% of the boom reach was utilised at each site (Table 5.7, p. 135). Interestingly at site 01K, 90% utilisation of the harvester boom reach, and therefore $V_{brashmat}$, did not prevent serious deterioration of the brash mat. The utilisation efficiency of 90% at this, and site 02N, was facilitated by a low product mix (chapter 2, Table 2.1), hence wider drifts could be used without compromising the efficiency of extraction. This is in contrast to only 53% utilisation of boom reach at site 05K, where a large product mix necessitated narrow drifts to accommodate the volume of individual products without compromising the efficiency of extraction. At site 06K, planting originally included a nurse species resulting in double spacing of the economic crop at the time of harvesting and requiring 85% utilisation of boom reach.

Given the variation in $V_{brashmat}$ according to silvicultural practice, derivation of a minimum drift width for every yield model scenario was beyond the scope of this study. However, for a range of silvicultural treatments at typical felling ages (Roger Coppock, 2000; personal communication)[5], a number of examples are given in Table 5.8 (p. 138) which reflect the narrow spacings employed prior to 1970, and as such are typical stand spacings encountered at contemporary clear fells. A maximum attainable drift width of 17 m is assumed, based on the harvesting machinery observed during year 1 and 2 trials (and considered typical of machinery currently available). Assuming that terrain factors are such that an 'operational' $V_{brashmat}$ (500-1000 m^3 ha^{-1}) is sufficient (section 5.3.2.3), recommended drift widths (thinned or non-thinned) range between 6-17 m. However, for Japanese larch the operational range will not be achieved even under 100% utilisation of the boom (equal to a maximum drift width of 17 m). Similarly, where a 'surplus' $V_{brashmat}$ (> 1000 m^3 ha^{-1}) is recommended, 100% utilisation of the boom is often insufficient, especially where previous thinning operations have taken place.

Based upon operational guidelines for harvesting machinery (Colin Saunders, 1999; personal communication)[6], 100% utilisation of the boom reach is often undesirable given its effect on the efficiency of extraction to roadside (described above, this section) and also given the large stresses it can place on the harvesting machinery. As such, and notwithstanding the recommendations given in Table 5.8 (p. 138), allowances should be made for occasions where the volume of logging residues generated may be insufficient for effective ground protection. This may include scheduling periods of brash maintenance and stock-piling of logging residues where appropriate. Additionally, it is important to note that the recommended $V_{brashmat}$ is not absolute, and, in the case of Japanese larch, with careful attention to the placement and maintenance of the brash mat, machine choice and soil conditions at the time of harvesting, failure of the brash mat may be largely avoided.

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[5] Roger Coppock. Forestry Commission, Forest Planning, Edinburgh, UK.

[6] Colin Saunders. Technical Development Branch, Forest Research, UK.

Table 5.8. Minimum recommended D_{width} (m)* and associated $V_{brashmat}$ (m^3 ha^{-1}) based on yield class (YC), spacing (Sp) in metres and typical age at clearfell (yrs).

	Sitka spruce					Norway spruce					Scots pine					Lodgepole pine					Japanese larch				
	YC	Sp	Age	D_{width}	$V_{brashmat}$	YC	Sp	Age	D_{width}	$V_{brashmat}$	YC	Sp	Age	D_{width}	$V_{brashmat}$	YC	Sp	Age	D_{width}	$V_{brashmat}$	YC	Sp	Age	D_{width}	$V_{brashmat}$
Operational $V_{brashmat}$ (500 m^3 ha^{-1}) where slope and ground roughness class are 1-2																									
No thin	8	1.7	56	**11**	**531**	8	1.8	62	**10**	**502**	8	1.8	61	**11**	**501**	8	1.8	50	**11**	**545**	8	1.7	44	**17**	**386**
	12	1.7	52	**7**	**514**	12	1.8	57	**7**	**501**	10	1.8	57	**10**	**552**	10	1.8	47	**9**	**548**	10	1.7	43	**17**	**463**
	16	1.7	49	**6**	**561**	16	1.8	53	**6**	**559**	12	1.8	55	**8**	**520**	12	1.8	45	**8**	**566**	12	1.7	41	**16**	**519**
Line thin (no delay)	8	1.7	63	**15**	**516**	8	1.5	71	**15**	**527**	8	1.4	69	**17**	**556**	8	1.5	62	**16**	**503**	8	1.7	54	**17**	**227**
	12	1.7	56	**11**	**523**	12	1.5	61	**11**	**536**	10	1.4	63	**17**	**626**	10	1.5	59	**13**	**501**	10	1.7	50	**17**	**274**
	16	1.7	49	**9**	**553**	16	1.5	53	**9**	**530**	12	1.4	58	**17**	**773**	12	1.5	54	**12**	**523**	12	1.7	46	**17**	**333**
Surplus $V_{brashmat}$ (>1000 m^3 ha^{-1}) where slope and/or ground roughness class are 3 or greater.																									
No thin	8	1.7	56	**17**	**821**	8	1.8	62	**17**	**854**	8	1.8	61	**17**	**774**	8	1.8	50	**17**	**842**	8	1.7	44	**17**	**386**
	12	1.7	52	**14**	**1028**	12	1.8	57	**14**	**1003**	10	1.8	57	**17**	**939**	10	1.8	47	**17**	**1034**	10	1.7	43	**17**	**463**
	16	1.7	49	**11**	**1029**	16	1.8	53	**11**	**1025**	12	1.8	55	**16**	**1040**	12	1.8	45	**15**	**1061**	12	1.7	41	**17**	**551**
Line thin (no delay)	8	1.7	63	**17**	**585**	8	1.5	71	**17**	**597**	8	1.4	69	**17**	**556**	8	1.5	62	**17**	**534**	8	1.7	54	**17**	**227**
	12	1.7	56	**17**	**809**	12	1.5	61	**17**	**829**	10	1.4	63	**17**	**626**	10	1.5	59	**17**	**655**	10	1.7	50	**17**	**274**
	16	1.7	49	**17**	**1045**	16	1.5	53	**17**	**1001**	12	1.4	58	**17**	**773**	12	1.5	54	**17**	**741**	12	1.7	46	**17**	**333**

*for equivalent boom reach divide D_{width} by 2.

5.3.3.2. Choosing tyres and traction aids.

Where tracks are fitted to wheeled machinery the applied loads are distributed more evenly and maximum ground pressures are reduced. Used in association with brash mats, this represents a significant (though as yet unquantified) reduction in the applied load. It is important to ensure that while traction is maintained (especially on steeper sites) the integrity of the brash mat is not compromised where overly aggressive traction aids are fitted. A review by Murgatroyd (1997b) describes a range of tyres and traction aids available in the UK and recommendations for their application. Table 5.9 illustrates the key design features affecting the relationship between tyres, traction aids and the longevity of the brash mat.

Table 5.9. The effect of rolling gear choice on brash mat longevity (after Murgatroyd, 1997b).

	Traction (and potential reduction in the longevity of the brash mat)		
Rolling Gear	High (high)	Moderate (moderate)	Low (low)
Tyres - tread pattern	Open V*	Open V (some parallel lugs)	Open V (more parallel lugs)
Make and model	Trelleborg 421	Trelleborg 423 Nokian ELS	Trelleborg 404 Nokian ELS L1-1
Chains (link pattern)	Close spaced rings (with studs)	Moderately spaced hexagonal or diamond (with or without studs)	
Make and model	Ovako (Tapio series) Norse and Rud	Ovako (Matti series) Norse and Rud	
Band-tracks (plate spacing)	High	Medium	Low
Make and model	Older Clark and Olofsfors		

* not suitable for use with band-tracks.

Where traction is a problem (as for steep sites such as 01K), the use of tyres or traction aids with moderate to aggressive traction may increase the incidence of brash deflection, and attention is drawn to the recommendations presented in section 5.2.1.2.

Chapter 6 - Conclusions.

The following chapter summarises the results of this study and presents recommendations for areas of further research.

6.1. General conclusions.

The effects of mechanised forest harvesting on soil physical properties in the UK employing the shortwood system of extraction have, until now, remained largely unknown. Previously, Nisbet (1996) stated that the UK Forestry Authority were confident that the Forests and Water Guidelines (Forestry Commission, 1988, 1991 and 1993) effectively tackled all the main water (and to a lesser extent soil) quality issues associated with silvicultural operations. The recently published Whole Tree Harvesting: A Guide to Good Practice (Nisbet *et al.,* 1997) and Forests and Soil Conservation Guidelines (Forestry Commission, 1998), have made considerable progress in addressing more directly, the issue of soil disturbance. However, validation of these, and the development of future operational guidelines, depends on continued research and monitoring.

Based on fundamental soil mechanical theory (summarised below), this study has demonstrated that, for deep peat and shallow peat over gleyed mineral soils at high water contents, and considered previously (Forestry Commission, 1998) to be at moderate risk of disturbance, potentially adverse structural changes can be largely avoided given adherence to the existing guidelines cited above (this section). The incidence of localised soil disturbance may be further reduced, and the efficiency of timber extraction maintained, where the longevity of ground protection measures (brash mats) is maximised according to a quantitative assessment of forest, soil (and terrain) and machine characteristics such as that developed in this study.

No significant increases soil density were found throughout the mineral (A-E) layers of the gleyed soils. Under the saturated conditions, and where the soil was confined by an overlying peat layer changes in soil volume were dependent on the period of machine loading (momentary) and soil permeability (low). It has been suggested in previous studies that machine logging operations on wet mineral soils should be avoided where soil compaction (occurring under water contents at or below field capacity and where air only is squeezed from soil voids) is rapid. However, based upon theoretical soil mechanics applied during the interpretation of soil response in this study, logging of mineral soils under wet conditions (above field capacity) may be preferable, where soil volumetric changes occur at a much slower rate when the peat (O) layer is retained *in situ* as a result of the brash mats (see below).

Armouring of designated extraction routes with logging residues (brash mats) has been demonstrated to be a highly effective means of reducing soil impacts during harvesting. Brash mats removed direct contact between the ground surface and the machinery. As a result, both the litter and peat horizons were retained *in situ* and hence, deep rutting and erosion of underlying mineral soil were avoided in all but a few isolated cases, despite high levels of trafficking.

No significant changes in bulk density throughout the peat (O) layer were found, and trafficked values of soil strength (soil penetration resistance) remained well below thresholds known to affect root growth. Further increases in soil strength may occur subsequent to those measured during the period immediately after each site was harvested as a result of age-hardening processes. Unfortunately, time restrictions meant that this could not be investigated during the course of this study. However, given the elastic properties of the peat (O) layer and the predisposition of root growth to follow the line of least resistance, impacts to root growth resulting from further increases in soil strength during subsequent rotations are unlikely. Preferential rooting may affect tree stability during future rotations, particularly along forest edges where primary extraction routes associated with heavy trafficking were located, placing the interior stand at greater risk from wind throw.

Given the measured increases in soil penetration resistance measured both centrally and adjacent to the wheel tracks, the marked, though non-significant, reduction of saturated hydraulic conductivity at site 05K (c. 35%) and site 06K (c.

75%) measured directly beneath the wheel tracks throughout the upper mineral (A) layer may extend laterally, and as such affect up to 50% of the site at this depth (based upon the total areal extent of brashed extraction routes). A reduction in drainage around the area of transition between the peat (O) and upper mineral (A) layers may, in the absence of tillage treatments, reduce the drainage efficiency altering the height of the water table, and therefore the depth of the rooting zone due to the onset of anaerobic conditions, with potential consequences for both tree growth and stability. In addition, subtle changes in the availability of water and oxygen due to increases in soil water potential throughout the peat (O) layer may also prove detrimental to root and tree growth.

6.2. Recommendations for further research.

Given the scale of the forest industry in the UK, cumulative reductions in productivity may seriously affect both the economic and ecological value of the forests which could not be balanced by increases in timber production. As harvesting costs generally dominate those of timber production, higher costs associated with less damaging practices or the application of ameliorative measures may be difficult to justify unless long-term benefits can be proven. In addition, given interest in the expansion of whole-tree harvesting throughout the UK, the short term economic benefits may be cancelled by the long-term impacts to soil productivity in the absence of brash mats. Assuming greater understanding of the economic and socio-economic impacts of long-term reductions in sustainable production, and standardisation of field and laboratory techniques, the following recommendations for further research are made;

(1). A regional audit to establish (a); the level of compliance with existing operational guidelines and (b), the extent of both soil and broader environmental disturbance under these guidelines.

(2). A review of existing guidelines, harvesting technologies and extraction systems and consideration of how, and to what extent, these may be (a) modified to limit ground disturbance or (b), relaxed to allow greater flexibility during machine based operations.

(3). An investigation of the potential economic impacts to the soil system over successive forest rotations in terms of (a); lost timber revenue and (b) the cost of ameliorative treatments.

(4). An investigation of the mechanical properties of logging residues (used in the construction of brash mats) under both wheeled and tracked machine loading over a range of terrain classes, and how these may change with time/water content and site/silvicultural conditions.

(5). Further trials under operational conditions to determine the effect of harvesting traffic on soils not encountered in this study, but common in upland plantation forestry. Priority should be given to sites where the effective rooting zone comprises unsaturated mineral soils of high permeability and broad particle size distribution (where the rate and extent of increases in soil density may be particularly high), and include both upland and lowland sites.

(6). Derivation of compressibility indices under controlled laboratory conditions for a range of (forest) soils which may be employed in a predictive approach to determining maximum soil densities following mechanised forest harvesting.

(7). Trials to determine soil properties limiting to tree rooting efficacy and long-term growth under (a) controlled laboratory conditions and (b) *in situ* during periodic sampling of representative stands. Such trials would allow the development of standards of site-preparation and re-stock cultivation based upon chemical, physical and biological thresholds known to limit root and tree growth.

Glossary.

Forestry (silvicultural) terminology.

Bandtracks - Crawler tracks (see below) fitted over tyres to improve vehicle traction and, in some instances, to reduce vehicle loads applied to the ground surface.

Butt off-cuts - Base of the tree stem where the diameter exceeds that required by the market or capacity of the harvesting head (see below).

Brash mats - Extraction routes comprising logging wastes (see below) used to armour the ground surface, reduce soil disturbance and improve vehicle traction.

Cable extraction - Removal of timber suspended partially clear of the ground (dragged) by cable (powered by a stationary winch) to log landings (see below).

Clear felling - Systematic harvesting of a large area of forest by either harvesting machinery (see below) or motor-manual methods (see below).

Coupe (compartment) - Area of forest (often divided into sub-compartments) comprising trees of specified characteristics including species, age and yield class (see below).

Crawler tracks - Linked steel plates (often studded) fitted over tyres to improve vehicle traction and, in some instances, to reduce vehicle loads applied to the ground surface.

Cross cutting - Cutting of felled tree stems into specified lengths.

Drains - Open trenches (ploughed) to improve drainage of wet soils.

Extraction machine - See forwarder (below) or skidder (below).

Extraction routes - Designated routes along which cut timber is removed to log landings (see below) by extraction machinery.

Footprint area - The vehicle tyre or track area in immediate contact with the ground surface, the area of which may be increased by using bandtracks (see above), low pressure tyres (see below) or high flotation tyres (see below).

Forks - Non-saleable portion of a tree stem where the stem splits into two separate stems.

Harvesting machine - Purpose built or modified machinery designed to fell and, often, sned (see below) and crosscut (see above) individual tree stems.

Harvesting (grapple) head - A compact felling, snedding and cross cutting device mounted on a hydraulically operated boom of a harvesting machine (see above).

Harvesting system - The entire clear felling operation combining both harvesting and extraction activities.

High flotation tyres - Large tyres designed to increase the vehicle footprint area (see above) thus reducing the loads applied to the ground surface.

Low pressure tyres - Tyres designed to run at low pressures thus increasing the vehicle footprint area (see above) and reduce the machine load applied to the ground surface.

Logging wastes - Comprising tree branches, forks (see above), butt off-cuts (see above) and stops (see below).

Log landing - Area off-site, and usually along permanent (unsealed roads) where cut timber is stacked ready for collection.

Lop and top - (see logging wastes)

Plough furrows - Ground features associated with soil tillage and/or drainage systems.

Productivity - The volume of saleable timber (in the context of commercial forestry) produced by a single stand (see below) or coupe (see above), and characterised by yield class (see below).

Ride - Unplanted area delineating the boundary between each coupe (see above).

Roadside - See log landing.

Rolling gear - Vehicle tyres or tracks.

Rotation (length) - Life cycle (years) from planting to clear felling (see above) of an individual forest coupe (see above).

Shortwood harvesting system - Harvesting system (see above) whereby a coupe is systematically clear felled (see above) and stems cut to specified lengths and left on site prior to extraction by either forwarders (see above) or skidders (see below).

Silviculture - The science of growing trees and forests for a specific purpose.

Skidder - Vehicle used to drag cut timber from the site to log landings (see above).

Skyline extraction - Removal of timber suspended wholly clear of the ground by cable (powered by a stationary winch) to log landings (see above).
Sned (snedding) - Remove branches from a felled tree stem either by harvesting machinery (see above) or motor-manually (see above).
Stand - Referring to the collection of trees contained within an individual coupe (see above)
Stops – A portion of the tree stem exhibiting a rapid change in diameter, and often discarded during conversion (e.g., too large or too small to be handled by the harvesting head – see above).
Thinning - A process sometimes carried out during the forest rotation (see above) whereby individual trees are removed to improve the growing conditions and productivity (see above) of a given stand (see above).
Tree length system - Harvesting system (see above) whereby the coupe (see above) is systematically clear felled (see above) and whole stems removed by either forwarders (see above) or skidders (see above) to log landings (see above) prior to cutting and sorting at roadside (see log landing).
Wheel chains - Linked chains fitted over tyres to improve vehicle traction.
Yield class - Denoting the volume of saleable timber (m^{-3} ha^{-1}) within a given coupe (see above)

Soil science terminology.

A horizon - Upper mineral horizons with relatively dark colours compared to E horizons (see below) due to the incorporation of humified organic matter resulting from biological activity and/or cultivation.
E horizon - Horizons of relatively pale colour compared to A horizons (see above) and lower organic matter and/or iron oxide and/or clay than underlying (usually B) horizon (see above).
O horizon - Soil horizons containing greater than 20% organic matter.
Bearing capacity (of ground/soil) - The ability of a given soil to support a specified load without significant changes in structure.
Bulk density - The mass of dry soil per unit bulk volume.
Compaction - An increase in the density of unsaturated soil following the application of a specified load whereby air only is expelled from the soil body.

Compressibility - The rate and/or extent of either compaction (see above) or consolidation (see below)

Consolidation - An increase in the density of a saturated soil following the application of a specified load whereby water only is expelled from the soil body.

Field capacity - The content of water, on a mass or volume basis, remaining in a soil 2 or 3 days after having been wetted with water and after free drainage (due to gravity) is negligible.

Hydraulic conductivity - The flow of water through a saturated or unsaturated soil.

Macropores - Pore space (> 50 μm) between individual soil particles.

Micropores - Pore space (< 50 μm) between individual soil particles.

Moisture holding capacity - The volume of water held within a given body of soil after drainage due to gravity (see field capacity).

Overland flow - The flow of water over the ground/soil surface.

Particle density - The density of the soil particles, the dry mass of the particles being divided by the solid (not bulk) volume of the particles, in contrast with bulk density.

Particle size distribution - The proportion of sand, silt and clay particles within a given soil volume (expressed as percentage of total volume).

Pore water pressure - The hydrostatic pressure of water held within the soil.

Permeability - The rate at which water percolates through a given body of soil.

Strength - The adhesive and cohesive status of a given body of soil.

Porosity - The volume of pore space in a given volume of soil.

Traffickability - The relationship between the off-road vehicles and ground/soil bearing capacity (see above).

Void ratio - The ratio of the volume of soil pore (or void) space to the solid-particle volume.

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