SOIL DAMAGE IN FORESTRY FROM MACHINERY USED IN THINNING OPERATIONS

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by

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DEDICATION

I wish to dedicate this thesis to my parents, James & Jennie.
They have given support and encouragement to all the family to
achieve a high quality and standard of education over the years.
For this we will be forever grateful.

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Abstract

The potential increase in timber yields achieved through the thinning process in the forest is often reduced by soil compaction caused by the machinery involved in the thinning. This is often compounded by use of unsuitable machinery on difficult sites that are poorly drained, or in waterlogged conditions during wet weather.

The aims of this project were to measure the degree of soil compaction and to investigate the impacts of different types of machinery. The parameters used to measure the soil compaction caused were bulk density, soil shear strength, cone penetration resistance and water infiltration rates. Soil chemical analyses were performed to investigate the possible impact on potassium, phosphorus, nitrate, total nitrogen, pH, organic carbon and organic matter levels in the soil. The impact on some microbial populations was also examined.

The harvester felling the timber during thinning was found to have little impact on soil compaction in comparison to the forwarders which all cause soil compaction to some extent during timber extraction.

On mineral soils it was found that the forwarder with the bigger load capacity, requiring fewer loaded passes over the extraction rack caused less soil compaction and disturbance. On wet soils the use of traction aids such as band tracks appears to reduce the soil damage and improve machine mobility. However when used unnecessarily during dry conditions, the band tracks will themselves cause significant soil compaction.

The use of brash mats on the extraction racks from felled tree branches are important to reduce soil compaction and ground disturbance. All the parameters measured indicate lower values for compaction on the extraction racks with brash mats. Brash protects the root mat layer from the direct compactive forces of the passing machinery and thus reduces potential tree root damage. On wet and slippery soils, brash acts as a good traction aid for the machinery.

Soil nutrients do not appear to be directly affected by increased soil compaction. Root damage, reduced water infiltration and soil rutting caused by machinery will affect the uptake of the nutrients by the growing trees.

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1.0 INTRODUCTION

The ideal of sustainable development is central to all aspects of modern forestry. Sustainability allows the continued growth and development in this industry, while still embracing and preserving the environment of the present for the future.

It was with this aim of sustainable development that Coillte Teoranta and the Institute of Technology Sligo began a joint research project. The objective was to determine the extent of impact of harvesting machinery on the forest soil, especially in young plantations, which can be compacted by machinery in the harvesting of the timber. Furthermore, the effects of soil compaction can last for 20-40 years before natural forces of weathering can alleviate the problem.

Soil compaction in forestry was not recognised as a significant problem until recently, unlike agriculture. According to Wästerlund (1989) it appears that the problem in forestry was first recognised in the U.S.A. and in a review article by Lull (1959).

Mechanisation of some forest operations has greatly intensified over the last decade, and forest managers are currently expressing concern about the compaction of forest soil and its consequences. The machinery used in the thinning and harvesting of timber is significantly larger and heavier - especially when laden - than most agricultural machinery. This can lead to significant soil disturbance and compaction, often resulting in deep ruts. This is often compounded by use of machinery on unsuitable or difficult sites that are poorly drained, or in waterlogged conditions during wet weather, often all year round.

Most (70-80%) of the tree root system is located within the upper 10cm of the forest floor. This means that when a heavy rut formation occurs a substantial part of the tree's water and nutrition absorbing organs may be cut off according to Wästerlund (1988). In his study of growth after mechanical cleaning, a 25% growth reduction was observed for the young trees standing nearest to the wheel rut during the following first two years. In the wheel ruts only a little root damage could be detected but the machine, having an average ground pressure of up to 90kPa, caused compaction of the soil. Wästerlund suggests that soil compaction may represent more severe and longer lasting damage than root wounds.

The majority of thinnings in Ireland are carried out using the shortwood system. Because the trees in forests were planted in regular rows 2m apart, the thinning is a systematic operation. Where thinning is mechanised, i.e., in 80% of cases, every seventh line is removed ahead of the machine, while selection takes place from three lines of trees on each side of this rack. All the brash (lop and top) from these seven lines is concentrated in the machines travel path. This is the extraction rack for the forwarder to extract the felled timber to the roadside.

Mechanical harvesters in early thinnings are predominately eight wheel machines with a few six wheel as well as a few excavator based thinning harvesters. All are less than 2.5m wide.

The remaining 20% is felled motor manually and is extracted by forwarder except on very steep or uneven terrain or other more environmentally sensitive sites. In such cases cable systems, horses or tractors with winches are used and full poles are extracted in some cases. In a limited number of cases, whole tree cable extraction is carried out. Payment is based on productivity for both mechanised and motor manual harvesting systems.

The project will look at different forwarders to gather information on which is most suitable for mineral soil conditions. The harvesting machine that fells and de-limbs the trees has being shown to have little effect on soil compaction measurements. It is the timber-laden forwarders that extract the timber out of the forestry caused the increase in soil compaction in trials on this project. The forwarders make repeated passes out of the forestry carrying loads of 4-10 tonnes, depending on the machine size. Most of the machine have hydrostatic transmissions which drive all the wheels and which make is possible to work on such different terrain. On wet or steep sites, band tracks are put on over the tyres to increase traction and spread the weight over a greater surface area to avoid sinking.

The Ponsse forwarder is a 9.6 tonne unladen weight machine with a 10 tonne load capacity, while the smaller Norcar 480 is 6.9 tonnes unladen, with a 5 tonne load capacity. Both machines are being tested for soil compaction with and without band tracks fitted. A Norcar 490 will also be used with an unladen weight of 7.5 tonnes and load capacity of 4 tonnes.

Cut branches (brash) are used on the extraction routes to improve machine traction and avoid problems crossing drains for the forwarders. The degree of protection afforded by the use of 'brash mats' on the soil in thinning racks under the fowarders is also being assessed.

Research suggests that brash can significantly reduce soil disturbance and improves machine mobility but no measure has being made of its influence on alleviate the extent of soil compaction

The effects of the soil compaction on the soil's physical, chemical and biological parameters is also under investigation.

2.0 AIMS & OBJECTIVES

The aim of this project is to investigate the impact on forest mineral soil from the machinery used in the timber thinning and extraction process. Soil disturbance and compaction, which are of concern in the thinning process, are dependant not only on the soil characteristics, but also on the machine design characteristics and associated work practices. This project attempts to assess the impacts of the different forwarder design characteristics and work practices used in thinning on the mineral soils with the following objectives:-

1. To investigate which design in fowarders causes the least soil compaction and soil damage during extraction operations in forest thinnings. Two different sized forwarders which represent the range of forwarders design options available for the thinning process are to be compared .

2. To compare the use of band-tracks with that of balloon tyres on the forwarder bogies in terms of soil compaction during the extraction of thinnings.

3. To investigate the role of 'Brash mats' (delimbed branches) on the soil - machine relationship during the thinning operations, especially in respect of soil protection.

4. To measure of soil compaction using the following parameters;
   Bulk density
   Cone Penetrometer
   Shear Vane Tester
   Infiltration Tests.

5. To assess the applicability and suitability of these parameters to monitor and measure soil disturbance and compaction in the forest soil.

6. To investigate the effects of soil compaction on soil nutrients and to assess the nutrient status of the mineral soil in response to the thinning process in the forest.

3.0 LITERATURE REVIEW

3.1 The Thinning Process

Historically, the main problem with the thinning process has been the high costs, due to a lesser degree of mechanisation and poorer productivity compared to clearfelling. Competitive mechanised systems were not developed for carrying out first commercial thinnings. Siren (1987) suggests that the machinery used was mainly smaller versions of the machinery used in clearfelling operations, for example, 70% of the total volume is hauled using small to medium sized forwarders with net weight of 10 tonnes, with cranes reaching 8-10m. Light processors , which can be mounted on farm tractors and light crawlers, have become widespread and are quite suitable in thinnings. However, as the degree of mechanisation increases, the state of thinning stands has become a cause for concern. Machine induced increment losses have occurred from stem and root damage, soil damage and soil compaction, and from productive soil being taken up by strip roads and even the removal of nutrients from the site.

The most serious consequence of current thinning systems according to Shepherd (1987) is seen to be the potential for soil damage, as this can have adverse effects on long term site productivity. This has resulted in some dramatic changes being made to establishment practices in recent years.

3.1.1 Negative Impacts associated with Thinning:

One of the main objectives of thinning is to create conditions for a future increase in the value of the stand according to Froding (1987). According to Wästerlund (1988) the Swedish concept of thinning is that of a tending operation to space the trees in a stand and to take care of and utilise the harvested timber.

This objective is rarely achieved fully, since the activities of thinning have associated negative side effects, such as:

- Damage to roots and stems which will decrease the increment and lessen the quality of the wood.
- Damage to the ground from wheel tracks and ground compression which will decrease the increment.
- Strip roads (extraction racks) that will cause a poorer selection of timber.
- A temporary increase in the risk of damages from wind, snow and insects (Froding, A. 1987).

In Ireland, forests have been planted in straight lines, two metres apart with trees at two metres intervals in the lines. At first thinning, one complete row is removed together with the removal of selected trees from the three rows on either side. This means that forwarder extraction racks are every seventh row. These extraction racks lead either to a main extraction rack or directly to the road. The most common extraction distance for forwarders is about 300m. First thinnings are carried out from 18 to 25 years of age at which stage the average tree size removed is about $0.07m^3$. This removes about 33% of stems and from 35 to $50m^3$/ha. Thinning methods are systematic, planned to suit machine extraction. Thinning guidelines are set out where thinnings are performed to marginal intensities, often removing 70% of the yield class of the crop according to Lyons (1994).

In practice, 16% of the stand is taken up by strip roads plus connecting roads, with 4 metre wide strip roads every 30 metres. These extraction racks/strip roads cause timber losses in a number of ways suggests Siren (1987).

1. To open strip roads, it is necessary to remove trees that would normally remain part of the standing crop and would otherwise not be selected for thinning.

2. Despite undamaged trees growing along the roads increasing timber yields, this marginal effect never fully compensates for the loss of ground of the strip road.

3. Partial and whole tree methods remove the entire biomass from the site, thus no branching and foliage are left to fertilise the soil.

3.1.2 Extraction Racks (Strip roads)

An extraction rack as stated above, in a newly thinned stand leaves an opening that may be regarded as an unproductive area. The production loss is blamed solely on the absence of trees in the opening which means that the soil is not utilised according to Wästerlund (1989).

However, Isomäki (1986) studied the growth of edge trees 10 years after corridor cutting a pass for electricity lines. He concluded that the extra growth of edge trees, for example, on a corridor 4m wide, would equal the growth of an area 2.3m wide (leaving 1.7m unproductive). On average the edge trees grew about 40% more in volume than trees further in. This demonstrates the benefit of the thinning principle in a forest stands.

A similar basal area increment of edge trees was measured by Eriksson (1987). Thinned plots had lower volume production (7-16%) than in the case of unthinned control, but the difference between 3.5 and 5m strip road width appear to be small. The results of the studies of Niemistö (1987) and Pullala (1988) indicate that a 2-3m wide opening would cause almost no growth reduction but 4-5m (a 17% treeless area) would cause about 6% growth loss. The data concerns 30-70 year old stands and in general it seems as if Norway spruce responds better than Scots pine to the opening. .

The removal of trees to make room for machines on the extraction rack will reduce the number of trees utilising the ground. The remaining edge trees can explore that part of the ground and grow better.

If the extraction rack were only an undamaged opening in the stand, then it would perhaps cause 5-7% loss in the wood production. If soil damage due to deep rut formation occurs, the extra growth loss of the edge trees could amount to 9%. According to these figures a poor extraction rack may cause roughly a 20% loss in wood production, whereas the hypothetical smooth 2.3m wide machine would not even cause the production loss entailed by the extraction rack itself as proposed by Wästerlund (1989).

More data is needed to make satisfactory predictions of edge tree growth and the effect of openings on the total stand volume production. However all of the data referred to shows the extra growth of undamaged trees close to an extraction rack can be regarded as a yield increase due to thinning as presented by Wästerlund (1989).

3.1.3 Thinning and the Soil - Machine Relationship:

Logging and transport operations in thinning stands take place among growing trees on ground that also serves also as a growth substrate for trees according to Wästerlund (1989). Higher product density per linear extraction rack length will increase machinery passes over the same extraction routes. Machine induced stem and root wounds can cause rot infection and reduce wood quality and growth.

The harvester can create brash mats from cut trees branches on the extraction racks that will support the harvesting and extraction equipment traversing the soil. Any rutting that penetrates through the brash mats to the underlying raw humus layer can be expected to damage the shallow rooted rack side conifers. This is particularly important for excavator harvestors where the sharp edged tracks will easily sever tree roots.

Forestry Commission Report (27/90) advises that time of year and weather conditions will affect the ability of the ground to withstand machine induced stresses. Sloping and rough terrain will increase the risk of ground damage. The greater driving power requirements of sloping and rough terrain require a higher resistance to shearing in the soil structure to avoid risk damage. Excessive power application, especially used with low ground pressures, will cause damage through wheel spin. The level and type of stand damage is highly dependent on the machine selected to harvest the site. Rack based grapple thinning harvesters with long crane reaches can produce denser rack brash mats than short reach and crop mobile machines.

In situations of soil compaction and rut formation caused by the thinning machinery, root and soil damage occurs making the extraction rack opening unproductive. There will be no extra edge tree growth and this growth loss as well as the empty part due to the road have to be considered as damage.

The reduction in growth depends on how much of the tree root system is affected. The closer the rut formation is to the tree and the deeper it is, the more the tree should be affected by the damage. The total growth effect will also depend on the tree species and the site characteristics.

On an average or poor than average Scandinavian site, the Norway spruce trees standing near a strip road with deep rut formation may lose up to 30% growth during a five year period after damage has occurred. A 10cm deep rut formation may cut off or damage many of the feeding tree roots. Even a 6cm rut may do harm according to Wästerlund (1989).

Research suggests that on poor and moist sites about 70% of all roots in thinnings are found in the humus layer which is generally 3 to 10cm thick.. Continuous extraction route rutting is common in many areas, especially in wetter seasons. Increased windblow sensitivity and reduced growth of neighbouring trees may also result from this form of machine induced soil damage (Forestry Commission report 27/90).

3.2 Soil Compaction:

Greacon & Sands (1980) submit that forest soils can be compacted in numerous ways ranging from grazing animals to the roots of the trees themselves, but more noticeably by vehicles used for a range of mechanised forest operations. Tree roots persist and apply mechanical forces for long periods of time compared to those with annual agricultural crops. Compaction is the process of increasing the density of a soil by packing the particles closer together with a reduction in the volume of air. There is no significant change in the volume of water in the soil according to Craig, Greacon & Sands, 1980 and Baver et al (1970). An agricultural definition of soil compaction from an unknown author is; "Soils or soil layers are considered to be compacted when total porosity, especially air filled porosity are so low as to restrict aeration, and its pores so small as to restrict root penetration and drainage". This has serious consequences in respect of crop yields.

3.2.1 Effects of Compaction on Soil:

Forest productivity can be decreased when machinery operations cause soil pudding, displace surface soil, create ruts and compact soil. Of these problems, soil compaction may be the most damaging because of the extent of the area affected and the longevity of the effect according to Jusoff (1991). Soil compaction can also be the least apparent form of damage.

When soil is compacted, soil strength is increased and total porosity is reduced at the expense of the large voids. Soil drainage and infiltration rates will also be affected by the reduction in large (macro-)pore spaces. Consequently surface runoff of water may increase and tree growth may be reduced because of a reduced water supply, restricted root space and poor aeration as suggested by Greacen & Sands, (1980); and McNabb (1983).

One of the main effects is the reduction of total porosity or pore size distribution. Because the micropores are relatively less affected than macropores by soil compaction, the proportion of micropores is increased, meaning that the soil behaves as if it were of finer texture as suggested by Greacen and Sands (1980). Patric and Reinhart (1971) propose that without amelioration techniques porosity may take a decade or more to return naturally to its original 'uncompacted' state.

When a soil is compacted aeration is reduced, normally due to the reduction in pore space. Soil compaction always reduces air filled porosity (non-capillary pore space) although not always water filled porosity according to Froehlich and McNabb (1983). Soil aeration is necessary for the development and functioning of the plants root system. It is also necessary for aerobic microbial action that takes place in the soil.

Reduction in soil aeration due to compaction can cause reduced root growth and microbial activity. This can lead to reduced site productivity in the compacted area.

Soil strength is defined by Beekman (1987) as "the resistance of a soil structure to the impact of forces which relates the forces on the soil to the reaction of the soil structure". Greacen and Sands (1980) define soil strength as the resistance to penetration, so that compaction can have important consequences for the root growth of the trees.

Compaction increases soil strength, which depends on a number of factors in the soil;

- Cohesive forces.
- Density of the soil.
- Frictional strength.
- Soil structure.

Although the cohesive forces and the soil structure tend to breakdown when a soil is disturbed significantly, the overall soil strength increases. This is mainly due to the increase bulk density.

The overall consequences of compaction on soil structure have been comprehensively summarised by Chi Yung Jim (1993) as;

- Breakdown of aggregates due to plastic or brittle deformation and the weakening of aggregate stability.
- Coalescence of original aggregates and their fragments, with an increase in size of some fuse aggregates.
- Collapse of some interpedal and intrapedal pores.
- Decrease in total porosity
- Loss of pore continuity necessary for the conductance of air and water.
- Alteration in the orientation of elongated pores in the form of thin fissures parallel to the soil surface associated with platey structure, and the resulting decrease in pores in the vertical direction.
- Decrease in air capacity porosity.
- Increase in available water porosity with light compaction but decrease with extreme compaction.
- Increase in bulk density.
- Increase in shear strength.
- Decrease in infiltration capacity.
- Water perched on soil surface, poor drainage and water logging.
- Decrease in saturated and unsaturated hydraulic conductivity, but increase in unsaturated hydraulic conductivity with increase in available water due to light compaction.
- Increase in thermal conductivity and heat absorption.

3.3 Effects of Soil Compaction on Root and Tree Growth:

Changes in soil strength and aeration appear to be the main results of compaction that affect root growth according to Froehlich and McNabb (1983).

Although volumetric water content and field capacity are increased, air content, water infiltration rate and saturated hydraulic conductivity are decreased, with the consequential adverse effects of restricted root growth and increased surface runoff described by Greacon & Sands (1980). Root elongation is reduced as soil strength is increased and is reported for Douglas-fir (Hielman, 1981), for Loblolly pine (Foil & Ralston, 1967), for Norway spruce and Scots pine (Wästerlund, 1985).

These findings for forest trees are in general agreement with numerous studies on agricultural and horticultural corps showing reductions in root growth and productivity when compaction leads to increased soil bulk density. Ample evidence exists, therefore, to indicate a decrease in site productivity with progressive compaction of the soil.

Field and laboratory experiments have shown that although germination of conifer seedlings is generally not inhibited by soil compaction, seedling height, weight and root length all decline with increases in soil bulk density, regardless of soil texture (Sands & Bowen 1978, Froehlich, 1979). Increased soil strength impedes downward root penetration and reductions in aeration, moisture and organic matter interact in a complex manner to reduce seedling growth. The root will often compensate by growing laterally in the surface three inches of soil as described by Heilman (1981), greatly inhibiting growth and making trees susceptible to windthrow.

Greacen & Sands (1980) argue that the weight of the crop itself could be contributing to the compaction problem. On certain soil types quite large 'root balls' (the mass of roots and soil adhering to the base of the stem) were observed, in many instances a hemisphere of compacted soil were apparently formed as a consequence of the weight of the tree stem and the effects of sway. For fine roots of crops and forage plants this action is considered meliorative for soil structure, since the roots soon decay and leave vacant channels which improve porosity and increase permeability.

The growth of soil compaction and root damages have been studied in three development stages of a forest stand by Wästerlund in 1987. He found that;

1. Five years after thinning in a 65 year old Norway spruce stand, trees standing near 20cm deep wheel ruts had on average 46% lower growth rate than trees standing in the middle between two strip roads.
2. The growth of young trees (7-15 years) was followed in three stands 2-3 years after mechanical cleaning. 5-8% of the seedlings were damaged due to the wheels and undamaged spruce seedlings standing near the wheel ruts had 25% annual growth reduction whereas the lodgepole pines showed no growth reduction.
3. Experimental soil compaction on a clear-cut area was unsuccessful since the soil was too wet. Intact humus layer proved to be valuable in such cases. A man walking on the plots increased the soil bulk density by 0.05g/cm. Accordingly, the growth of the planted seedling was not affected by the compaction treatment but loosening of the soil by hand increased seedling growth and resulted in deeper root systems.

A literature survey by Wästerlund (1993)of growth damages gave new ideas on the subject. Norway spruce trees appear to suffer much more than Scots pine trees, and trees on normal to poor sites are much more impeded than trees on good sites. The reasons are most likely that pine trees in general have a deeper root system than spruce trees and a low nutrient level in the soil gives a slower recovery.

Six groups of physical properties have been chosen as yardsticks of compaction based on empirical studies of urban soils. They provide both direct and indirect diagnostic clues to the degree of compaction and its effects on tree establishment and survival. Exceeding these thresholds could become limiting to tree growth according to Chi Yung Jim (1993).

- Bulk density of air-dried undisturbed samples can be assessed with a good degree of precision and reproducibility. It is therefore a reliable and commonly-adopted indicator of soil compaction. The critical threshold should take into account the texture factor. For sandy soils, a higher limit of 1.75Mg/m3 should be used, whereas for clayey soil 1.55Mg/m3 should suffice. Literature suggests that a bulk density exceeding 1.6Mg/m3 can rarely result in successful seeding establishment. 1.4Mg/m3 is restrictive for root growth, but as the amount of organic matter species concerned compound the picture, 1.6Mg/m3 is proposed as the value above which root growth could be hampered for most trees .
- Soil penetration resistance evaluated with a cone penetrometer, is greatly influenced by several extraneous factors. as texture and moisture content at the time of measurement affect shear-strength properties, it is a relatively unreliable indicator of compaction. assessment should be carried out at field capacity of

moisture content to minimise this important source of variability. Whereas 3.0MPa is generally regarded as the upper limit for root growth, 2.5MPa is generally high enough to impose constraints.

- Total porosity falling below 40% restricts aeration and root growth, by reducing air capacity and available water porosity.
- Aeration levels falling below 10% v/v is considered to be inadequate for root respiration and other needs of the aerobic soil organisms according to Henderson & Patrick (1982).
- Infiltration capacity measured with cylinder infiltrometer shows that rates of <5cm/hr indicates quite severe compaction and that rates of >10cm/hr is the preferred level after Chi Yung, (1993).

3.4 Mechanics of & Factors Influencing Soil Vulnerability to Compaction:

The relative vulnerability of soils to compaction can be influenced by a number of factors, including soil type, texture, soil moisture content, and organic matter content according to Felt (1986).

3.4.1 Texture:

Soil texture is defined by Brady (1974) as a physical property concerned with the proportions of various sized mineral particles in a given soil. Medium-textured soils (loams and silt loams) appear to compact to greater densities than predominantly fine or course-textured soils according to Swanston and Dyrness (1973) and Froehlich (1976).

When soil is compacted the soil macroporosity is reduced according to Greacen & Sands (1980). Course textured soils protect the macropores due to larger particles sizes. In fine textured soils the degree of compaction occurring depends on the relationship between water content and specific surface area of soil particles.

Pritchett and Fisher (1987) found that texture itself has little effect on tree growth as long as moisture, nutrients and aeration are adequate. However, experiments have shown that soil texture can be associated with varying root growth patterns. For example the roots of fruit trees penetrated to a depth of thirty feet in course textured soil, but only three feet in clay soils as reported by Garner & Radford (1980). Therefore, possibly a more important effect of compaction in heavy textured soils such as surface water gleys, is the reduction of tree stability due to reduced root growth.

3.4.2 Soil Moisture Content:

Regardless of whether a soil is classified as moisture sensitive or insensitive, substantial compaction from vehicles can occur at any moisture content. Soil moisture should not be the sole criterion determining where and when ground based operations should proceed advise Froehlich & McNabb (1984).

However, water plays several important roles in the compaction process. At low suctions and high water contents, soils have low resistance to deformation and are prone to compaction . Numerous studies have shown that drainage of wet soils reduced compaction from traffic according to Greacen & Sands (1980). Films of water of increasing thickness around soil particles decrease the cohesion between adjacent particles and provide lubrication, thus permitting the particles to slide over each other with increasing facility to form a closer packing under pressure.

For a given compactive force, the density of a soil is found to increase progressively with the water content of the soil up to a limit, and to decrease thereafter. If comparable samples are tested with different forces of compaction, the maximum density is found to increase and the optimum water content for compaction to decrease with increasing force suggests Felt (1986).

Soil moisture resulting in the greatest compaction is about midway between field capacity and the permanent wilting point as found by Swanston and Dyrness (1973).

3.4.3 Organic Matter:

The susceptibility of a soil compaction may also largely depend on the organic matter content in the soil. There are frequent examples found by Larson & Allmaras (1970) where the addition of organic matter to soil has improved structure and reduced compaction as the soil will be more difficult to compact. Increased organic matter in the sandy soils under pine forests in South Australia was associated with reduced bulk density, reduced compaction under a given load and increased water retention.

Organic matter also influences compaction through improving soil structure and texture in soil according to Sands et al (1979). In areas where the surface organic matter (leaf litter) has not been removed prior to skidding operations, soil strength within the wheel rut was 20% less after the operation, compared to tracks where litter had been removed. Organic matter has a high elasticity under compression forces and reduced soil compactability by increasing the resistance to deformation and/or increasing the re-bound effects is advised by Wronski & Murphy (1994).

3.4.4 Soil Type:

Forestry Commission Report (35/91) advises that the soil types at risk are;

1. Surface water gleys, ploughed or turf-mounded with various drainage patterns usually combined with slopes and flatter areas. Where brash is insufficient and water is present silt will be rapidly generated due to poor load bearing capacity of the soil.
2. Peat less than 1m deep over clays, gravel's etc. Usually poorly drained with inferior crops leading to brash shortages.
3. Deeper peat's, usually with a good drainage network that may have become blocked, resulting in extremely difficult harvesting conditions.
4. Heavy clays with few drains, which readily break down during long periods of rain.
5. Soft mineral soil over form rocky substrate, typical fertile valley-sides or steeper slopes.

Although many of these site types reflect upland forest conditions, there are areas of lowland forest which will be liable to similar conditions unless preventative measures are taken.

3.5 Evaluation of Soil Trafficability:

Yong et al (1984) examined the question of trafficability. An exact definition and quantification of soil trafficability is quite difficult since it is specific to the particular soil and the particular vehicle. All existing techniques for evaluating trafficability are based on the ground strength for supporting the vehicle, but the terrain may still be untrafficable due to natural or man-made obstacles or extreme terrain roughness. Thus the definition and quantification of trafficability should be restricted to special conditions such as flat ground surfaces bare of obstacles. Also trafficability can only be assessed fully and comprehensively by consideration of the forces at the track or wheel and the soil response under those forces. This requires such an amount of time, computers, measurements of the vehicle and the substrate that it is only economical for the evaluation of a specific vehicle with respect to certain soil types.

This does not include the terrain variability which can be severe over a few meters not to mention kilometres. Recognising these requirements and the limitations of analytical techniques, a successful trafficability prediction procedure requires a simple portable tool and a technique where decision-makers can rapidly ascertain whether or not the vehicles under consideration can successfully negotiate the highly variable terrain they would encounter. To meet this need several field measuring parameters and devices have been devised to aid the predictability of substrate trafficability. It is widely accepted that these tool may not provide exact or even the rational predictability that can be achieved through painstaking field correlation's and measurements. None the less, they do enable relatively accurate comparsion techniques for different substrates and factors affecting the different substrates.

3.5.1 Bulk Density:

Soil bulk density is most often used as an index of soil trafficability and compaction. It is defined as the mass of dry soil per unit volume of solid, liquid and gaseous phase by Froehlich & McNabb (1984). Most productive soils are characterised by relatively low bulk densities, ranging from about 0.5 g/cm^3 to 0.9 g/cm^3, and as a result have high macro porosity, high infiltration rates and low soil strength according to Froehlich (1976). Froehlich observed a 35% increase in bulk density on tractor trails after six trips with a tractor under wet conditions compared with a 18% increase under dry conditions.

He concluded that while physical soil properties interrelate with soil moisture and soil texture in a complex manner, most of these forest soils are vulnerable to compaction from ground based harvesting and machine site preparation.

Consistent, reliable methods of assessing soil properties are a prerequisite for examining the effects of compaction in forest operations. While several methods are described in the literature for measuring bulk density, their application in forest conditions will have an associated experimental error. Steele and others (1993) compared soil bulk density and moisture content measurements obtained by using two nuclear gauge systems (Troxler Model 3411 and Campbell Pacific model MC-1) to those obtained form a Cornelison soil core sampler. The tests were conducted in controlled conditions with homogeneous soils. After calibration for the different soil types, the nuclear gauges still underestimated bulk density by 3-6 %, a statistically significant difference. This study emphasised the need for careful calibration of nuclear gauges to specific soil conditions to minimise error.

Core samples may also be subject to experimental error in soils with coarse fractions. Standard 5cm ring samplers are affected by rocks. Larger diameter samplers require high driving and extraction forces in coarse soils and are generally vehicle mounted. Tuttle et al designed a portable tool for obtaining large diameter (7.62-cm) cores to minimise error in sampling clayey or rocky soil. The sampler extracts 45cm long cores in a single sample. Bulk density samples taken with the new sampler were compared to matched samples collected using the incremental method with 7.62 by 7.62cm rings. For most soil and depth conditions, there was no statistically significant difference between the two techniques.

3.5.2 Shear Strength:

Bulk density may be used as an index of relative compaction, but it does not allow an assessment of soil strength, and it is soil strength which determines resistance to compaction. Description of the relationship between strength and compaction depends largely on soil mechanics theory according to Jusoff (1991).

A shear vane tester estimates soil strength and mechanical characteristics. Shear strength is measured using an apparatus with winglets that are embedded about 10cm into the mineral soil. The torque ($N\text{-}M/m^2$) required to deform the soil was defined as the soil's "torque index". This is not the true "shear resistance" as defined by Bowles (1986), but some limitations of the Bowles' method are accepted to allow rapid and inexpensive measurements. The applied torque provides only an approximation of the shear resistance.

3.5.3 Resistance to Penetration:

The resistance of a soil to the penetration of a probing instrument is an integrated index of soil compaction, moisture content, texture and type of clay mineral. In other words, it is an index of soil strength under the conditions of the measurement. The amount of penetration per unit force applied to a given soil will vary with the shape and kind of instrument used. As the penetrometer enters the soil, it encounter resistance to compression, friction between soil and metal, and the shear strength of the soil, which involves both internal friction and cohesion.

Although there are many types of penetrometer, they fall into two categories: the impact and the electronic recording type. The impact type measures the resistance to penetration by determining the energy needed to drive the cone one inch into the soil (number of blows) according to Parker & Jenny (1945).

With the electronic recording type there is a pronounced effect of moisture content on penetrometer readings. It is a rapid increase in resistance with decreasing moisture, indicating that soil strength becomes greater as the particles are brought closer together during the drying process. While soil moisture appears to be the dominant factor influencing the penetrometer readings, there is no simple relationship between reading and the water content.

Henin (1937) said that the pattern of resistance to penetration is not affected by the type of instrument. In loose sandy soil, the resistance to penetration increased proportionally with the depth. In a silt loam soil with 16 percent clay that has been compacted in the moist state, the resistance increased rapidly with depth for several centimetres and then remains constant.

The penetrometer can be a useful tool to obtain information on soil strength and soil compaction if one keeps in mind the composite nature of the effects it measures

Davidson (1965) has given description of several types of penetrometer that have proven satisfactory in soil studies.

According to Sands & Greacon (1980), soil being compacted by the tyre of a vehicle applying a pressure of 250kPa will eventually reach a state of compaction at equilibrium which will have a penetrometer resistance of 2500kPa; this value of often regarded as being critical for the growth of plant roots.

3.5.4 Water Infiltration Rates:

Chi Yung (1993) lists infiltration as one of the yardsticks for soil compaction in urban subtropical soils. The saturated flow of water through a compacted soil is substantially less, because large pore space is reduced. Because micropore space in soil may not be changed by compaction, unsaturated hydraulic conductivity is less effected and may sometimes increase as found by Sands et al (1979) and Greacen & Sands (1980).

Froehlich (1978) states that infiltration is reduced by soil compaction caused by forest traffic. He observed that although it took six trips with the tractor over a moist soil to reach maximum compaction, nearly all the loss in infiltration rates occurred with the first two trips. It is also reported that a 50% loss in non-capillary pore space brought about a 3.5 fold reduction in infiltration rates.

3.6 Soil - Machine Interactions in Forestry:

A team of two machines working together in the forest is a typical sight nowadays according to Seppo (1994), when timber is been thinned or harvested using the cut-to-length harvestor system and a fowarder for extraction to the roadside. Wästerlund (1988) states that soil and tree damages are quite often seen along temporary roads (extraction racks) in the forest after forestry machines, so that either individually or collectively, soil compaction, rut and stem damages will give a reduced growth and poorer wood quality.

Soil and tree damage is usually the result of several simultaneously acting factors.

Siren (1987) research results have shown that the factors involved are the time of the year when logging is carried out, the density of the remaining stand, the terrain, strip road width and density, the logging method, and the experience of planners and logging operators .

To appreciate the difficulties encountered in Ireland at present requires some knowledge of the cultivation techniques carried out at planting stages in the 1960's & 1970's . On soft ground areas and peatlands, the most popular method of cultivation was deep ploughing. This involved pulling a large single mould board or double mould board plough by means of a powerful tracked machine. This aided establishment of the crop but the resulting uneven terrain poses severe problems at harvesting stages in terms of trafficability and mobility according to Lyons (1994).

3.6.1 Trafficability Vs Mobility:

It is necessary at this stage to differentiate between two terms that are often used interchangeably although they do represent two distinct phenomena, i.e. mobility and trafficability. Yong et al (1984) give the following;

Trafficability can be defined as " the capability of the terrain under consideration to provide the mobility of a particular set of vehicles" and refers to the ability of a piece of terrain to support vehicles.

Mobility refers to the "ability of a vehicle to establish motion between two designated points over a prescribed course" and refers to the relative ease or difficulty of the vehicle to establish traverse motion over the prescribed terrain. Thus mobility is a term which applies to the vehicle under consideration.

However, an area of terrain may be trafficable for a particular type of vehicle, but due to poorer mobility, not for another,- or indeed the same vehicle with, for example, a larger load.

Trafficability prediction is based on a knowledge of combinations of factors related to vehicles and those related to both terrain cover and substrate material. Factors related to vehicles are fixed and easily determined, depending on the mechanical characteristics such as tyres, tracks, suspension, engine power, vehicle weight, load and number of driving wheels. The terrain cover and substrate factors are mainly those which are concerned with the strength and deformability of the cover and the bearing material, i.e. vegetation , leaf litter and the soil or road according to Yong et al (1984).

Soil compaction constitutes one of the main applications of soil vehicle traction mechanics. Yong et al (1984) states that efficient and proper compaction are desirable features in construction engineering and soil engineering. In the translating of motion of off-road vehicles on initially unprepared ground, compaction of the soil occurs under the front set of wheels as well as the rear set, but since the rear set of wheels will meet the soil partly compacted by the front, the motion resistance to the rear set of wheels will be generally lesser. Therefore, soil compaction may increase traction and therefore the efficiency of vehicles moving on roads and tracks in the forest according to Greacen & Sands (1980).

Soil compaction is often visually recognisable due to rut formation on vehicle tracks. Laboratory experiments by Wästerlund (1987) have shown that till soil may be considerably compacted even at quite low pressures. Soil compaction by itself may be a more severe growth restriction than damaged roots, although to date no one has being able to quantify the effect of each type of damage separately. Or is it the interaction of these two factors combined which is the worst situation for tree growth?

3.6.2 Harvesters:

Modified excavator base units were the initial machine used for harvesting in forestry especially in clearfell sites and windblow areas, where their efficiently is at an optimum. However standard excavators fitted with harvesting heads are unsuitable for thinnings for the following reasons according to Lyons (1990);

- Driving in the forestry is not as smooth as rubber tyre base units.
- Less cab ergonomics to working in forestry.
- May not have ROP's (Roll Over Protection) or FOB's (Falling Object Protection).
- Low ground clearance.
- Link breakage's on tracks are common.
- Machine cannot move between sites on the tarred road, therefore always requiring transport even over relatively short distances.
- Machine crane may not rise high enough - is designed for digging.
- With main crane raised during thinning machine may rock considerably.
- A long track can break peat surface and displace brash while turning.
- Wide tracks while reducing ground pressure will cause root and stem damage.

Forestry Commission Reports (27/90) describe the purpose built grapple harvester as the type that has had, and is currently seeing the greatest development changes. Mounted at the end of the loader crane, this machine is designed to reach out to fell trees, bring them into a processing position, then delimb, cross-cut and stack with varying degrees of a assistance from the cab mounted computer console. Most thinning harvesters currently in use in the U.K. and Ireland are of this type. Delimbing is carried out by forcing the stem through a set of encircling knives, either by hydraulically powered feed rollers or by a reciprocating crane "delimber" mechanism alternatively gripping and releasing the stem. Length measurement is usually obtained by electronically recording the rotation of either a spiked measuring wheel or the feed rollers. Diameter sensing, where fitted, is by electronically recording the movement of the delimbing knives or a tree gripping mechanism. More expensive systems include computer control and recording of cutting work.

Forestry & British Timber (1992) outline some of the requirements of a suitable harvester designed for working in thinning in the U.K. and Ireland.

- Low ground pressure and acceptable of working on soft sites and slopes of up to 40 degrees.
- Good manoeuvrability to avoid crop and ground damage.
- Ability to cut, debranch and accurately cross-cut Sitka spruce in first and seconds thinnings.
- Removal of only a single row of trees to gain access into the crop and select trees from in between rows.
- Removed, therefore about 2.0 metres wide.
- Adequate power to cope with the hydraulic requirements of the harvesting head.
- Good ground clearance especially for ploughed sites.
- Good operator ergonomics and cab safety.
- Good work visibility and lighting for night work.
- Cost effective price-tag and reliability, with good efficient backup service for parts and repairs.

3.6.3 Forwarders:

The fowarder is clearly more problematic than the harvester as far as the environment is concerned according to Seppo (1994). When the off-road operation of a fowarder is compared with that of a harvester, the use of the forwarder involves the following complicated issues:

- The fowarder needs a lot of space.
- It is longer and wider.
- When loaded, the ground pressures are sizeable.
- The driving speed is usually higher than that of a harvester.
- Productivity is heavily dependant on driving speed and the size of payload.

Thinning and clearfelling prescriptions using tractors are among the extraction procedures most likely to produce compaction advises Greacen & Sands (1980). Froehlich (1974) found that ground based logging machinery can cause compaction by a combination of tyre or tread pressure, kneading action, vibration, and scarification and pressure from a turn of logs being skidded. A study found that the feller-buncher, grapple skidder, loader/slasher system caused significantly more compaction and ground disturbance than the harvestor/fowarder system. The harvester/fowarder system only compacted and disturbed the soil at the 5cm depth unlike the skidder system according to Stokes et al(1994).

The risk of damage with forwarders of high footprint pressures is high since it is necessary to travel close to the trees in thinning operations. Presently most thinning machines have a rated footprint pressure of 50-70kPa. Width of forwarders currently used for thinnings are usually restricted to 2.2 - 2.8m wide, to permit sufficient space for mounting wide tyres stated Taatila (1994) and use in the narrow extraction racks.

Eight-wheeled forwarder machines are better suited to wet ground than six-wheelers unless the latter are fitted with very high flotation front tyres. Different permutations of tyre size and bandtracks can be used to contribute to low ground pressure. It may be necessary to reduce ground damage by reducing axle load, while incurring an output penalty according to Forestry Commission Report (35/91).

The stability of most centre articulated machines is reduced when they turn because the centres of gravity for the front and rear frames move sideways during turns. Stabilising cylinders are often installed to improve stability when machines are standing still loading or harvesting at the stump as found by Taatila (1994).

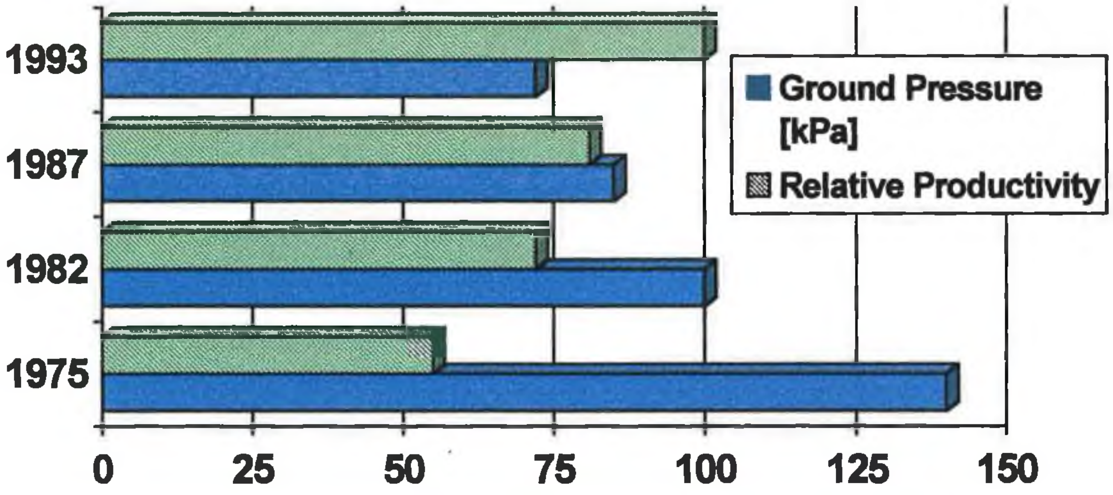
Eight wheeled, articulated machines have better stability then six wheeled fowarders because of the heavy bogies and smaller wheels.

The productivity of the fowarder can be upgraded only by increasing the driving speed and/or by enlarging the payload. Both these factors also increase the environmental risk incurred by the machine in terms of soil and tree damage. Nobody involved in the process is willing to compromise the productivity of fowarders; the landowner, buyer of timber, contractor, forestry company etc. are all reluctant to pay for the increased costs that would be the result of reduced productivity. A simple example; if current loads were cut in half, the damage inflicted on the ground by the machine would be reduced to a mere fraction of current levels. However, the costs of transportation would be almost doubled at the same time.

The machine must be reliable and structurally sound regardless of the design features states Lyons (1990). Bearing this in mind all these requirements - some of them somewhat contradictory - it seems that those who design machines are confronted by an impossible mission when they strive to find the right compromise between structural integrity, reliability, ground pressure properties and productivity.

Progress has been made in developing technical properties in recent years, a prime example of this being the progress of productivity and ground pressure in the light wheeled fowarder class, a trend which should continue unchanged in the near future according to Taatila (1994). This is illustrated by Taatila in the following graph which demonstrates how despite forwarder ground pressures falling, productivity has actually increased.

Fig 1: The Development of Productivity and Ground Pressure in Small Fowarders.



When driving straight forward on level ground with an eight wheeled 12.7 tonne forwarder the total torque in the ground contact is about 3kN on asphalt, 5kN on firm lawn and 11kN on firm forest ground according to Marklund (1986 & 1988). With more wheels or larger/wider tyres on the machine it is possible to reduce the ground pressure. The machines today have on average calculated ground pressure between 50 and 150kPa. Preferably it should be as low as 30-50kPa which can be hard to reach for a fully loaded forwarder. More driven wheels give also the advantage that the necessary torque per wheel can be reduced. On the forest land a four wheeled machine has to produce 2.75kN per wheel to move forward but an eight wheeled machine needs just about 1.4kN to progress as measured by Taatila (1994).

Ala-Ilomäki(1987) proposes that another inherent problem is load distribution. Most eight-wheel forwarders have about the same footprint pressure on the front wheels whether the machine is loaded or not according to Taatila (1994). Consequently, about the same ground damage and rutting occurs whether the machine is loaded or unloaded. Ala-Ilomäki (1987) has shown that rut formation increased as front axle mass increased and weight distribution between front and rear axles had a clear effect on rut formation. Therefore reduced loads on sensitive terrain would not improve the situation.

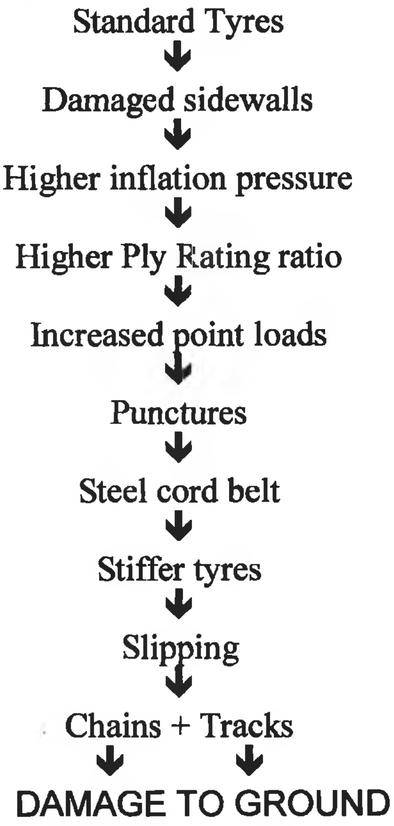
3.7 Tyre Choice and Forwarder Performance:

Victor (1994) describes the historical changes in tyre technology in forestry. In the early days it was simply a matter of using those tyres that were already available for tractors, trailers and contracting machinery. Manufacturers of forestry machines chose the PR ratio and the inflation pressure to suit the loads encountered in traditional farming or contracting applications.

However, conditions in forestry turned out to be much more difficult to cope with. The sidewalls of tyres were easily damaged as they bulged out during deflection and were punctured by stumps or rocks.

- The solution was to increase the inflation pressure to make the sidewalls stiffer. This in turn called for tyres with a higher PR ratio to cope with the increased inflation pressure.
- The increased pressure certainly reduced damage to the sidewalls, but on the other hand the tread was subjected to higher point loads, which often resulted in sharp stones of hard stumps penetrating the tread and puncturing the tyre.
- Tyres were then fitted with puncture protection under the tread, in the form of a steel cord belt or the like.
- Increasing inflation pressures and stiffer tyres had a negative effect on the mobility of forestry machines. The use of anti-skid devices such as chains and tracks therefore became necessary to improve mobility.
- However, anti-skid devices cause considerable damage to the land, particularly in summer. This is not felt to be a serious problem in final felling because the land has to be prepared afterwards in any case.

Fig. 2 Summary of technological advances and increasing ground damage: (after Victor (1994)



Fowarders where first introduced by Coillte in the mid 1980's, using Bruunett 578 fowarders. On soft sites soil damage occurred particularly in winter where machines had only 500mm wide tyre. Deep rutting caused root damage and led to crop instability and windthrow.

Band tracks were used on some of these machines while others used wider tyres but in many cases damage was still caused according to work by Lyons (1994). The need for a more 'forest friendly' Low Ground Pressure (LGP) machine was apparent.

The size of tyres has gradually increased, in particular the section width, which over the years has risen from 400mm to 850mm. Each time the width has been increased, concern has been expressed that the machines were becoming too wide and their mobility would be impaired, especially for thinning processes. But in practice the reverse has happened, i.e. mobility has increased, which in turn has improved the load-carrying capacity of these machines.

The effect of tyre width on rut formation has been investigated by the Forest Operations Institute, among others, who found that increased tyre width resulted in higher load carrying capacity for a given degree of rut formation, i.e. for a given load, the wider the tyres the less damage there was to the ground according to Victor (1994).

Studies have been conducted examining the relationships among tyre size, operability, and site disturbance associated with conventional rubber tyre skidder (tyres 127cm wide) and a high floatation tyre skidder (tyres 173cm wide). Soil bulk density values for both types of tyres were significantly higher as a result of trafficking. Where wide (173cm) and narrow (127cm) tyres were operating under identical conditions, results showed that wider tyres do decrease the degree of compaction after nine passes. As expected, rut depths increased with the number of passes, but more for the 127cm wide tyres than for the 173cm tyres according to Stokes et al(1994).

McDonald et al (1993) found that rut depth alone was not a good indicator of total soil displacement, especially on the wetter soil, where the additional confounding factor of berm formation made it difficult to determine actual negative displacement. The number of passes was the most significant factor influencing rut formation. The first pass on an upland soil caused about the half the total observed displacement in both depth and area. On a bottomland soil, disturbance increased uniformly with every pass.

Burt et al (1982) found that tyre width had little effect on either net traction or tractive efficiency of forwarder. Also that for a particular level of ballast, tyres should be operated at the minimum recommended inflation efficiency. Therefore, oversize tyres could offer an advantage by allowing operation within the recommended load range at low inflation pressure levels.

Koger et al (1982) found that there was little effect due to tyre width when operating on reasonably dry soils conditions, and at dynamic load values greater than 25kN, the effects of inflation pressure on both net traction and tractive efficiency were important.

Rummer & Ashmore (1985) also investigated the effects of tyre size, inflation pressure, dynamic load and dynamic load distribution on the motion resistance of a rubber-tyre skidder. The results showed that increasing the load increases motion resistance and that increasing tyre size, either in width or diameter, decreases motion resistance.

Inflation pressure had an effect through its relationship with rated load. Increasing inflation pressure raised the rated load of a tyre and decreasing the motion resistance according Stokes et al(1994).

Generally studies have shown that the increasing size of tyres also means that lower inflation pressures can be used for the same load; Lower inflation pressure implies softer tyres advises Victor (1994).

In summary, wider tyres and softer tyres;

- Spare the ground by less skidding, rut formation.
- Spare the tyres by better grip and tread wear.
- Spare the machine by less power required, less bumping, higher traction forces.
- Spare the driver by less bumping, therefore less tiring for operator.
- Reduce rolling resistance due to less rutting.
- Increase productivity by higher travel speeds with bigger loads.

3.7.1 Dual Tyres:

Dual tyres have rarely proved effective in forestry logging operations. Dual tyres have four sidewalls compared to two sidewalls on one wide tyre. This makes machines with dual tyres heavy and sluggish. Also debris frequently gets jammed between the tyres and cause tyre and rim problems. Dual tyres increase the stresses on the axles because the tyres are not as flexible as wide tyres of the same total width. When the outer tyre travels over a stump the axle is subjected to the full load at the very end of the axle according to observations of Mellgren (1987).

Koger et al (1984) commented that the biggest advantage of dual-tyres was the greatly improved machine mobility. On swampy sites, the dual-tyres caused much less rutting than the single-tyre machine. Dual-tyre skidders were able to skid loads through areas that single-tyre skidders could not traverse when empty.

3.7.2 Tyres with Chains:

Research by National Soil Dynamics Laboratory (NSDL) has shown there was a traction advantage associated with using chains on tyres under the right conditions, but little benefit is gained by using chains as traction aids in good ground conditions. Studies with a new tyre showed the benefits of good surface contact, while the worn tyre with chains showed reduced traction performance. Hence, the use of chains to compensate for worn tyres is of limited value.

3.7.3 Tracks and Band-tracks:

Efforts to solve soil damage and compaction problems with tracked vehicles have had only limited success, mainly because of prohibitive track and undercarriage maintenance costs as documented by Mellgren (1987).

The trend has been for forwarder machine size and weight to increase with each new model, which has meant particular problems for tracks in terms of

reconditioning and durability. Track shredding is also a problem when machines work parallel in the ploughed furrows . Track tensioner's have to be modified and annual reconditioning of all tracks is necessary as found by Lyons (1990).
Band-tracks, i.e. steel tracks around the rubber tyres on double bogie machines, are very efficient on thinnings despite high maintenance costs, which are intrinsic to tracked machines, while still having lower maintenance costs then tracked forwarders according to Mellgren (1987) and Lyons (1990).

Recent tests have shown, that following mechanical harvesting, where adequate branching (brash/slash) is available to travel on, small wheeled fowarders with band tracks can perform satisfactorily with little damage to the forest. These have better ground clearance and can avoid many of the difficulties associated with dedicated tracked machines in the wood suggest Lyons (1990).

There are four basic designs of track, each suited to different ground conditions as documented by Forestry Commission Report(35/91).

- **Standard tracks**: Made up of bars with wide gaps in between. Suited to dry and stony ground where flotation is not important, and also well suited to ice and snow. They do not pick up mud from the forest and so little debris is brought onto roads. Traction is improved on steep terrain. They are widely used in Scandinavia, but infrequently used in the British Isles.

- **Flotation tracks**: Made up of plates to reduce ground pressure and increase flotation. Raised edges of the plates give grip. Suitable for gleys and peaty gleys where some flotation is necessary. They also give good traction on steep ground and over stumps. The wide plates pick up debris in the wood, which is brought onto the road. This is the type of bandtrack most commonly used in the UK and Ireland.

- **Combination tracks**: Consisting of alternative flotation plates and standard bars. They give less flotation than flotation tracks but good traction and may be suitable where a machine covers very diverse ground conditions to save carrying with flotation tracks.

- **Super Flotation or Swamp Tracks**: These are built up from very broad plates with only a small gap between plates. The edges of the plates are flat. Traction is poor on slopes, stones and stumps. Maximum flotation and minimum ground damage is provided and they are suitable for very wet, soft peaty ground.

- **Moccasin tracks**: These tracks are made of urethane rubber. Claims to give good flotation whilst not damaging, ground, root systems or roads. They are very expensive and designing for use on deep peat. There is doubt about their durability, on stony ground.

In general, tracks reduce travel speed, increase machine wear and may prevent further wheeled access. Band tracks, especially aggressive types, should be only used as and when circumstances dictate, e.g. assistance on steep slopes or greasy pine brash sites, and should not be left on a machine solely because fitted on arrival. Use of two sets of bandtracks on eight-wheeled forwarders, although useful on deep peat with poor brash support, should not normally be necessary.

3.8 Brash Mat Use on Extraction Racks:

There is evidence that a litter layer of logging slash on a skid trail may act as a buffer and reduce the amount and depth of compaction according to Froehlich (1978). Wästerlund (1987) suggests that the placing of brash from coniferous trees in the wheel tracks can considerably reduce soil damage.

Using brash is the most common and often the only measure used to minimise ground damage. Carefully located and constructed brash roads formed during harvesting or processing are essential where durable routes are required.

However, other measures may be required to minimise water movement onto and down brash routes report the Forestry Commission (35/91). Harvesters placing brash in the drains causes problems when travelled on by forwarder. The forwarder compacts the brash, blocking the drain and drainage water flows down the extraction racks as noted by Lyons (1990). When slurry begins to form small ponds on lower lying sections of the route, it can be diverted with a log step and prevented form flowing directly into drains and watercourse by encircling the spillage zone with brash, forming a dam or bund. The brash will contain the slurry and allow some nominal filtration of soil particles. Brash may periodically be brought out on top of a load to raise the bund level or reinforce areas of weakness along the extraction rack. Problem areas readily identify themselves. Bunding is very cheap and effective and the machine operator can be responsible for prompt remedial action throughout. If the silt volume is such that containment becomes impossible, due to exceptionally wet weather and lack of alternative routes, harvesting may have to be curtailed. In extreme cases the use of an excavator to make a major silt trap may be necessary advise Forestry Commission Report (35/91).

Where local wet spots occur throughout the wood as a result of poor drainage since planting time, the poor stocking and /or lack of growth in the immediate area resulted in less brash, thus compounding the existing problem found Lyons (1990). Brash mats in subsequent thinning, especially from harvester machines with loader reaches less than 7.5m can be sparse. This may lead to terrain and root damage upon extraction according to Forestry Commission Report(35/91).
On larger thinnings sites, adequate brash mats can be an important consideration where longer and more repeated runs for forwarder extraction may result.
Lesser damages occurs in first thinning sections of the site. This was largely due to the fact that these areas were at the top of long racks and therefore subjected to less machine passes, or were on the edges of the test area where the racks were short. The increased amount of brash also helped.

3.9 Soil Compaction Effects on Soil Nutrients

In the forest ecosystem there is a continuous recycling of plant nutrients such as nitrogen, phosphorus, and potassium: the decomposition of fallen leaves and other decaying vegetation releases these nutrients to the soil from where they are absorbed through the tree roots and used for further growth. When a forest is clearfelled, this cycle is broken. Although nutrient uptake ceases until vegetation is re-established, decomposition continues, which means that nutrients accumulate in the soil according to Gosz & Dyck (1976).
Miller & Sirois (1986) note that soil compaction does not seem to affect the nutrient content of the soil to a significant extent but the microbial immobilisation might be slowed down due to poor aeration. Poor aeration and mechanical resistance seem to be the main results of soil compaction according to Wästerlund (1985).
In addition, the displacement of the organic layers can lead to nutritional problems, particularly nitrogen loss in the wheel tracks according to Miller (1987).
On dry sites, Froehlich (1976) found moderate compaction could have a favourable effect by increasing the water holding capacity of the soil, the indirect result of increased micro-pores.

Rut formation with breakage of the humus layer and mixing of soil and humus might favour the microbial turn over is suggested by Miller & Sirois (1986).
However, soil compaction drastically decreases the rain water infiltration rate. If the rut formation occurs on slopes, there is considerable risk of nutrient leakage together with soil erosion according to Wästerlund (1989).

This according to Miller (1987) is the most serious consequence of forestry practices on soil nutrients. Poorly designed drainage and road schemes can cause serious soil erosion and nutrient losses.

Re-distribution of surface soils caused localised reductions in available levels of organic matter, phosphorus, calcium, potassium and available water holding capacity according to Miller & Sirois (1986).

The study also found that the reduction in available phosphorus was found to significantly reduce the growth in height of loblolly pine seedlings. Calcium availability in sandy loam soil, was reduced by 85 and 90% on deeply disturbed and compacted soils. The resultant levels of calcium approach those producing severe deficiency symptoms in loblolly pine seedlings, and any further reduction in magnesium and potassium would result in growth reduction of the seedlings.

Other studies have found that water and nutrient stressed environments affected the root growth compared to the control seedlings. Nutrient stress affected shoot height and diameter development to a greater extent than water stress. Where water stress did affect growth it was not evident in the diameter growth according to Mattsson (1994).

Miller (1987) report on work that has drawn attention to the plastic nature of soils and the extent to which developments manifest early in a forest rotation, and are subsequently reversed so that the net long-term effect may be of little or no damage. For example, pH at 15cm depth in the soil declined from 4.5 to 4.2 over the first half of the rotation of coniferous trees, only to return to pH 4.5 by the time of final felling. Clearly comparisons made early, only midway through the rotation would be very misleading indications of long-term trends. Therefore, discussion on the likely effects of forest operations on soils has to involve reasonable deductions based upon knowledge of soil and plant processes comparing studies with soils beneath similar species and of similar age of trees.

3.10 Amelioration of Soil Compaction

Natural recovery of soils is very slow, taking decades, and often reaches only the upper soil horizons. Site preparation methods, therefore, must be employed to restore soils to their original conditions and productivity according to Hanns (1994). Every soil ecosystem has the properties of stability and elasticity. These properties consist of physical processes (swelling and shrinking; freezing and thawing) as well as of biological elements (earthworms - soil fauna; and plant roots - soil flora). They only work if soil is sensitive to the processes, if the climate offers the necessary temperature and moisture regimes, and if the processes occur frequently.

According to Teiwes (1988), swelling and shrinking only works in soils with a considerable clay content, and freezing and thawing is depending on frequency of events and the soil depths reached.
Biological restoration is severely impeded by the soil compaction itself due to increased penetration resistance and limited availability of water, air, and nutrients.

Examples of how slow the natural recovery from compaction is and the need for amelioration processes are shown below.

- Wert et al. (1981) found that the soil in skid trails was still heavily compacted 32 years after the operation with bulk densities exceeding 1.2mg/cm3 at depths between 20 to 30 cm. Some recovery had occurred in the surface at 15cm.

- Hildebrand & Wiebel (1981) mention that for loess soils 10 years was not enough to allow physical improvements of the soils measured.

- Froehlich et al. (1985) conclude that none of the bulk densities on major skid roads had returned to the undisturbed values in 23 years since logging.

- Cheatle (1991) detected few signs of soil recovery seven years after crawler tractor logging on the Solomon Islands.

- Congdon & Herbohn (1993) showed that differences between unlogged and disturbed plots in North Queensland were still apparent after 25 years, the logged plots still having higher bulk densities, higher pH values and lower cation exchange capacities.

- Marfenina et al. (1984) pointed out that the soil microfungal community recovers more slowly than the ground vegetation.

It becomes clear that natural recovery of compacted soils ;

- takes years or decades,
- reaches only the uppermost layer (5-10cm) of soils,
- does not affect all elements of the forest ecosystem.

Therefore the possibilities of restoration by human interference must be studied thoroughly. It is very often unknown what if any parts of the soil have been disturbed by forest traffic. According to Benecke (1992) the overall target for soil treatment or soil restoration in forestry could be stated as "a biologically active, deeply rooted soil that is part of a forestry ecosystem with closed nutrient cycles". Soil treatment in forestry might also be needed because of adverse affects other than those originating from traffic during forest operations:

- Natural hard pans or iron pans should be broken.
- Nutrient deficiencies call for correction: these might be natural due to the geological origin of the soil or man-made due to maltreatment in the past such as overuse of forest biomass.
- Negative impacts of acid rain have seriously damaged soil in many parts of Europe, to a point where soils fail to act as store nutrients and filter dangerous substances such as heavy metals.

Site preparation might also have undesirable negative effects, such as;

- Erosion.
- Compaction.
- Mobilisation of nutrients at the wrong time causing loss of nutrients.
- Reduction of bio-diversity in general.
- Loss of soil fauna in particular.

Höfle (1994) formulated the following objectives for site restoration;

- The negative impacts of soil disturbance should be fully corrected without substituting one set of negative effects by another, (e.g. compaction for loss of nutrients).
- The treatment must be deep enough so that the subsoil compaction is corrected.
- Restored soils must offer optimal conditions for growth of desired plants.
- The effect of restoration must be sustainable.
- The operation should be economic in terms of costs and benefits.

4.0 METHODS

The procedures and methods used to measure the compaction of the soil caused by machinery in the forestry, and the analytical methods used for the nutrient analysis of the soil are described below.

A separate control for each extraction rack was measured rather than having a single overall average value for the background values of the soil physical and chemical parameters. This should be more representative of the soil background values taking into consideration any spatial differences or variations on the site.

4.1 Bulk Density

Samples were taken with a soil sample ring (diam. 50x53mm). The ring was placed inside a closed ring holder which was attached to a handle with beating head supplied by Ejikelkamp Agrisearch Equipment.

The leaf litter layer was gently removed to below the organic matter layer. The corer was inserted into the soil vertically and without twisting. It was then withdrawn from the soil.

The soil sample ring was carefully removed from the closed ring holder. The excess soil outside the ring was removed using a sharp knife. This ring now contained a 100cc of undisturbed soil sample, which was then placed into a sealable plastic sample bag.

This sample was then dried at 104°C for 24 hours in a fan oven on an aluminium tray. The sample was then cooled and weighted. The bulk density was weight(g)/Vol(cc).

4.2 Shear Strength

The Shear Strength Inspection Vane Tester was used to measure the in situ undrained shear strength in soils. It is primarily intended for use in trenches and excavations at a depth not influenced by drying and excavation procedure.

The range of the instrument is from 0 to 26 t/m^2 when three different sizes of vanes are used. The accuracy of the instrument should be within 10% of the reading. The Calibration Certificate supplied states that the calibration tolerance is ±7%.

The measuring part of the instrument is a spiral-spring, (max. torque transmitted 30 Kg/cm).

When the handle is turned, the spring deforms and the handle and the sliding scale of the instrument get a mutual displacement. The size of this displacement depends on the torque which is necessary to turn the vane in the soil. When the soil shears the sliding ring remains at the maximum point of spring deformation giving the reading in KPa.

Three sizes of four-blades vanes are used; 16x32mm (extra) - multiply readings by 2, 20x40mm (standard) - direct readings, and 25.4x50.8mm (1"x2") (extra) - multiply reading with 0.5, which makes it possible to measure shear strength of 0 to 26; 0 to 13 and 0 to 6.5 t/m^2 respectively. This allow for measurements in varying soil conditions and soil types.

Measuring the soil shear strength in the forest was performed by taking over thirty (~32) measurements on the trafficked area and non-trafficked (control) areas along each extraction rack. All measurements were taken at a depth of 5 cm in the soil.

The results were statistically analysed to determine if any significant increase in resistance is found on the rack.

4.3 Cone Penetration Resistance

The measurements were taken with a Soil 'Bush' Penetrometer.
This measured the resistant force in 'Kilograms of force (Kg f)' on the cone as it was pushed through the soil at 15mm intervals. This allows the calibration of the instrument with kilogram weights as described by Anderson et al (1980). Each kg f unit is equivalent to 100KPa (Larney et al, 1986). The first 15 readings were recorded as a set. Five sets were then averaged to give one representative sample result. Six sample results were taken on each trial plot. The soil litter layer is included in the sample set.

Control samples were simultaneously taken in the same manner alongside the extraction racks. The results were plotted for each of the trials. Only at the Lissadell site were measurements taken.

The penetrometer has a cone of 12.83mm in diameter. Using the handles the operator pushes this down through the soil profile at a constant rate of approximately 3cm per second. Every 15mm the logger records the resistance against the cone in Kg of force. The logger stored the set of readings, which were written down by the operator before commencing the next measurement. The penetrometer had a maximum reading of 50 Kg f, which was signalled by a bleep to prevent over-loading of the instrument.

When stones, roots or other obstructions were meet, the reading was abandoned and another measurement taken.

The readings taken are a profile of the soil resistance including that of any leaf litter layer that may exist on the soil surface and the influence of the root mat layer from the trees. This often resulted in relatively high resistance in the upper centimetres of the profile. Cone penetration resistance is the only parameter to include the upper forest leaf litter layer in terms of quantifiable values, as the litter and root mat where by-passed or removed in the taking of measurements for other parameters.

4.4 Water Infiltration Rates

The apparatus used to measure water infiltration was a Double Ring Infiltrometer supplied by Ejikelkamp Agrisearch Equipment.

It was found that realistic results could only be achieved by removing the root mat layer and placing the rings on the soil. This was due to the roots and the needles preventing the rings from penetrating the ground sufficiently to avoid leaking of water under the rings.

The inner and outer ring were filled with water. The fall in water level in the inner ring was recorded while the water level in the outer ring was maintained at the same level as that in the inner ring. This was to reduce the effects of the side wall infiltration.

4.5 Analytical Procedures for Soil

4.5.1 Sampling Procedure

Samples were taken with a 59mm diameter corer along each extraction rack. Four samples were taken from each extraction rack plots, with two random cores taken per sample.

Control and trafficked samples were taken simultaneously in the forest to a depth of 10 cm. The cores where placed in externally labelled plastic bags and sealed. Samples were mixed well before analysis.

4.5.2 Soil Nutrient Analysis

Nutrient analysis includes available phosphorus, available potassium, total nitrogen and nitrate. All method where carried out in accordance with procedures in Methods of Soil Analysis, Part 1 & 2 (1986).

4.5.2.1 Total nitrogen. The total nitrogen content was carried out using the standard digestion technique (Kjeldahl method) as in Methods of Soil Analysis, 1986.

4.5.2.2 Nitrate. The nitrate content of the soil was performed using the Ion Selective Electrode method as described in Methods of Soil Analysis, 1986.

4.5.2.3 Available Phosphorus. The extraction of phosphorus and potassium was carried out with Bray's Extraction solution. Of the total phosphorus in soils, less than 1% is available to plants and Bray's extraction solution is used to dissolve an amount of phosphorus proportional to this available fraction. Methods of Soil Analysis (1986) described how phosphorus is analysed colorimetrically using the chemical reaction between phosphorus and ammonium molybdate. A characteristic blue colour is produced, when the molybdate or its complexes are partially reduced.

4.5.2.4 Available Potassium. Flame photometry was used to determine the potassium content in the Bray's solution extract as described in Methods of Soil Analysis (1986).

4.5.3. Organic Carbon

The method used was the Walkley Black organic carbon method. The percentage recovery of organic carbon by this method varies from 60 - 90% and the results obtained for each of the soil samples are recorded only as Organic Carbon Walkley Black values (Methods of Soil Analysis, 1986).

4.5.4. Organic Matter Content

The method used was the standard Direct Estimation Method{High Temperature Ignition Method} at 650 to 900°C as outlined in Methods of Soil Analysis, 1986.

4.5.5 Soil pH

The method used water to extract the hydrogen ions as described in Methods of Soil Analysis, 1986.

4.5.6 Soil Moisture Content

The moisture content of the soil in the trial plots was measured during machine operations using the procedure described Methods of Soil Analysis (1986).

4.6 Microbiological Procedures for Soil

The microbial sampling was undertaken to determine the affects of soil compaction on the microbial populations.

4.6.1 Sampling Procedures

The leaf litter layer is removed using a small hand-rake and the roots removed to allow the sampler retrieve the soil sample. Samples were taken with a 59mm diameter corer to a depth of 10 cm. Four random cores were taken per sample along the sampling site and where combined in the plastic sampling bags to form a composite sample.

Control samples:
Taken randomly in areas untraversed by the machinery, but close to the extraction rack track opening to avoid differences in exposure and moisture.

Trafficked samples:
Taken randomly on extraction rack tracks which have shown significant increase in bulk density and shear vane parameters demonstrating significant compaction.
Following sampling the samples were returned to the laboratory and stored overnight in the refrigerator at 4°C. Standard Methods (1986) have shown that samples handled is this fashion may be kept for about 7 to 14 days without significant alteration in their biological properties. However, all analyses were performed within 2 days of sampling.

4.6.2 Sample Preparation:

The samples were sieved using a 2mm mesh sieve to remove any large unwanted material such as stones, twigs, and needles that may occur in the sample.
This also aided the mixing of the sub-samples to form the composite samples.
The subsequent procedures for the processing of the samples, preparation of dilution's and preparation of plates as outlined in Methods of Soil Analysis (1986) were followed. The spread plate technique was used in conjunction with the following media types.

4.6.3 Total Microbial Count

For total bacteria enumeration, a combination of soil extract and Tryptic soy agar was used. The soil extract agar was prepared as per Methods of Soil Analysis (1986) with 3 grams of Tryptic Soy Broth per litre added.

4.6.4 Fungi

For enumeration of fungi Martin's Rose Bengal media and the spread plate technique were used as per Methods of Soil Analysis (1986).

4.6.5 Nitrifying Bacteria

For nitrogen fixing bacteria such as *Azomonas* and *Azotobacter* the methods and media recommended in Methods of Soil Analysis (1986) were used.

4.7 Trial Plot Design

The following tables illustrate the layout of the trial plots used on the project.
The first set of trials were performed in a section of forestry near Lissadell in County Sligo, which was thinned in the summer of 1995. Subsequent trials were carried out in Lugnaskeehan, Co. Leitrim, and Hollyford, Co. Tipperary.

First thinning of a forest stand involves cutting one row of trees into the stand and using the harvester crane thinning out trees either side of this row. This row becomes the extraction rack (path) for the forwarders who extract the timber to the roadside yarding piles. Thus an extraction path is created every seventh row generally.
The samples for compaction determination where taken on ground traversed by the machine tyres/tracks while control samples were taken alongside in the untrafficked areas in the stand.

Table 4.7.1 Trial plot layout in Lissadell forest.

Trial Plot	**Machine**	**Wheel**	**Traffic on Rack**	**Soil Cover**
Plot A	Ponsse S10	Band-Tracks†	5 loaded passes	No Brash
Plot B	Ponsse S10	Band-Tracks†	5 loaded passes	Brash
Plot C	Ponsse S10	Tyres only	5 loaded passes	Brash
Plot D	Ponsse S10	Tyres only	5 loaded passes	No Brash
Plot E	Norcar 480	Band-Tracks	8 loaded passes	No Brash
Plot F	Norcar 480	Band-Tracks	8 loaded passes	Brash
Plot G	Norcar 480	Tyres only	8 loaded passes	Brash
Plot H	Norcar 480	Tyres only	8 loaded passes	No Brash
Plot I‡	Teva Harvester	Combination*	1 return pass	Brash
Plot J‡	Teva Harvester	Combination*	1 return pass	No Brash

Approximately forty tonnes of timber was estimated, by volume to weight conversion, as the amount extracted by each of the forwarders across each extraction rack in Lissadell. The Ponsse S10 had an 8 ton load, while the Norcar 480 had a 5 ton (approx.) load.

As it is an intrinsic characteristic of a larger forwarder the Ponsse had the advantage of making less passes. It was decided that this fact must not be disregarded in the trials.

Table 4.7.2 Plot layout in the Lugnaskeehan forest. (Approximately 12 tons of timber was extracted across each extraction rack plot at this site).

Trial Plot	**Machine**	**Wheel**	**Traffic on Rack**	**Soil Cover**
Plot K	Ponsse S10	Band-Tracks†	3 loaded passes	Brash
Plot L	Ponsse S10	Band-Tracks†	3 loaded passes	No Brash

Table 4.7.3 Plot layout in the Hollyford forest. (Approximately 12 tons of timber was extracted by the forwarder across the extraction rack plots at this site).

Trial Plot	**Machine**	**Wheel**	**Traffic on Rack**	**Soil Cover**
Plot M	Norcar 490	Band-Tracks	3 loaded passes	Brash
Plot N	Norcar 490	Band-Tracks	3 loaded passes	No Brash

Notes:

† - Band tracks were only available for the trailer bogie on the Ponsse S10 forwarder.

‡ - Measurements taken before forwarders entered plots.

* - Combination refers to tyres in crane bogie and band tracks on rear bogie of the harvester.

In Lugnaskeehan (Ponsse S10) and Hollyford (Norcar 490), only trials using band tracks were performed for a variety of logistical reasons, but also because the terrain was not becoming to forwarder mobility without some form of traction aid. This also influenced the decision to limit the number of loaded passes to three on both sites. The larger load capacity advantage of the Ponsse S10 over the Norcar 490 forwarder was removed, as the number of loaded passes and tonnage extracted as were constant. The forwarders extracted only twelve tonnes in three loaded passes. This was due to light, short timber in Lugnaskeehan for the Ponsse S10 and a steep uphill climb for the Hollyford Norcar 490 from the stand to the roadside, inhibiting full loading of the Norcar.

The sites at Lugnaskeehan and Hollyford were both ploughed during planting with double mould-board ploughs. The extraction racks were at right angles to the ridges and furrows. Sampling was performed in such a manner that half of all samples were taken on the ridges and half in the furrows.

4.8 Trial Machines

The machines used in the trials are listed below. The results of the trials are in no way to be seen as an endorsement or otherwise of the machines or their manufacturers.

They represent only the available range in terms of size or weight and tyre or band track on current market as forwarders suitable for thinnings. There may be both lighter and heavier machines available on the market, but these were not available for the purposes of these trials.

The harvester used was the Teva harvester. This was use in both the Lissadell and Lugnaskeehan trials but not in the trials in Hollyford. This stand was cut manually with chainsaws before the Norcar 490 forwarder entered. The Teva harvester has a gross weight of 9000kgs, with 500mm wide tyres front and rear.

Table 4.8 Description of the forwarders used in the trials

Specification	**Ponsse S10**	**Norcar HTP 480**	**Norcar 490**
Weight (unladen)	9,800Kg	6,900Kg	7,500Kg
Load Capacity	10,000Kg	5,000Kg	4,000Kg
Tyres-Front	600/50-22.5	500mm	500mm
- Rear	700/45-22.5	500mm	500mm
Band Tracks	700mm (rear only)	500mm(Front & rear)	500mm(Front & rear)

4.9 Statistical Analysis of Data

Statistical analysis of data was performed to enable determination the significance of any changes displayed in the data. The statistical methods employed were performed on 'Microsoft Excel Version 4.0' which contains a range of different options. The following statistics where used.

4.9.1 t-Test: Two-Sample Assuming Unequal Variances

Performs a two-sample student's t-Test. This form of the test assumes that the variances of both ranges of data are equal and is referred to as a heteroscedastic t-test. The t-tests are used to determine whether two sample means are equal, i.e. to determine if significant difference has occurred following the trial. Use this test when the groups under study are distinct i.e. unpaired data. This test was used when data samples small (n<30).

The tests were performed at 0.01 and 0.05 levels of significance giving confidence intervals of 99% and 95% respectively.

4.9.2 z-Test: Two-Sample for Means

Performs a two-sample z-test for means with known variances. This procedure is commonly used to test hypotheses about the difference between two population means. This is more suitable for larger samples (n>30). The variance is calculated for each data range.

Plate No. 1:(above) The Teva Harvester with Silvatec harvesting head. A combination of band tracks and tyres were used for the harvester trials.

Plate No. 2:(below) The extraction rack following the harvester. Note the branches (brash mat) left on the rack for the machines to pass over and the timber on the left and right for the forwarder to remove.

Plate No. 3:(above) The extraction rack with the brash removed for the 'No Brash' trials. Note the stumps remaining from the row felled by the harvester when entering the stand. An extraction rack is normally opened on every seventh row throughout the stand being thinned.

Plate No. 4:(below) The band tracks used on the Ponsse S10 Forwarder. These steel tracks are used on soft ground to improve traction, mobility and prevent the machine sinking.

Plate No. 5:(above) The Norcar 480 forwarder used in Lissadell forest with 500mm wide band tracks.

Plate No. 6:(left) The Ponsse S10 forwarder. The tyres were also used without band tracks. Tyres were 600mm wide on front and 700mm wide on the trailer bogie.

5.0 RESULTS

5.1 Bulk Density.

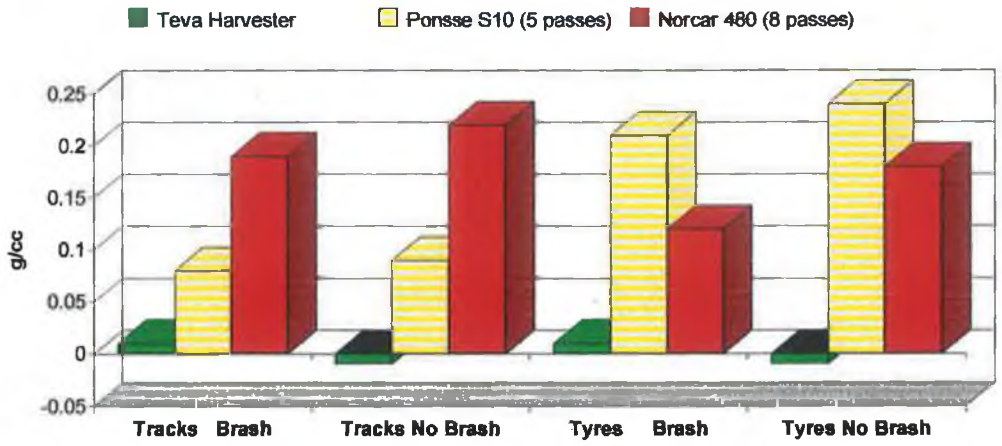
The tables below present the results of the bulk density analysis in the forest. Each result is an average value calculated from at least eight samples from the forest soil. A table of results is presented for each forestry used in the trials.

Table 5.1.1 Bulk Density Results for Trials in Lissadell Forest.

Plot	Machine	Wheels	Soil Cover	Control BD (g/cc)	Ext. Rack BD (g/cc)
A	Ponsse S10	Band Tracks	No Brash	0.85	0.94
B	Ponsse S10	Band Tracks	Brash	0.90	0.98
C	Ponsse S10	Tyres	Brash	0.83	1.05
D	Ponsse S10	Tyres	No Brash	0.79	1.03
E	Norcar 480	Band Tracks	No Brash	0.88	1.10
F	Norcar 480	Band Tracks	Brash	0.92	1.11
G	Norcar 480	Tyres	Brash	0.90	1.02
H	Norcar 480	Tyres	No Brash	0.87	1.05
I	Harvester	Combination	Brash	0.80	0.81
J	Harvester	Combination	No Brash	0.88	0.87

The changes in bulk density in Table 5.1.1 resulted from the extraction of approximately 40 tonnes of timber with the Ponsse S10 and the Norcar 480 forwarders. These are illustrated in Fig. 5.1.1below. The changes in bulk density after the harvester, whch used a comnination of tyres and tracks, are shown twice on the graph alongside both forwarders for comparsion.

Fig. 5.1.1 Increase in Bulk Density in Lissadell Forest Trial Plots.



The mean values in the bulk density measurements show the increase significantly. These range from 0.08 g/cc increase (Ponsse, Tracks, Brash) to a 0.24 g/cc increase (Ponsse, Tyres, No brash). The values for the Norcar 480 are within this range. Brash on the extraction racks appears to have reduced the bulk density increase for both forwarders, for band-tracks and tyres.

On examination of the changes in bulk density values with the t-Test statistic, the significance of these results is assessed. Table 5.1.2 summarises the statistical findings of the bulk density.

Table 5.1.2 Summary of Statistical Analysis of Bulk Density in Lissadell.

Plot	Machine	Wheel	Soil Cover	Level of Significance	
				$\alpha = 0.01$	$\alpha = 0.05$
Plot A	Ponsse S10	Band-Tracks	No Brash	No change	Increase
Plot B	Ponsse S10	Band-Tracks	Brash	No change	Increase
Plot C	Ponsse S10	Tyres only	Brash	Increase	Increase
Plot D	Ponsse S10	Tyres only	No Brash	Increase	Increase
Plot E	Norcar 480	Band-Tracks	No Brash	Increase	Increase
Plot F	Norcar 480	Band-Tracks	Brash	Increase	Increase
Plot G	Norcar 480	Tyres only	Brash	Increase	Increase
Plot H	Norcar 480	Tyres only	No Brash	Increase	Increase
Plot I	Teva Harvester	Combination	Brash	No change	No change
Plot J	Teva Harvester	Combination	No Brash	No change	No change

The increases in bulk density were found to be consequential with the exception of the Ponsse with band tracks on brash, and the Teva harvester.

When the payload of timber extracted is equal (at 12 tonnes approx.) and the number of passes used to achieve this is the same (at three each), which forwarder causes the least change in bulk density? Despite being on different sites, the general soil conditions were similar. Both sites were ploughed with the extraction racks at right angles to the furrows. The soil on both sites were heavy clayey soils and moisture content was 47 % and 50%.

Table 5.1.2 Bulk Density Results for Trials in Lugnaskeehan Forest.

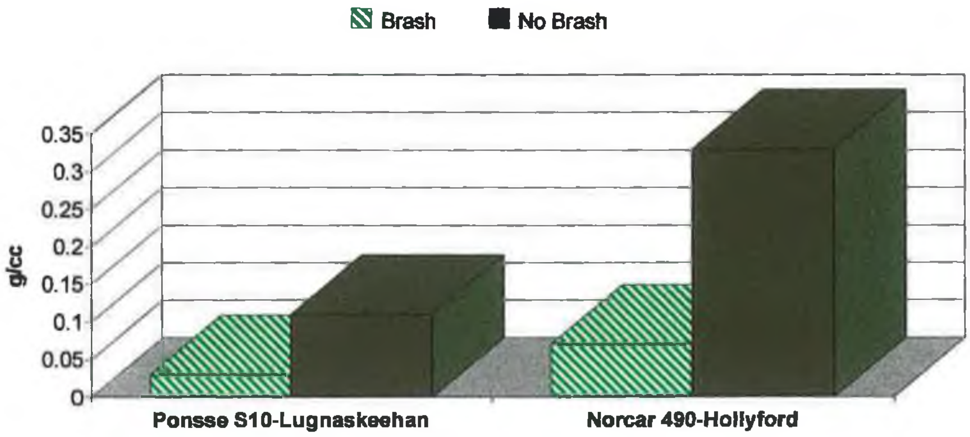
Plot	Machine	Wheels	Soil Cover	Control BD (g/cc)	Ext. Rack BD (g/cc)
K	Ponsse S10	Band Tracks	Brash	0.34	0.36
L	Ponsse S10	Band Tracks	No Brash	0.34	0.44

Table 5.1.3 Bulk Density Results for Trials in Hollyford Forest.

Plot	Machine	Wheels	Soil Cover	Control BD (g/cc)	Ext. Rack BD (g/cc)
M	Norcar 490	Band Tracks	Brash	0.61	0.68
N	Norcar 490	Band Tracks	No Brash	0.61	0.94

Figure 5.1.2 represents the data from Table 5.1.2 from the trials at Hollyford, and Table 5.1.3 from the Lugnaskeehan trials, with the Norcar 490 and Ponsse S10 forwarders respectively.

Fig. 5.1.2 Change in Bulk Density from 3 Loaded Passes of Tracked Forwarders.



The Ponsse S10 forwarder caused a lesser increase in bulk density than the Norcar 490. This change is more significant when considering the fact that a harvester was used in conjunction with the Ponsse in Lugnaskeehan, while cutting was performed using chainsaws in Hollyford. Also that the control bulk density is lower for the Ponsse S10 which means that the soil has a lower soil strength to resist a compactive force. Therfore, allowing for the differences due to sites, the Ponsse S10 appears overall to have a lesser impact on bulk density than the Norcar 490.

It is also worth noting that a Norcar 490 is one tonne (unladen) heavier then the Norcar 480.

5.2 Shear Strength.

The following tables present the resultant changes in soil shear strength after the machinery has traversed the forest floor. Thirty two individual measurements were taken on the control and trafficked ground, and then averaged to give the values in the tables. Appendix A contains the complete set of measurements.

Table 5.2.1 Soil Shear Strength Values Measured at Lissadell Forest.

Plot	Machine	Wheels	Soil Cover	Control SS (KPa)	Ext. Rack SS (KPa)
A	Ponsse S10	Band Tracks	No Brash	76	93
B	Ponsse S10	Band Tracks	Brash	70	84
C	Ponsse S10	Tyres	Brash	66	82
D	Ponsse S10	Tyres	No Brash	73	93
E	Norcar 480	Band Tracks	No Brash	100	155
F	Norcar 480	Band Tracks	Brash	100	164
G	Norcar 480	Tyres	Brash	100	134
H	Norcar 480	Tyres	No Brash	112	159
I	Harvester	Combination	Brash	83	96
J	Harvester	Combination	No Brash	83	93

Table 5.2.2 Soil Shear Strength Values Measured at Lugnaskeehan Forest.

Plot	Machine	Wheels	Soil Cover	Control SS (KPa)	Ext. Rack SS (KPa)
L	Ponsse S10	Band Tracks	No Brash	47	57
K	Ponsse S10	Band Tracks	Brash	47	54

Table 5.2.3 Soil Shear Strength Values Measured at Hollyford Forest.

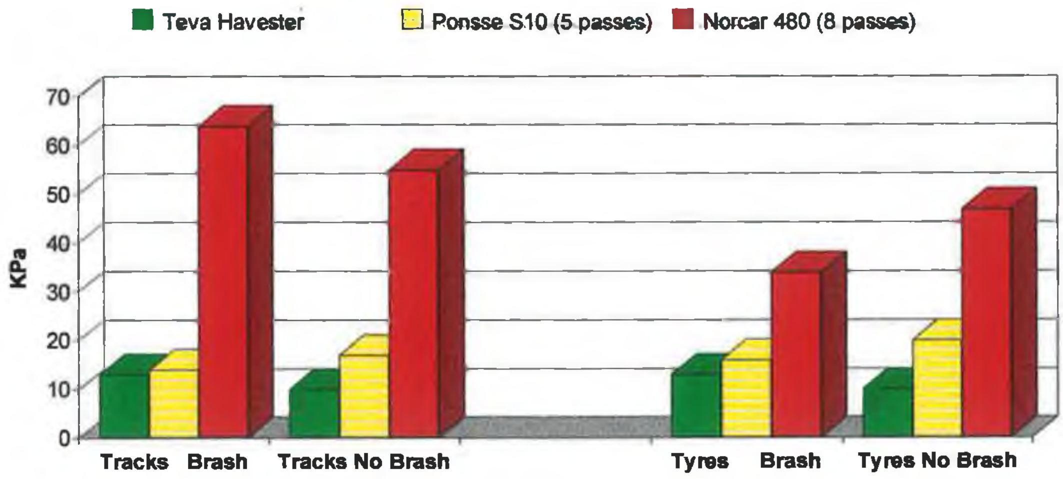
Plot	Machine	Wheels	Soil Cover	Control SS (KPa)	Ext. Rack SS (KPa)
N	Norcar 490	Band Tracks	No Brash	46	59
M	Norcar 490	Band Tracks	Brash	46	57

Figure 5.2.1 depicts the increase recorded in soil shear strength from results in Table 5.2.1. A comparsion of the different machines should not be made for these results due to sampling differences.

Three observations can be deducted from these results;

1. The harvester caused the lesser increase in soil shear strength compared to the forwarders. This mirrors the trend shown with the bulk density measurements.
2. The Norcar 480 forwarder caused a greater increase in soil shear strength compared to the Ponsse forwarder. This observation is made on the assumption that the increase in soil strength is greater than the influence of the different soil moisture content on the measurements.
3. The lower the soil moisture content the soil the greater the soil strength. This is reflected in the higher control (un-trafficked) values recorded when the soil moisture content is lower. This has also being noted by Jusoff (1991).

Fig 5.2.1 Increase in Soil Shear Strength in Lissadell Trial Plots



The comparsion with shear strength values from trials with the same machine is possible since all sampling of the soil strength was performed simultaneously, thus eliminating the effect of changing soil moisture.

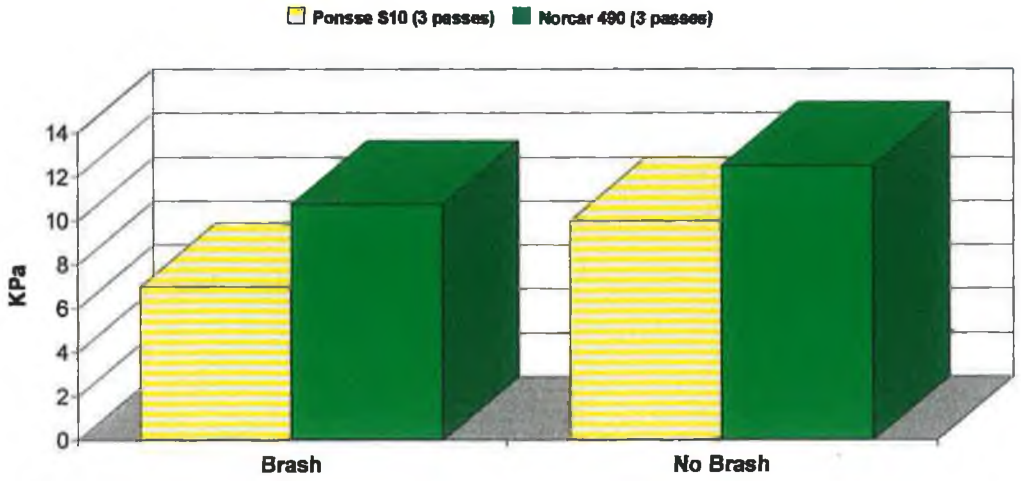
On examination of the Ponsse S10 trials, there appears to be little difference between tyres, tracks and the presence of brash on the soil. All Ponsse trials result in a 14 to 20 KPa increases in the mean values recorded. Higher values are recorded where no brash was present on the extraction rack for all machines on all sites.

The shear strength values recorded for the Norcar 480 forwarder, have a greater increase in values, ranging from a 34 to 65 KPa increase on trafficked measurements compared to control measurements.

Examining Fig. 6.2.2 for changes in shear strength resulting from the extraction of 12 ton of timber in 3 loaded passes, shows little difference in values recorded. The shear strength values for the control measurements are the same for both these sites at 46 and 47 KPa, and with only 3% difference in soil moisture comparsion of the sites is possible. As with the bulk density results the Ponsse S10 appears to have a lesser impact on the soil in wetter conditions on ploughed terrain.

Figure 5.2.2 illustrates the soil shear strength results from Tables 5.2.2 and 5.2.3.

Fig. 5.2.2 Increase in Soil Shear Strength from Tracked Forwarders.



Using the z - test and the t - test, an increase in soil shear strength, at 0.01 level of significance, is shown for all the machines. Thus it would appear the shear strength parameter is more sensitive to soil traffic than bulk density judging by the results achieved by the harvester trials.

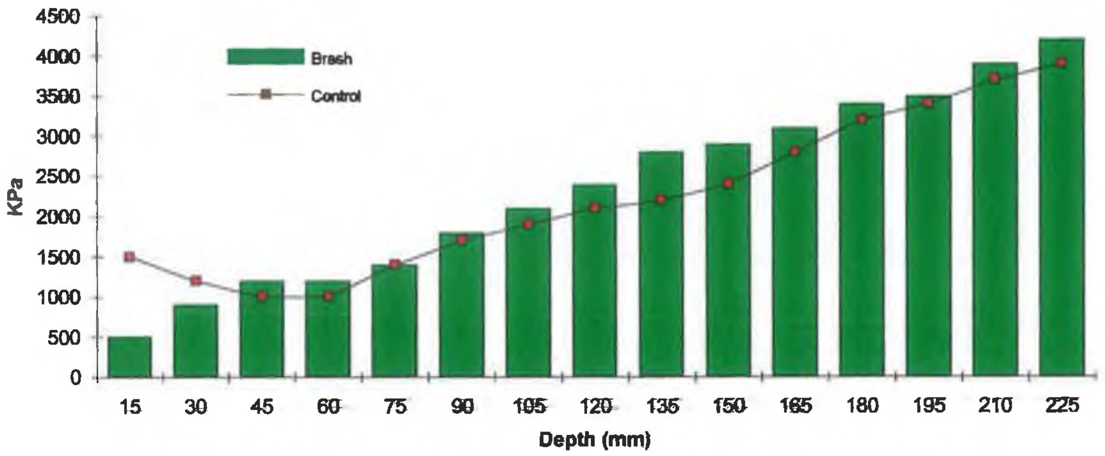
5.3 Cone Penetrometer.

Five separate profiles were measured with the cone penetrometer, and these were averaged to give one sample profile as shown in tables in Appendix A. There were six samples profiles measured for each trial trafficked area and control area. The average soil profiles shown in the following tables is a average value of the six sample profiles; therefore each profile shown below is an average resistance taken from thirty individual measurements in the field. The KiloPaschal (KPa) is the unit of measure for penetration resistance.

Table 5.3.1. Cone Penetration Resistance after the Harvester on Plots I & J.

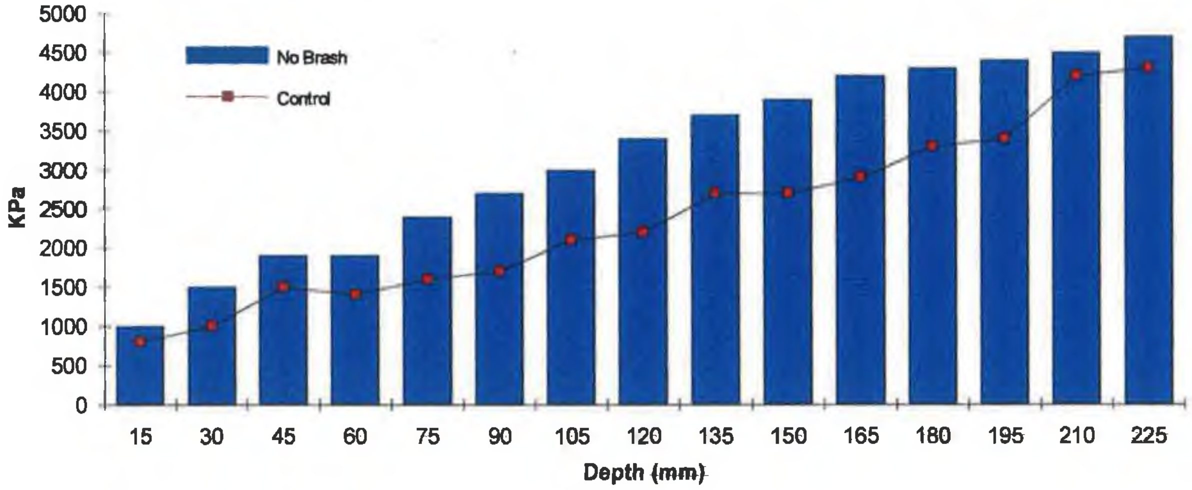
	Teva Harvester			
Soil Depth (mm)	Brash	Brash Control	No Brash Control	No Brash
	(KPa)	(KPa)	(KPa)	(KPa)
15	500	1500	800	1000
30	900	1200	1000	1500
45	1200	1000	1500	1900
60	1200	1000	1400	1900
75	1400	1400	1600	2400
90	1800	1700	1700	2700
105	2100	1900	2100	3000
120	2400	2100	2200	3400
135	2800	2200	2700	3700
150	2900	2400	2700	3900
165	3100	2800	2900	4200
180	3400	3200	3300	4300
195	3500	3400	3400	4400
210	3900	3700	4200	4500
225	4200	3900	4300	4700

Fig. 5.3.1 Cone Penetrometer after the Harvester on Plot I with Brash.



In Figures 5.3.1 & 5.3.2 the results of the cone penetration resistance readings after the harvester are illustrated. Because like soil shear strength, the measurements are dependant on the soil moisture content, only the results on each graph can be compared. Even though the measurements for the harvester, with and without brash were taken on consecutive days, no precipitation events occurred so a limited comparison may be undertaken. With brash present on the extraction rack, there is little difference between the control and the extraction rack measurements.

Fig. 5.3.2 Cone Penetrometer after the Harvester on Plot J with No Brash.



However without constructing a brash mat in the path of the harvester, the difference between control and rack measurements appears to be greater.

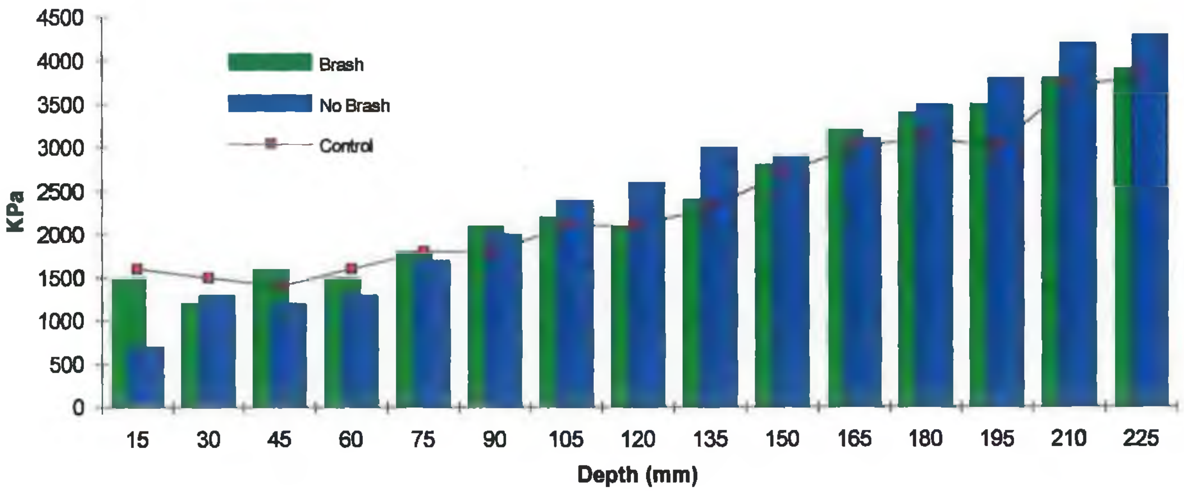
Control and extraction rack measurements where taken simultaneously for the Ponsse S10 (on band-tracks) at Lissadell. These are illustrated on Fig. 5.3.3. on the following page. At the lower soil depths the control measurements are higher than both the brashed and unbrashed . This possibly indicates that the resistance of the leaf litter and root mat layer on the control plots.
Another observation is that the control measurements appear to be lower than the 'No Brash' and 'Brash' racks in all measurements at depths greater than 90mm.

Table 5.3.2. Cone Penetration Resistance after the Ponsse S10 with Band Tracks on Plots A & B.

	Ponsse S10 with Band Tracks		
Soil Depth (mm)	Brash	No Brash	Control
	(KPa)	(KPa)	(KPa)
15	1500	700	1600
30	1200	1300	1500
45	1600	1200	1400
60	1500	1300	1600
75	1800	1700	1800
90	2100	2000	1800
105	2200	2400	2100
120	2100	2600	2100
135	2400	3000	2300
150	2800	2900	2700
165	3200	3100	3000
180	3400	3500	3100
195	3500	3800	3000
210	3800	4200	3700
225	3900	4300	3800

Figure 5.3.3 illustrates the differences between plot A (No Brash) and plot B (Brash).

Fig. 5.3.3 Cone Penetrometer after the Ponsse S10 with Band Tracks.

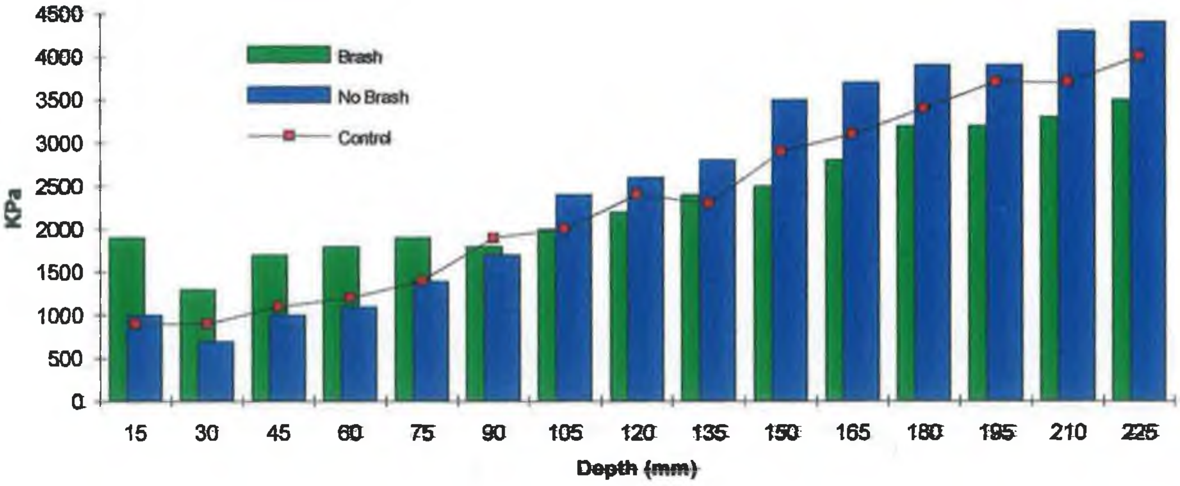


The presence of brash under the Ponsse with tyres (Fig. 5.3.4) appears to prevent increases in penetration resistance at depth in the soil, but cause increases in the upper 75mm of the profile compared to the control values. The opposite occurs with the 'No Brash' extraction rack.

Table 5.3.3. Cone Penetration Resistance after the Ponsse S10 on Plots C & D.

	Ponsse S10 with Tyres		
Soil Depth (mm)	Brash	No Brash	Control
	(KPa)	(KPa)	(KPa)
15	1900	1000	900
30	1300	700	900
45	1700	1000	1100
60	1800	1100	1200
75	1900	1400	1400
90	1800	1700	1900
105	2000	2400	2000
120	2200	2600	2400
135	2400	2800	2300
150	2500	3500	2900
165	2800	3700	3100
180	3200	3900	3400
195	3200	3900	3700
210	3300	4300	3700
225	3500	4400	4000

Fig. 5.3.4 Cone Penetrometer after the Ponsse S10 on Plots C&D with Tyres.

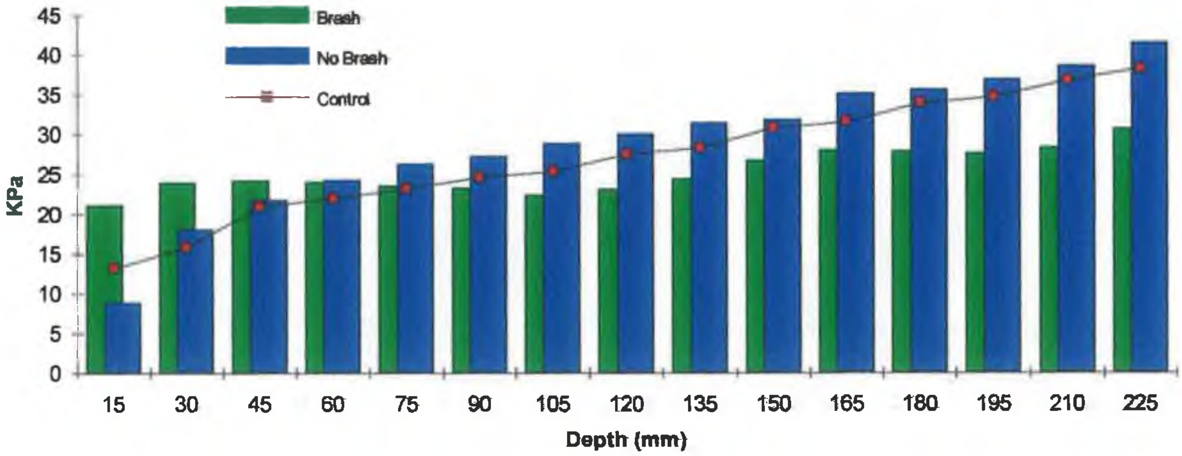


This trend can also be observed in the following trials illustrated in Figures 5.3.4 & 5.3.5. In these graphs the trend appears to have a focal point around the 90mm depth in the soil profile where a reversal in the observation occurs regardless of the presence or otherwise of brash on the extraction rack. The reason for this is unclear.

Table 5.3.4. Cone Penetration Resistance after the Norcar 480 forwarder with Band tracks on Plots E & F.

	Norcar 480 with Band Tracks		
Soil Depth (mm)	Brash	No Brash	Control
	(KPa)	(KPa)	(KPa)
15	2100	900	1300
30	2400	1800	1600
45	2400	2200	2100
60	2400	2400	2200
75	2400	2600	2300
90	2300	2700	2500
105	2200	2900	2500
120	2300	3000	2800
135	2400	3100	2800
150	2700	3200	3100
165	2800	3500	3200
180	2800	3600	3400
195	2800	3700	3500
210	2800	3900	3700
225	3100	4200	3800

Fig. 5.3.5 Cone Penetrometer after the Norcar 480 with Band Tracks on Plots E&F.



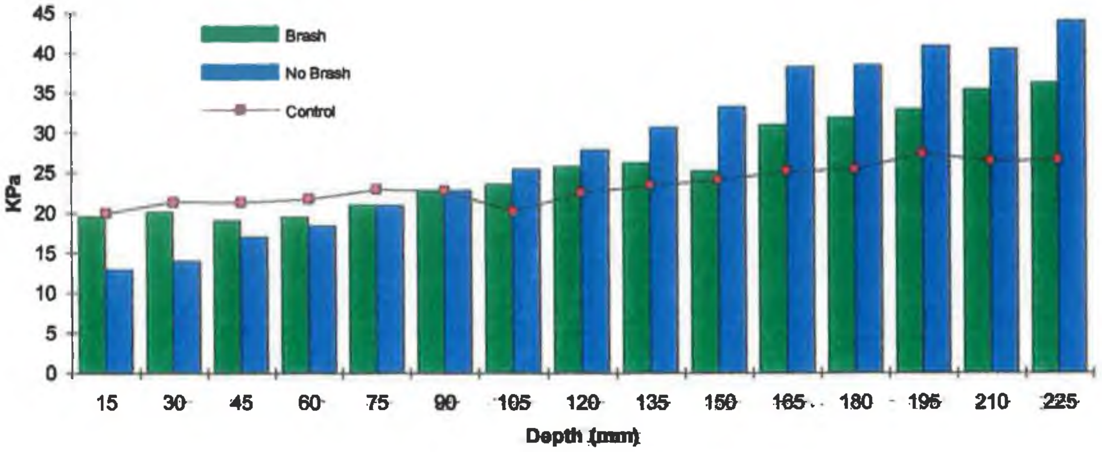
In absence of brash on the extraction rack the forwarder may weaken the structure of the matted layer of tree roots due to lack of aerial protection from the passing load. This results in a lesser penetration resistance in the upper regions of the soil where the majority of roots exist (top 100mm).

If this is the correct explanation, it means that the presence of brash on the extraction rack not only reduces increases in cone penetration resistance at depth in the soil profile, but that brash also protects the integrity and structure of the tree's root mat layer (including the soil present in it) from potential damage from passing forwarders.

Table 5.3.5. Cone Penetration Resistance after the Norcar 480 on Plots G & H.

	Norcar 480 Tyres		
Soil Depth (mm)	Brash	No Brash	Control
	(KPa)	(KPa)	(KPa)
15	1955	1290	2000
30	2010	1395	2100
45	1910	1700	2100
60	1945	1840	2200
75	2100	2090	2300
90	2285	2280	2300
105	2360	2550	2000
120	2580	2790	2200
135	2630	3065	2300
150	2520	3325	2400
165	3100	3815	2500
180	3185	3845	2600
195	3290	4085	2700
210	3535	4040	2600
225	3620	4390	2700

Fig. 5.3.6 Cone Penetrometer after the Norcar 480 on Plots G&H.



An explanation for the higher cone penetration resistance on the upper section of the soil profile on brashed extraction racks, is the presence of additional leaf litter and debris form the brash mat onto the soil. On soil without brash mats, the forwarders removed or incorporated the leaf litter on the forest floor into the soil. This often made it difficult to tell where the forwarders wheels had passed on the brashed racks while it was very evident on the un-brashed racks (Plates No. 9 to 12).

The forwarder may have compacted the leaf litter and debris somewhat thus increasing the cone penetration resistance values in comparsion to control values which were not subject to any interference. Thus the higher cone penetration resistance in the upper 30mm of the extraction racks with brash mats.

Table 5.3.5 Soil Depth at which Machines caused 2500KPa Penetration Resistance.

Plot	Machine	Wheels	Soil Cover	Control mm	Ext. Rack mm
A	Ponsse S10	Band Tracks	No Brash	145	120
B	Ponsse S10	Band Tracks	Brash	145	150
C	Ponsse S10	Tyres	Brash	140	150
D	Ponsse S10	Tyres	No Brash	140	120
E	Norcar 480	Band Tracks	No Brash	90	75
F	Norcar 480	Band Tracks	Brash	90	150
G	Norcar 480	Tyres	Brash	165	120
H	Norcar 480	Tyres	No Brash	165	105
I	Harvester	Combination	Brash	160	135
J	Harvester	Combination	No Brash	135	90

The Norcar 480 with band tracks and without brash reached the critical 2500KPa at the least depth of 75mm into the soil profile. This is the only trial in which the penetration resistance is greater than 2500KPa within the 100mm soil depth at which most root activity occurs in the soil. It is also worth noting that in all the trials, the brashed racks reached 2500KPa at greater depths than racks without brash mats.

5.4 Water Infiltration.

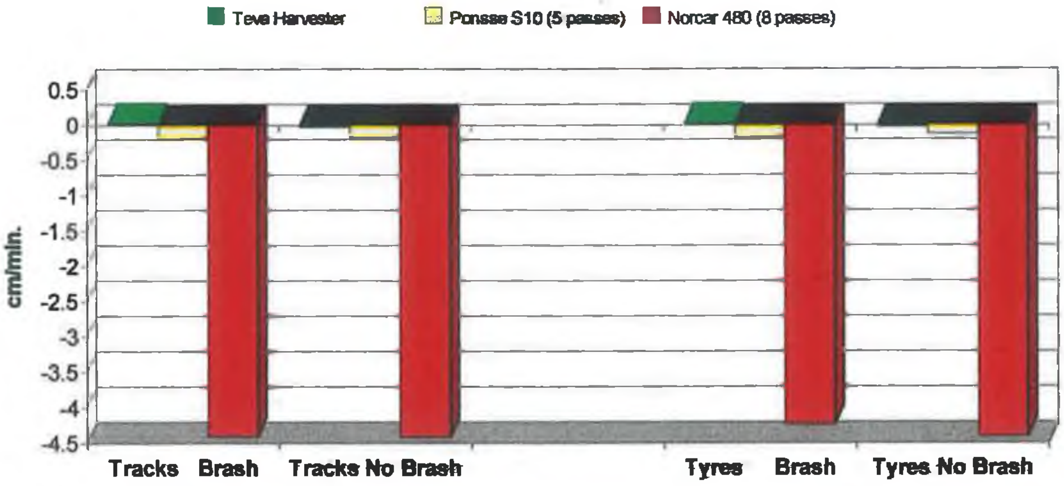
The table below presents the data concerning soil infiltration rates of water measured during the Lissadell forest trials. The values shown are an average of at least three individual measurements in the forest.

Table 5.4.1 Water Infiltration rates through the soil at Lissadell forest.

Plot	Machine	Wheels	Soil Cover	Control cm/min	Ext. Rack cm/min
A	Ponsse S10	Band Tracks	No Brash	0.37	0.19
B	Ponsse S10	Band Tracks	Brash	0.37	0.17
C	Ponsse S10	Tyres	Brash	0.28	0.10
D	Ponsse S10	Tyres	No Brash	0.28	0.14
E	Norcar 480	Band Tracks	No Brash	4.44	0.01
F	Norcar 480	Band Tracks	Brash	4.44	0.02
G	Norcar 480	Tyres	Brash	4.44	0.19
H	Norcar 480	Tyres	No Brash	4.44	0.02
I	Harvester	Combination	Brash	0.37	0.39
J	Harvester	Combination	No Brash	0.37	0.33

In Figure 5.4.1 the reduction in water infiltration rates are plotted. Despite the higher control infiltration rates for the Norcar reading, due to the greater soil moisture deficit at sampling, the infiltration rate on the extraction rack remains very low by comparison. Statistical analysis of the results confirms that a reduction in water infiltration rates occurred on the extraction rack due to the forwarder traffic.

Fig 5.4.1 Reduction of Water Infiltration Rates in Machine Trials.



It was observed in Lissadell that on the extraction racks where infiltration rates were low, that puddling or ponding of precipitation occurred and on sloping ground machine tracks act as drains for surface runoff, aided by any rutting that may have occurred. Few values are given in the literature as to the upper limits of soil infiltration that are acceptable beyond which tree growth is inhibited or affected significantly. Infiltration capacity measured with cylinder infiltrometers show that rates of <0.08cm/min indicates quite severe compaction and that rates of >0.16cm/min is the preferred level according to Chi Yung (1993).

The results in Lissadell would indicate that the Norcar 480 forwarder cause some severe compaction, while the Ponsse S10 forwarder on band tracks was above the preferred level. The Ponsse S10 on tyres alone was just under the 0.16cm/min level but above the severe compaction threshold limit.

5.5 Soil Chemical Analysis.

The following tables show the values from the soil analysis performed to investigate the affect of compaction on the soil nutrients. These are average values calculated from four individual samples from each plot. Appendix A has the complete set of results.

Table 5.5.1 Results of pH Analysis of the Soil from the Lissadell Trials.

Plot	Machine	Wheels	Soil Cover	Control pH units	Ext. Rack pH units
A	Ponsse S10	Band Tracks	No Brash	4.5	5.0
B	Ponsse S10	Band Tracks	Brash	4.3	4.2
C	Ponsse S10	Tyres	Brash	4.5	4.5
D	Ponsse S10	Tyres	No Brash	4.6	4.8
E	Norcar 480	Band Tracks	No Brash	4.3	4.3
F	Norcar 480	Band Tracks	Brash	4.3	4.3
G	Norcar 480	Tyres	Brash	4.5	4.6
H	Norcar 480	Tyres	No Brash	4.4	4.6

The pH of the control samples had a mean value of 4.4 (±0.2 Std. Dev.) while the extraction rack mean value was 4.5 (±0.3 Std. Dev.). This would indicate that any change is within the expected sampling variation of the soil pH.

Table 5.5.2 Results of Nitrate Analysis of the Soil from the Lissadell Trials.

Plot	Machine	Wheels	Soil Cover	Control ppm	Ext. Rack ppm
A	Ponsse S10	Band Tracks	No Brash	1.2	2.1
B	Ponsse S10	Band Tracks	Brash	2.0	2.2
C	Ponsse S10	Tyres	Brash	1.9	1.9
D	Ponsse S10	Tyres	No Brash	1.0	1.0
E	Norcar 480	Band Tracks	No Brash	0.9	1.5
F	Norcar 480	Band Tracks	Brash	1.2	1.1
G	Norcar 480	Tyres	Brash	1.1	1.2
H	Norcar 480	Tyres	No Brash	1.3	1.1

The mean nitrate result is 1.3 (±0.5)ppm on the control areas and is 1.5(±0.5)ppm on the trafficked areas. Thus again no significant change has been recorded.

Table 5.5.3 Results of Total Nitrogen Analysis of the Soil from the Lissadell

Plot	Machine	Wheels	Soil Cover	Control ppm	Ext. Rack ppm
A	Ponsse S10	Band Tracks	No Brash	0.7	1.5
B	Ponsse S10	Band Tracks	Brash	2.1	1.6
C	Ponsse S10	Tyres	Brash	1.6	2.1
D	Ponsse S10	Tyres	No Brash	1.4	1.9
E	Norcar 480	Band Tracks	No Brash	1.3	1.5
F	Norcar 480	Band Tracks	Brash	1.3	1.1
G	Norcar 480	Tyres	Brash	2.0	1.6
H	Norcar 480	Tyres	No Brash	1.1	1.4

For Total Nitrogen the mean control value is 1.4(±0.5)ppm compared to the 1.6(±0.5)ppm for the extraction rack. This also illustrates an insignificant change.

Table 5.5.4 Results of Available Potassium Analysis in Soil from Lissadell.

Plot	Machine	Wheels	Soil Cover	Control ppm	Ext. Rack ppm
A	Ponsse S10	Band Tracks	No Brash	111.0	71.0
B	Ponsse S10	Band Tracks	Brash	107.0	92.0
C	Ponsse S10	Tyres	Brash	121.0	120.0
D	Ponsse S10	Tyres	No Brash	91.0	114.0
E	Norcar 480	Band Tracks	No Brash	95.0	85.0
F	Norcar 480	Band Tracks	Brash	83.0	85.0
G	Norcar 480	Tyres	Brash	75.0	94.0
H	Norcar 480	Tyres	No Brash	77.0	73.0

While some noticeable increases occurred on the first two trials under the Ponsse S10, overall the mean control value recorded was 95.0(±16.7)ppm P and 91.8 (±12.2)ppm P on the extraction rack. Hence the impact on available Potassium is somewhat uncertain.

The following Table 5.5.5 illustrates that the organic matter content of the soil may have increased slightly on the extraction rack. The mean control value was 12.7 (±2.1)% while the extraction rack value was 14.9(±2.0)%. There is no definite increase using the average results but the individual trials show a significant increase in organic matter content. On the extraction racks without brash cover the forwarders appear to have 'pressed' all the litter into the soil. This is reflected in the fact that some of the No Brash racks have increases in organic matter as large as brashed racks.

Table 5.5.5 Results of Organic Matter Analysis of the Soil from Lissadell Trials.

Plot	Machine	Wheels	Soil Cover	Control % O.M.	Ext. Rack % O.M.
A	Ponsse S10	Band Tracks	No Brash	15.04	15.46
B	Ponsse S10	Band Tracks	Brash	13.12	14.60
C	Ponsse S10	Tyres	Brash	15.51	18.77
D	Ponsse S10	Tyres	No Brash	14.10	15.92
E	Norcar 480	Band Tracks	No Brash	10.87	13.13
F	Norcar 480	Band Tracks	Brash	11.50	11.88
G	Norcar 480	Tyres	Brash	9.55	14.77
H	Norcar 480	Tyres	No Brash	12.07	14.95

Table 5.5.6 Results of Organic Carbon Analysis of the Soil from Lissadell Trials.

Plot	Machine	Wheels	Soil Cover	Control % O.C.	Ext. Rack % O.C.
A	Ponsse S10	Band Tracks	No Brash	5.2	5.4
B	Ponsse S10	Band Tracks	Brash	5.0	5.7
C	Ponsse S10	Tyres	Brash	5.8	6.2
D	Ponsse S10	Tyres	No Brash	5.9	5.9
E	Norcar 480	Band Tracks	No Brash	4.1	4.3
F	Norcar 480	Band Tracks	Brash	3.7	3.2
G	Norcar 480	Tyres	Brash	3.8	3.2
H	Norcar 480	Tyres	No Brash	5.3	4.2

No change is evident for organic carbon between the control and extraction rack samples, means of 4.6 (±0.9)% and 4.8(±0.8)% respectively. Looking at the trial results it appears that the Ponsse trials caused an increase while Norcar trials show signs of a decrease in carbon. A reason for this is not clear.

Table 5.5.7 shows the Phosphorus results from the trials. The extraction racks mean value was 5.2(±2.2)ppm and the control was 6.8(±2.9)ppm. This net reduction is relatively large compared to the other parameters, but it is within the 95% confidence intervals for the mean values as with the standard deviation above.
The biggest reduction appears to have occurred on three of the four extraction racks with no brash, where as brashed racks appear to have remained relatively unchanged.

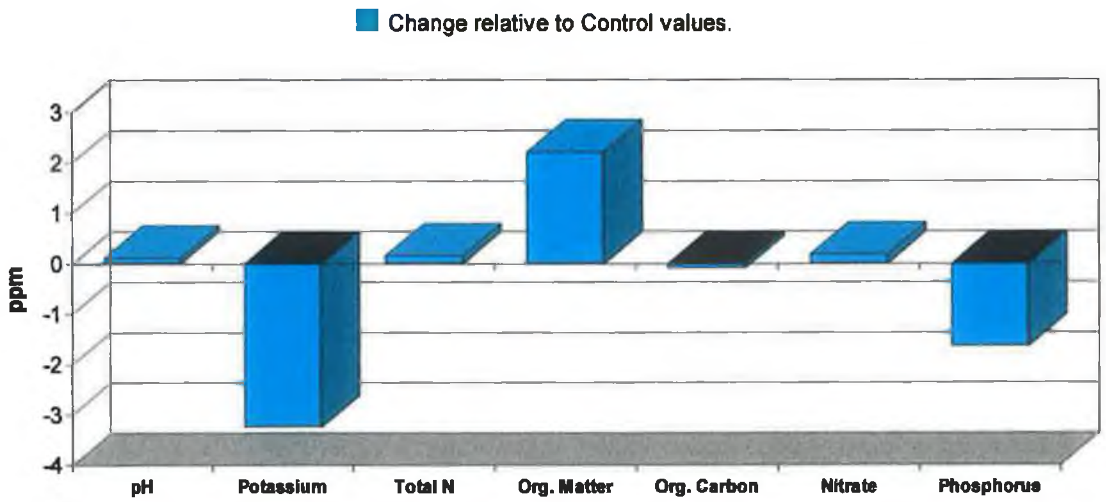
Table 5.5.7 Results of Phosphorus Analysis of the Soil from the Lissadell Trials.

Plot	Machine	Wheels	Soil Cover	Control ppm	Ext. Rack ppm
A	Ponsse S10	Band Tracks	No Brash	11.7	5.8
B	Ponsse S10	Band Tracks	Brash	7.1	7.4
C	Ponsse S10	Tyres	Brash	7.8	8.8
D	Ponsse S10	Tyres	No Brash	6.2	3.6
E	Norcar 480	Band Tracks	No Brash	9.0	2.5
F	Norcar 480	Band Tracks	Brash	6.8	5.0
G	Norcar 480	Tyres	Brash	3.0	3.0
H	Norcar 480	Tyres	No Brash	3.0	5.4

The following graph will illustrate the changes measured in the soil analysis when the sum of results from each trial are averaged.

Figure 5.5.1 shows the increase in the trafficked soil chemical values compared to the control values, regardless of the trial, with a decrease represented by the bar column below the x-axis, for example Potassium.

Fig. 5.5.1 Change in the Mean Values of the Soil Nutrient Parameters.



The different parameters are not directly comparable with each other, but the graph summarises the indications produced by the measured values in the field.

5.6 Soil Microbiological Analysis.

The table presented displays the results of the microbiological analysis of the Lissadell forest. A total count of aerobic, fungi and nitrifying bacteria was estimated using general purpose and selective media. The extraction racks selected for sampling illustrated a significant increase in bulk density during extraction. The results are in colony forming units (cfu's) per 10 grams of soil.

Table 5.6.1 Enumeration of micro-organisms (cfu's per 10 grams of soil).

Test Micro-organism	**Extraction Rack Samples**					**Mean**
Total Aerobes @ 22°C	71000	92000	170000	128000	120000	116200
Fungi @ 22°C	16300	3600	37000	4800	15000	15340
Nitrifying @ 22°C	0	6700	6000	750	3500	3390
Test Micro-organism	**Control Samples**					**Mean**
Total Aerobes @ 22°C	11800	58000	70000	63000	50000	50560
Fungi @ 22°C	3600	3800	6500	9200	6000	5820
Nitrifying @ 22°C	7000	710	410	6300	3200	3524

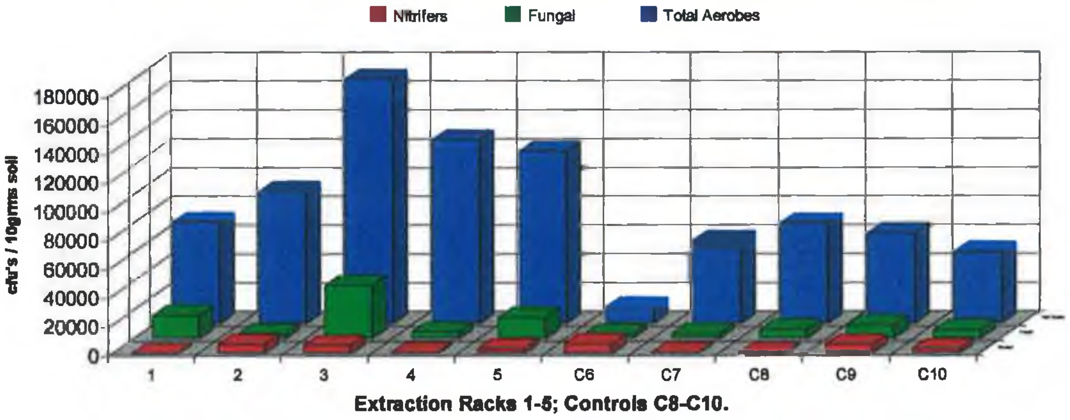
The microbiological analysis performed indicate that an increase of colony forming units(cfu's) occurred on the extraction racks.

The total aerobic count using the soil extract / tryptic soy agar media displays a two fold increase in viable count microbes following the traffic and increases in soil compaction (116,2000 cfu's - extraction rack, 50,560 - control).

A three fold increase is recorded for fungal microbes on the Rose Bengal media (5,820 cfu's - control; 15,340 cfu's - extraction rack).

The increase for nitrogen fixing bacteria is not significant with the mean control of 4,262 cfu's and 3390 cfu's on the extraction racks. This indicates that the nitrifying populations were not significantly affected by the thinning process unlike the total aerobes and fungi. It appears that the compaction of the clayey sand soil enhances the aerobic and fungi populations. The reasons may be the combination of many factors such as light, reduced infiltration, mixing of soil horizons or fresh litter on the soil surface. The following graph illustrates the results recorded.

Fig. 5.6.1 Microbial Population Reponse to Forwarder Traffic in Lissadell.



5.7 Soil Moisture Content

This table summarises the results of the soil moisture measurements taken for each of the trial sites. The complete table (A.31) of percentage moisture values is provided in Appendix A. This table below shows the site average at the time of thinning for the harvester and extraction for the forwarders.

Table 5.7.1 Statistical Summary of Soil Moisture Measurements.

	Lissadell Trials			Hollyford	Lugnaskeehan
Descriptive Statistic	**Harvester**	**Ponsse S10**	**Norcar 480**	**Norcar 490**	**Ponsse S10**
Mean	31	33	26	47	50
Median	31	33	25	49	53
Standard Deviation	8	5	3	11	13
Variance	57	30	11	122	163
Minimum	10	24	22	28	27
Maximum	43	44	61	69	69
Count	16	24	8	12	12
Confidence Level (99%)	5	3	10	9	9

The results presented illustrate that there was a difference in moisture levels recorded during the compaction trials at Lissadell with the Ponsse S10 and the Norcar 480 forwarders. However the difference is only slight when the confidence intervals are considered for the mean values. The Ponsse trials were undertaken on soil with 33 (±3)% and the Norcar 480 with soil moisture of 26 (±10)%.

The trials in Hollyford and Lugnaskeehan were undertaken on much wetter ground but the two sites recorded moisture levels that are very close at 47 and 50% (±9%).

Plate No. 7:(above) The Norcar 490 forwarder. This forwarder complete with band tracks was used in the Hollyford trials.

Plate No. 8:(below) The soil disturbance and rutting resulting from forwarder operations during wet weather. Poor site drainage and a lack of brash compound the problem for each additional pass of the forwarder.

6.0 DISCUSSION

6.1 Measurement of Soil Compaction

One of the aims of the study was to access suitability of one or more parameters to monitor the level of soil compaction in the field. These parameter(s) could then be used by foresters or even operators in the forest to measure soil compaction, and with experience they could assess the potential susceptibility of a stand to soil damage and compaction.

Ideally a suitable method would provide instantaneous results to the operator in the forest, should be easy to measure, require minimal amount of equipment, and allow comparisons between different sites and different soil types. The parameter would also have a definite limit, above which any increase would be undesirable in terms of soil compaction and its impact on tree growth.

Cone penetrometer resistance measurements require the use of special equipment. The measurements are affected by soil moisture, soil depth and soil bulk density (Sands et al, 1979; Henin, 1937). In addition the root mat and leaf litter layer interfere with the results recorded by the penetrometer, in that undisturbed penetration resistance is higher than trafficked ground initially and then it decreases with increasing number of passes. Gravel and stone in the soil influence the results as do areas of shallow soil. Trends in the measurements are difficult to assess without taking numerous samples and this may be problematic were continuous monitoring may be needed to assess changing conditions on a site. A specialised instrument is also needed. However, the parameter is a good indicator of the compaction zone at depth in the soil profile which is often undetected by other parameters according to Davidson (1965).

Soil shear strength is very practicable in terms of speed of sampling and taking larger number of samples over a large area. A shear vane tester is a simple and easy to piece of equipment to use and carry in the forest. Measurements are specific to soil moisture conditions thus limiting comparisons being made. The shear strength is also specific to individual soil types and comparisons cannot be made between sites with differing soils. Also in clayey or heavy gley soils the continual passing of the forwarder may cause the shear strength to decrease after an initial increase in soil strength as the soil is moulded and re-moulded by the wheels. In conditions like this deep rut formation is common with large displacement of soil and significant berm formation along the edge of the rut.

However, like the cone penetrometer results, the shear vane measurements taken on the same day and under the same soil conditions present a valuable picture of the brashed versus unbrashed racks and the use of tyre and band-tracks for each machine.

Water infiltration tests are very labour intensive and require large quantities of water on site to perform the tests. For accurate results the larger diameter infiltration ring is better and also the use of the double infiltration rings. During the sampling in Lissadell over 1800 litres (400 gallons) of water was used from a small river 0.5km from the trail plots. This is not practicable in most situations even where a forwarder is used to transport the water (extra passes - more compaction!). The results are also very influenced by soil moisture content and in dry weather there may be difficulty in pushing the infiltration rings into the soil to avoid sidewall leakage.

Bulk density was the most informative parameter in relation to the measurement of soil compaction in the forest soil in this project. This is also reflected in the number of others studies that use bulk density to measure and monitor the impact of machinery on soil in both forestry and agricultural studies (Section 2). Similar to the other parameters changes in soil bulk density is dependant on soil moisture content and the soil load causing the change but the actual sampling is relatively independent of the soil moisture.

Sampling is easy with the proper equipment to ensure accurate samples and large numbers can be taken in a short period, approximately 5 minutes per sample. Occasionally roots and stones can be problematic during sampling.

The main disadvantage is that the samples need to be dried at 104°C and then weighed on balance. This would mean at least a minimum 24 hour turnover time for results.

6.2 The Harvester Impacts on Forest Soil

The harvester appears to have a much lesser impact on various parameter measurements in comparison to the forwarders. For bulk density, shear strength, cone penetration and infiltration the measured change is noticeably less in terms of soil compaction. This confirms similar findings in the literature by Taatila (1994) about the impact of the harvester. Duffer (1994) found that despite the frequent movements back and forth, and the winding and twisting practised during harvesting to compliment crane manoeuvres, soil compaction was lower than for forwarder activities.

This practice was evident during the trials in this study and was the result of the operator having a poor line of vision from the cab. Harvesters with the operator cab positioned on the rear bogie axles are even more prone to slow-speed-curving to allow the operator a better view of the felling operations. This movement back & forth during harvesting results from the limited space available to pull out the felled tree from the stand for delimbing according to Duffer (1994).

The fact that harvester appears to cause noticeably less soil compaction should thus be maximised in the forest in preparing for the subsequent forwarding operations. This is especially important in the production of brash mats as the harvester advances into the stand and is opening new extraction racks.

6.3 The Forwarder Impacts on Forest Soil

The notable changes in soil compaction result from the forwarder's activities in the forest. Both the Ponsse and the Norcar forwarders caused impacts on the bulk density, shear strength, cone penetration resistance and infiltration rates of the soil as they extracted timber from each plot.

Due to logistical problems it was impossible to get both forwarders onto the one site at the same time. This caused a problem for the comparison of the compaction caused by the different forwarders using soil moisture dependant parameters such as shear strength and cone penetration resistance. Bulk density and water infiltration were the only reliable parameters to monitor which forwarder causes the least compaction in Lissadell.

Bulk density results in Section 5.1 show little difference exists in soil bulk densities after the two forwarders. The Ponsse S10 is only a fraction lower (1.00g/cm^3) than the Norcar 480 (1.07g/cm^3). Taking the soil moisture into consideration (Ponsse trials - 33%; Norcar - 26%) the Norcar had better conditions to work with in terms of avoiding compaction. This is supported by the higher control shear strength values measured for the Norcar trials (Table 5.2.1). Water infiltration rates were significantly lower after the Norcar extraction's than for the Ponsse also. The cone penetration results show that overall the Ponsse S10 did cause the soil to reach the 2500KPa limit at greater depths compared to the Norcar 480 plots.

Therefore, the lower soil strength of the soil during the Ponsse S10 extraction's coupled with the lower measurements after extraction indicate that overall the Ponsse S10 forwarder had a lesser impact in Lissadell. This can be attributable to wider tyres / band tracks and/or fewer passes to extract the same amount of timber.

Plate No.9:(left)
Plot A after the
Ponsse S10 forwarder,
Band tracks & no brash.
Note visible tracks on
ground from wheels.

Plate No. 10:(right)
Plot B after the
Ponsse S10 forwarder,
Band tracks & brash.
No visible signs of
where the wheels
passed.

Plate No.11:(above)
Plot C after the
Ponsse S10 forwarder,
tyres and brash.
No evidence of the
loaded passes can be
seen.

Plate No. 12:(left)
Plot D after the
Ponsse S10 forwarder,
tyres and no brash.
Clearly visible tracks
from the wheels after 5
loaded passes.

Plate No. 13: The extraction route from the forest stand to the yarding area at the roadside. Despite the dry soil conditions rutting is evident on the route after 8 loaded passes with the Norcar 490. Band tracks where essential to achieve traction and maintain mobility especially after rainfall. The rut depth is approximately 5cm deep along the length of the track and soil berms are evident on the sides of the tracks as the soil is displaced.

6.4 The Number of Machine Passes Vs Compaction

Many researchers have found that the first number of passes have the greatest impact on the compaction of the soil. Migunga (1995), Rollerson (1990), and Wästerlund (1991), all found that there was a significant increase in soil bulk density with an increasing number of machine passes indicating that soil compaction results from multiple passes of forest machinery. They observed that the increase in bulk density was more significant after the first five passes.

A farm tractor caused an increase from 0.87 g/cm^3 to 1.16 g/cm^3 (33%) over it first passes, with the additional increase of 17% over the subsequent five passes. Similarly, an articulated skidder resulted in the bulk density increasing from 0.87 g/cm^3 to 1.53 g/cm^3 (88%) over five passes, compared to a further 3% rise over ten passes according to Migunga (1995).

Meeke (1994) found that penetration resistance increases rapidly over the first few passes, then subsequently begins to shows signs of stabilising for both sand and clay soils. This resistance increased progressively with increasing numbers of passes and lead to the prediction of a continuous improvement in the soil's resistance to the shearing forces from a moving wheel.

In terms of the number of passes affecting the formation of ruts, no significant ruts were formed in Lissadell from the Ponsse with only slight berms along the tyre tracks on the unbrashed tracks Plate No.12. The Norcar 480 displayed relatively significant formation of ruts with distinct berms of 10 to 15cm deep ruts at some points along extraction racks.

Only along the main extraction rack which was often subject to severe ponding did rutting occur on the Lissadell site. This ponding resulting from a combination of poor site drainage and traffic rutting adds to soil damage in the forest. When a machine subsequently passes along these ruts it pushes a soil slurry in front of the wheels down the extraction rack, resulting in further soil damage and sediment entering the site drains. A few hours of precipitation or a short heavy rain storm can turn a relatively dry, damage free site into a mud pool, often through which one could not even walk. In these situations each pass adding to the soil disturbance even when passing without a load.

In the trials on Lugnaskeehan (Ponsse S10) and Hollyford (Norcar 490), where machine traffic was kept to three four tonne passes for each forwarder, and no significant difference in soil moisture (50% and 47% respectively), the Ponsse S10 bulk density results are significantly better than the smaller Norcar 490 results.

At both Lugnaskeehan and Hollyford, rut formation and shearing of the ground occurred, a characteristic result of the plough furrow forest terrain. This was especially noticeable at any point where the machine wheel travelled down the furrow parallel to plough direction. (In this type of ploughed terrain, the number of passes is also problematic for operator stress and discomfort as well as soil damage).

Rut formation and soil displacement have been shown to the depend on the number of passes of the machine, although soil texture, clay and sand content and moistures also contribute according to MacDonald (1993). In Lissadell, no significant rutting occurred except some slight traces on the Norcar extraction racks to a depth of 10 to 15cm. On the wetter sites used (Hollyford and Lugnaskeehan) the Ponsse S10 forwarder would appear to have had a lesser impact for the given three loaded passes compared to the Norcar 490.

At the Hollyford site rutting occurred on the main extraction rack from the stand to the yarding area along the road. Plate No.13 shows the extraction route. This was a steep gradient climb, with the Norcar 490 labouring while carrying a payload of approximately 4 tonne. The photograph was taken after 8 loads had been transported to the road. On average the rut was only 5cm deep but significant berms formed which disturbed the young trees growing alongside the rack. After 12 loaded passes the ruts had deepened to approximately 6.5cm with no significant increase thereafter. This may reflect the courser textured gravel till subsoil that was found in this area. This was also noticed by Jakobsen & Greacen (1985) who recorded that the courser texture in sandy soils affected the formation of wheel ruts compared to finer textured clay soil as commonly found in agricultural land.

They state that the use of a lighter machine carrying a smaller load and mounted with smaller tyres, but maintaining the same ground pressure, would have only a limited effect on soil compaction. Their findings on sandy soils that a reduction in the total weight on one wheel by 50% would reduce the depth of the compaction zone by only 20%, but that the same compacted soil density would be achieved. Unfortunately, no method of measuring the ground pressure of the forwarders was available during the course of this project.

Another finding presented by Jakobsen & Greacen (1985) was that avoiding work in wet weather would not be a sufficient precaution to overcome compaction in the sandy soils, unlike on agricultural soil (usually with higher clay content), where avoiding work in wet conditions can be a very effective precaution against compaction.

For sandy soils a reduction in ground pressure and shear stress offer the most promising strategy. This is achieved by using wider tyres at low tyre inflation pressures.

This could explain the similar final bulk density values recorded in Lissadell with the sandy clay soil on the site. The zones of compaction may have differed, that is the depth to which compaction affected the soils, but samples taken in the topsoil layers would have compacted similarly. Measures of the soil compaction zones where not possible during this project.

6.5 Tyres Vs Band Tracks on Forest Soils

It is difficult to establish whether the tyres or band tracks are best at alleviating soil compaction from the different parameters used to measure soil compaction.

The soil bulk density and shear vane test results strongly suggest that the Ponsse S10 with band tracks have had the least impact on compaction in the extraction racks at Lissadell. Infiltration values indicate that the Ponsse S10 with tyres caused a lesser change while no difference is indicated by cone penetrometer measurements. The band tracks where noted to cause greater soil disturbance due to their more aggressive especially on unbrashed paths. This is evident from Plate No. 9. which shows how the band tracks disturbed the top 5cm of the soil.

However, the opposite is suggested from the Norcar 480 results. Tyres appear better from the bulk density, shear vane and infiltration monitoring while tracks are better with the cone penetrometer. The reason appears to be that ground conditions were good for forwarder operations during the Norcar 480 trials, and the use of band tracks was unnecessary. The Forestry Commission Report-8/91 says that correct use of band-tracks enables a forwarder to work effectively on a wide range of wetter site types by improving traction and flotation, and even stability. In contrast, in dryer soil conditions the band-tracks appears to result in more adverse affects than the tyres in term of soil compaction judging from both bulk density and shear strength measurements for the Norcar 480. The tracks did not dig or shift the topsoil but just compacted and compressed the soil surface. This was reflected in the increase in soil compaction after the Norcar band-track plots compared to the tyre plots.

Thus the use of band-tracks unnecessarily in dry conditions can result in soil damage. This combined with the added stresses and wear associated with the use of band-tracks on forwarders, requires that the use of band-tracks be dictated by ground conditions and site trafficability. Tracks will undoubtedly give forwarders increased mobility on sites that have poor trafficability, but their aggressive nature on the soil most always be considered.

The width of tyres or tracks is also important in terms soil compaction. The wider the wheel the greater the surface under the wheel and the less the ground pressure according to Mellgren's (1987) investigations. The Ponsse S10 had 600mm wide front tyres and 700mm on the rear compared to the Norcar's with 500mm all round. The trials at Lugnaskeehan and Hollyford would indicate that for the same number of passes the bigger forwarder appears to cause less compaction. Undoubtedly, this is an important factor in allowing bigger forwarders into the thinning operations provided that overall machine width is not a problem. However, wider tyres can cause occasional mobility (traction) problems especially on wet and/or sloped ground without the use of brash mats or where brash is sparse. This is the downside of a low ground pressure machine. The Ponsse S10 forwarder normally operated with chains on one pair of wheel on the trailer bogie. During the Lissadell trials when no chains were present on the tyres, the mobility of the forwarder was occasionally impeded by wet or slippery conditions with obstacles such as tree stumps.

The trials on the wetter furrowed Lugnaskeehan site display the benefits of the Ponsse's wide wheels (with band-tracks on trailer bogie only) in poorer soil conditions. The Hollyford site with the Norcar 490 forwarder and band-tracks (front & rear bogie) while not increasing the bulk density to a level that would limit growth appears to have a slightly greater affect on the soil by comparison.

Mellgren (1987) and the Swedish Forest Service have shown in trials that 800mm wide tyres improved mobility, increased load carrying capacity, higher travel speeds, increased lateral stability and lowered fuel consumption. They also achieved increased productivity on soft ground in addition to greater operation flexibility by continuing to work during wet periods of the year. This increased access to timber reserves further suggests that wider tyre may be very economical was well as soil "friendly".

Another interesting point raised by Mellgren was that their proposed forwarder was traction-steered, and that after 100 hours of tests was found to cause less ground damage than the Brunnett Mini 678 articulated forwarder having either single axles or double axles when making the same turn.

Most forwarders like the Ponsse S10 and the Norcar's 480 / 490 have automatic "No-spin" differentials which transfer all the torque to the inner wheels during turns. Consequentially, the inner wheels transmits all the traction until the forwarder moves or they start to slip. In fact, the one-sided traction on the inner wheels opposes the steering, which makes these machines harder to steer and causes additional ground pressures and hence damage.

During the course of this project, it was observed that the operator of the forwarder or harvester often used the articulated steering to assist when traction was poor, "wriggling" the machine by arcing from left to right and vice versa to gain ground. This resulted in much ground disturbance and soil damage by pushing soil sideways and increasing the width of the extraction path especially when it occurred in rutted racks. In many instances it was the only option for the operator to achieve the traction to advance the machine, but it was often tried first before the addition of brash to the forwarder path. This would probably still occur to some extend with a traction-steered machine, but operator training should emphasise that "wriggling" the machine should only be used as a last resort to achieving traction and on brashed ground only.

In summary, results from the Lissadell trials indicate that the resultant bulk densities after the Ponsse tyres and Norcar on tyres were relatively similar. The only difference being that the increase measured after the Ponsse with tyres was greater than for the Norcar with tyres. The Ponsse S10 and Norcar 480 / 490 trials with band-tracks show that the Ponsse had considerably less of an impact on soil bulk densities. These results indicate that in wetter soil conditions where band tracks are required, that fewer passes with a larger forwarder with wider wheel will have a lesser impact on soil compaction.

6.6 Brash Mat Use on Extraction Racks

During the Ponsse S10 trials it became obvious the brash mats had an important role in alleviating damage to the forest floor. Plates No. 10 & 11 illustrate the contribution by brash mats to soil protection on the extraction racks.

Plates No. 9 & 12 show the extraction rack used by the Ponsse S10 without brash. The track of the forwarder wheels is obvious on both extraction racks. In both cases where brash mats were used, no distinct marks were available to illustrate where the forwarder passed even after five loaded passes. The same was found on trials after the Norcar 480 and 490 trials, where only slight tracks were noticeable on the crushed brash mat due to the dry wilted brash and the increased number of passes.

The brash in Hollyford appeared to be particularly effective at preventing soil damage and compaction. This may be attributable to the fact that harvesting was performed manually, producing longer and larger tops for brashing. This seemed to produce a larger volume and stronger brash mat under the forwarder. In contrast, the brash at Lissadell and Lugnaskeehan were harvester cut, and the harvester operator(same on both sites) always gave the 'top' an extra cut to shorten it. Another observation made was, the fresher the foliage on the brash when the forwarder is working the lesser the impact on the brash mat and the more passes can be made before the mat integrity was destroyed.

Therefore, it would appear that soil disturbance is significantly reduced and site trafficability enhanced by the presence and use of brash mats on extraction racks during thinning operations. During the trials the presence or absence of brash greatly affected the mobility of both the harvester and forwarder, when lack of brash material often prevented either the harvester or forwarder from advancing up a gradient until the operator placed brash in the machine path. This was especially true of the wider wheeled Ponsse S10 (without chains or tracks) when entering the stand unladen. Where this is a problem chains and brash mats are utilised to maintain mobility the gradients. While wider tyres may reduce ground pressures and reduce soil damage, it can also reduce traction on slippery ground. Brash is then even more important and especially in areas where chains are used as traction aids.

The results indicate the benefit of the use of brash on the extraction racks to reduce the impact of forwarders on soil damage and compaction. This reflects findings by other researchers such as Froehlich (1978) and Wästerlund (1987) that the use of logging slash or brash may act as a buffer and reduce compaction.

All the parameters measured reflect that brash, with tyres or tracks, harvester or forwarder, reduced the impact on the soil on the extraction rack.

The cone penetration results although inconclusive, are significant enough to warrant further investigation. The results indicate that brash may reduce compaction at depth in the soil profile, while also protecting the integrity of the trees roots from the passing forwarders on the ground surface (Fig 5.3.3 to 5.3.5).

Donnelly & Shane (1986) found that the application of bark mulch to the soil surface prior to soil compaction was effective in reducing increases in bulk density. Densities in plots with this treatment were not significantly different from the control plot in the 0-5cm measurements, although slightly higher at 5-15cm depths. Densities were still significantly lower than plots with compaction but without mulch, and compaction followed by mulching plots at all depths.

Key brash roads must be carefully planned and the most suitable machine, usually the harvester, should be used to create them according to Forestry Commission Report-35/91. In early thinnings of young stands abundant branches accumulate to form a soil and root protecting mattress for the harvester and fowarder will drive on. In later thinnings when less trees are removed, usually the amount of slash is too small for a continuous mattress. Even with the best of planning and upkeep key routes will eventually degenerate through wear and tear. Ruts will form, together with ponding in low lying areas.

Some damage on long hauls is inevitable, especially where brash supplies are exhausted and a limited choice of key routes exist. Chains and aggressive band tracks are likely to destroy brash mats quicker than tyres. Flotation tracks may reduce the time needed for patching because they tend to bridge weak spots, and will often prevent bogging on the worst sites according to Forestry Commission Report 35/91.

6.7 Nutrient Analysis

Very little research has been undertaken into the affects of soil compaction on the soil nutrients and the availability of these nutrients to the trees. While some changes in the soil chemistry were recorded, the impact or significance of such changes is very unclear. The concept of the principle of the 'limiting factor' is important to nutrient elements in forest according to Curlin (1974). This means that the level of crop production can be no greater than that allowed by the most limiting of essential tree nutrients. Not only is the supply of a given element important, but also the relationship of this supply to all other factors which may affect tree growth. Curlin (1974) states that macro nutrients such as nitrogen, phosphorus, and potassium are primary elements and are required in relatively large amounts for growth. Growth may be retarded because these elements are lacking in the soil, or become available too slowly, or even because they are not balanced by other nutrients.

Therefore, reductions in the levels of potassium and phosphorus as measured in Lissadell, may in theory have a significant effect on the overall nutrient supply in the soil in trial extraction racks. The slight increase in nitrogen or organic matter measured may not be of any benefit to growth as it is limited by the other elements. However in practice, the extent of this effect (if any) may be quite small because of;

1. The relatively small area affected in the extraction rack, and
2. The duration of this reduction in potassium and phosphorus.

Both total nitrogen and nitrate increased on the extraction racks by 0.2ppm each. Nitrogen deficiency in the wheel tracks on the extraction rack is one of the effects of the displacement of the organic layers according to Miller (1987). However losses were only recorded on two and three of the eight extraction racks for nitrate and total nitrogen respectively in Lissadell.

Soils of reasonable mineral content will release cations due to weathering which exceed the rate of uptake by the tree roots and the soil base will recover to pre-thinning levels according to Miller (1987). The problem arises with poorer soils which will result in the nutrient deficiency for longer periods. Curlin (1974) suggests that nitrogen and phosphorus are almost always present in comparatively small amounts in mineral soils and a large proportion of these elements are held in combinations unavailable to plants.

The problem is more serious where the thinning operations may have damaged the soil by reducing infiltration rates as measured in Lissadell and/or if deep rutting has caused water to flow down the extraction rack which will lead to soil erosion or nutrient leaching on a continuing basis. This will depend on a wide variety of factors including soil characteristics, site characteristics, rainfall events, depth and orientation of rutting tracks and the extend of the soil damage around the site.

The uptake of nutrients by plants is determined not only by the availability of soil held nutrients but by the supply of these nutrients to the plant root surfaces and by the nutrient absorption rates at these surfaces. Root interception, where the root hairs come into direct contact with soil colloids is the first type. Mass flow, occurs where nutrients move along with water which the plant absorbs for normal growth. Diffusion, where nutrients are absorbed by the roots due to a concentration gradient between immediate soil and the internal structure of the root .

If the increase in soil shear strength and/or bulk density is high enough, root penetration into the soil will be restricted and uptake decrease. These physical affects of soil compaction could possibly be more influential on the nutrient adsorption ability of the tree rather than any direct chemical changes to the soil.

More research over a longer period of time with more periodic sampling would be required before conclusions that direct soil compaction and related nutrient changes exist.

6.8 Soil Microbial Activity

Little direction from the literature on the soil compaction and microbial relationship was found. This meant that the time frame for microbial sampling on the extraction racks was uncertain and somewhat innovative.

The samples were taken six weeks after the forwarders travelled the extraction racks. This period it was felt, provided sufficient time for changes in microbial activity to occur in response to the traffic and soil compaction effects to have an affect.

The increase in bulk density that is evident on the extraction racks may have enhanced microbial activity by increasing micropore space and reducing the macropore space in the soil as discussed by Sands & Greacen (1980). This may also increase the total surface area available to microbes in the soil.

There was also an increase in the levels of soil organic matter following soil traffic and the mixing of the surface litter layer into the topsoil. There was significantly more fresh leaf litter on the extraction racks following thinning due the delimbing actions of the harvester. Any traffic travelling the extraction rack would help towards incorporating this litter into the soil microbial activity zones in the soil.

Soil microbial activity will also affect soil nutrients according to Curlin (1974). Most of the nitrogen in the soil utilised by higher plants is absorbed in the ammonium and nitrate forms. This involves two oxidation stages changes called nitrification and are the result of a specialised bacterial - the nitrifying bacteria. The Lissadell results show a slight increase in these nitrifiers was found in the extraction racks after the machine passes. These organisms are sensitive to changes in conditions such as temperature, soil water, pH and soil air. The literature in Chapter 2 shows that soil compaction affects these parameters and thus indirectly the microbial populations.

When organic matter containing a large amount of carbon compared to nitrogen is added to a soil, the above processes may be reversed temporarily. The soil microorganisms, having large amounts of energy producing materials at their disposal, multiply rapidly and use the nitrogen themselves, thus interfering with the appearance of ammonium and nitrate.

Microorganisms readily appropriate simple and soluble phosphorus compounds and build them into complex organic forms which liberate their phosphorus very reluctantly and are not available to higher plants. The organisms are then competing directly with the higher plants for available soil nutrients according to Curlin (1974).

Shifts in the balances due to soil disturbance and soil compaction may not only affect tree growth directly through physical and chemical means, but even at microbiological levels.

Curlin (1974) also suggests that the microbes play significant roles in the nutrient cycling within the forest ecosystem. Therefore any changes in the soil environment affecting the level of nutrients will be intrinsically linked to the microbial populations.

7.0 Recommendations for Further Research

- Further investigation into the manner in which brash mats are constructed by the harvester operator should be addressed. Should the 'lop and top' be placed lengthways or transversely on the extraction rack? Should the operators leave the tops longer or continue cutting it in two shorter lengths? It was observed during this project that the longer lop and top from the manual felling in Hollyford, appeared to produce a greater bulked brash mat for the forwarder to travel on.

- The possibility of reducing the number of thinning operations in the forest life cycle should be investigated, with the view to minimising the impact on the soil and avoiding problems of insufficient brash in second or subsequent thinnings. There may be a role for forwarders with wider (800mm or more) wheels which would specialise (which have more operational and manoeuvring space) on subsequent thinnings. The wider wheels may help compensate for the lesser availability of brash. The success of this would depend on the degree of damage already inflicted on the stand from previous thinning operations..

- A method of assessing potential available brash before thinning commences with a view to planning the time of year or even weather conditions in which the site is suitable for thinning should be explored. When selecting sites for thinning operations on mineral soils, sites that have 'adequate' reserves of potential brash, notably first thinning sites, may be left until the winter months. This would allow the mineral soil sites with lesser amounts of potential brash to be thinned during the summer when soil and weather conditions are better.

- The brashing of fire lines may be a worthwhile exercise for supplying extra brash and simultaneously maintaining the fire break. Edge tree growth along the fire lines is usually greater and is a readily assessable area for the forwarder to retrieve the brash. This will also help to re-establish the fire break which is often grown closed.

- A 'Site Vulnerability Index' which would indicate the vulnerability of a stand to soil damage should be developed. This would involve a formal assessment of the site features including soil characteristics, condition of site drainage system, gradient of slopes, distance of extraction racks required and other characteristics relating to soil damage and compaction. From this information the optimum method of thinning operations could be planned and the optimum extraction forwarder for the site. Any special provisions required for the site could be organised such as bunding, log bridges, drain maintenance or the cutting of extra brash.

- The use of longer reach craned harvestors should be investigated to help reduce soil compaction by, a) having less racks in the stand or, b) providing more brash on each extraction rack? Would the benefit be overshadowed by the increased loads for extraction in the racks and hence increased traffic and loaded passes? Would increased weight of the harvester required to carry a long reach crane cause compaction problems?

- The potential for the smaller forwarder (E.g. Norcar 490) if modified with 700 or even 800 mm wide tyres could be explored. This may be of benefit to the operators of many existing forwarders of this size and specification.

- Planning for thinning operation should be incorporated into the planting process with the view to designing a more suitable extraction route for extraction of thinnings. This planning could take into consideration the site drainage and the strategic placement of drains on site to facilitate and compliment extraction and help reduce the number of drains to be crossed by an extracting forwarder or harvester.

- The ground pressure rating of the forwarders should also be determined in any future studies. Then the direct effects of different types of forwarder could be related to the number of passes and load carried.

8.0 CONCLUSION

Harvesting of first thinnings is necessary to improve timber yields in the forests. It appears that the level of mechanisation is crucial to determine a positive economic result by enabling foresters to perform efficient thinning operations. However, the actual mechanisation does not achieve these set objectives because of the increased environmental concerns according to Bouvarel (1994). Managing to limit soil compaction to a biologically tolerable level by careful operational procedures and suitable machine design can lead to a better prospect for improved tree yields. Bouvarel and others suggest that forestry can afford a desired network of logging trails, that allow mechanical felling with harvesters and forwarder transportation. Machine design should be strong, not too heavy and contact pressure on soil is an important issue. A balance between weight, width and boom range of harvesters is essential according to Duffner (1994).

When considering wheeled machines, soil compaction is reduced by lowering tyre inflation pressure and increasing tyre widths. Wider tyres increased access to wet sites, with some lack of manoeuvrability, but also increased site disturbance. The disturbance can be reduced by confining the machinery traffic to designated trails, thereby reducing the area of compacted soil. The largest increment in bulk densities and rut formation tended to occur after the first pass, especially on dryer soils. Furthermore, increasing tyre size, either in width or diameter decreases motion resistance according to Stokes et al (1994).

Bulk density is the best parameter to indicate and measure the degree of soil compaction in the forestry. Limits can be set to control increases in soil bulk density and quickly highlight problems areas.
Cone penetrometer studies could also be used as it illustrates the depth of the compaction in the soil profile, although this will take longer and involve the use of specialised equipment.

The extent of soil compaction caused by the harvester is not significant in comparison to the forwarders. All forwarders cause soil compaction but this can be significantly reduced in a number of ways:

1. Use brash mats to their full potential in all sites. In areas where brash may be scarce careful planning of work is required.

2. Careful use of traction aids such as band tracks and chains especially when conditions dictate will reduce soil damage. Remove these aids when soil conditions improves again.
3. On wetter sites the wider the wheels of the forwarder the lesser the damage caused.
4. On mineral soils, the bigger payload with fewer passes is more desirable in terms of soil compaction.

Brash mats have important role in protecting the soil from compactive forces, but also in protecting the root mat layer of the remaining trees from the loads of the passing forwarders.

Forwarders with wider wheels and reduced ground pressures will also require brash to aid mobility especially on slopes and slippery ground conditions.

Soil nutrients do not appear to be directly affected by increases in soil compaction. However, the factors that influence the uptake rate of nutrients especially on poorer site are of greater concern. Root damage, reduced water infiltration and soil rutting due to machines will all affect the uptake of nutrients by the trees.

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Table A.1 Bulk Density Values for Control Plots at Lissadell

Plot	Sample	Weigh (Dry)	Bulk Density (W/100)	Average
I	1	68.8	0.69	
	2	74.9	0.75	
	3	76.9	0.77	
	4	89.6	0.90	
	5	82.8	0.83	
	6	83.5	0.84	
	7	86.2	0.86	
	8	80.1	0.80	0.8035
J	9	88.4	0.88	
	10	82.4	0.82	
	11	96.8	0.97	
	12	83.7	0.84	
	13	84.4	0.84	
	14	91.3	0.91	
	15	90.2	0.90	
	16	97.6	0.98	
	17	85.5	0.86	
	18	76.7	0.77	0.877
A	1	76.6	0.77	
	2	81.3	0.81	
	3	98.1	0.98	
	4	79	0.79	
	5	88.8	0.89	0.8476
B	6	101.5	1.02	
	7	81.8	0.82	
	8	83.7	0.84	
	9	89.9	0.90	
	10	91.9	0.92	0.8976
C	1	98	0.98	
	2	88	0.88	
	3	78.9	0.79	
	4	70.4	0.70	
	5	81.6	0.82	0.8338
D	6	80.7	0.81	
	7	95.4	0.95	
	8	88.3	0.88	
	9	71.3	0.71	
	10	59	0.59	0.7894
E	1	103.3	1.03	
	2	79.5	0.80	
	3	76.8	0.77	
	4	83	0.83	
	5	97.9	0.98	0.881
F	6	85.5	0.86	
	7	97.7	0.98	
	8	102	1.02	
	9	94	0.94	
	10	82.4	0.82	0.9232
G	11	92.4	0.92	
	12	80	0.80	
	13	95.8	0.96	
	14	87.2	0.87	
	15	92.5	0.93	0.8958
H	1	78.1	0.78	
	2	91.1	0.91	
	3	84.3	0.84	
	4	101.9	1.02	
	5	79.3	0.79	0.8694

Table A.2 Bulk Density Values for the Extraction Racks at Lissadell

Plot	Sample	Weigh (Dry)	Bulk Density (W/100)	Average
I	1	76	0.76	
	2	86.4	0.86	
	3	63.5	0.64	
	4	88	0.88	
	5	86.2	0.86	
	6	81.5	0.82	
	7	86.7	0.87	
	8	81.1	0.81	0.812
J	1	96.7	0.97	
	2	88.6	0.89	
	3	82.2	0.82	
	4	82.9	0.83	
	5	88.8	0.89	
	6	101.1	1.01	
	7	74.5	0.75	
	8	82	0.82	0.871
A	1	93.1	0.93	
	2	86.8	0.87	
	3	87.3	0.87	
	4	96.1	0.96	
	5	91.6	0.92	
	6	100.3	1.00	
	7	102.8	1.03	0.940
B	1	103.2	1.03	
	2	89.9	0.90	
	3	97.2	0.97	
	4	97.8	0.98	
	5	96.1	0.96	
	6	103.2	1.03	0.979
C	1	105.6	1.06	
	2	84.4	0.84	
	3	104.4	1.04	
	4	108.5	1.09	
	5	116.9	1.17	
	6	107.6	1.08	1.046
D	1	101.8	1.02	
	2	98.6	0.99	
	3	105	1.05	
	4	103	1.03	
	5	115.9	1.16	
	6	94.2	0.94	1.031
E	1	98.28	0.98	
	2	127.8	1.28	
	3	107.33	1.07	
	4	111.33	1.11	
	5	111.63	1.12	
	6	104.08	1.04	1.101
F	1	97.62	0.98	
	2	105.95	1.06	
	3	113.97	1.14	
	4	123	1.23	
	5	116.17	1.16	
	6	108.64	1.09	1.109
G	1	100.95	1.01	
	2	97.28	0.97	
	3	111.12	1.11	
	4	97.1	0.97	
	5	117.12	1.17	
	6	86.02	0.86	
	7	102.45	1.02	
	8	104.14	1.04	1.020

Table A.2 Bulk Density Values for the Extraction Racks at Lissadell (con't)

Plot	Sample	Weigh (Dry)	Bulk Density (W/100)	Average
H	1	100.47	1.00	
	2	86.93	0.87	
	3	102.43	1.02	
	4	97.74	0.98	
	5	111.85	1.12	
	6	117.81	1.18	
	7	110.93	1.11	
	8	114.3	1.14	1.053

Table A.3 Bulk Density Values for the Plots at Lugnaskeehan

Plot	Sample	Weigh (Dry)	Bulk Density (W/100)	Average
K	1	45.886	0.46	
	2	15.413	0.15	
	3	36.231	0.36	
	4	21.731	0.22	
	5	37.241	0.37	
	6	49.873	0.50	
	7	32.143	0.32	
	8	51.933	0.52	0.363
L	1	38.912	0.39	
	2	19.0496	0.19	
	3	20.981	0.21	
	4	34.1351	0.34	
	5	46.5753	0.47	
	6	48.258	0.48	
	7	58.5431	0.59	
	8	43.1248	0.43	0.387
Control for K & L	1	44.91081	0.45	
	2	8.2944	0.08	
	3	32.684	0.33	
	4	56.2563	0.56	
	5	41.6227	0.42	
	6	12.552	0.13	
	7	28.961	0.29	
	8	43.7515	0.44	0.336

Table A.4 Bulk Density Values for the Plots at Hollyford

Plot	Sample	Weigh (Dry)	Bulk Density (W/100)	Average
Control for M & N	1	61.579	0.62	
	2	112.681	1.13	
	3	33.255	0.33	
	4	47.164	0.47	
	5	66.967	0.67	
	6	50.727	0.51	
	7	46.484	0.46	
	8	65.432	0.65	0.61
M	1	94.877	0.95	
	2	43.165	0.43	
	3	69.013	0.69	
	4	62.972	0.63	
	5	59.194	0.59	
	6	81.647	0.82	
	7	62.358	0.62	0.68
N	1	65.631	0.66	
	2	92.601	0.93	
	3	92.124	0.92	
	4	77.138	0.77	
	5	124.350	1.24	
	6	133.452	1.33	
	7	54.539	0.55	
	8	110.982	1.11	0.94

Table A.5 Shear Vane Results for Lissadell Plots

Plot A		Plot B		Plot C		Plot D		Plot E	
Control	Ext. Rack	Control	Ext. Rack	Control	Ext. Rack	Control	Ext. Rack	Control	Ext. Rack
54	92	112	74	52	96	62	132	124	264
84	96	92	110	94	98	92	80	184	160
82	124	44	100	70	92	68	78	136	156
104	100	104	82	78	78	84	116	168	232
60	104	44	92	70	60	62	84	124	168
96	100	66	102	56	126	84	94	168	188
106	120	50	118	66	72	80	78	160	156
58	114	62	74	64	78	74	130	148	260
74	106	62	72	66	98	54	80	108	160
74	58	66	110	38	82	90	78	180	156
64	84	66	80	70	112	72	84	144	168
56	80	68	80	78	84	80	62	160	124
90	122	62	58	72	62	90	70	180	140
44	80	68	80	62	54	40	52	80	104
86	70	78	52	52	110	20	88	40	176
86	94	48	80	28	62	76	70	152	140
78	76	34	100	110	64	102	72	204	144
72	104	48	82	62	88	72	40	144	80
80	62	60	60	32	84	74	48	148	96
92	122	110	94	34	72	80	50	160	100
74	60	54	86	62	70	30	42	60	84
76	70	72	92	44	75	82	90	164	180
80	50	76	54	80	64	76	62	152	124
44	48	76	76	54	52	104	84	208	168
80	92	78	94	84	94	62	88	124	176
78	140	74	108	76	66	60	142	120	284
82	88	68	64	75	102	76	100	152	200
84	124	68	74	82	88	90	110	180	220
72	98	96	58	68	70	70	116	140	232
74	78	76	46	48	88	64	126	128	252
48	110	76	118	76	86	106	148	212	296
110	112	84	100	100	66	82	150	164	300
			96		122		114	0	
			108		88		126	0	
			86		76		118	0	
			76		80		130	0	
					91				

Table A.5 Shear Vane Results for Lissadell Plots (con't)

Plot F		Plot G		Plot H		Plot I		Plot J	
Control	Ext. Rack	Control	Ext. Rack	Control	Ext. Rack	Control	Ext. Rack	Control	Ext. Rack
160	160	320	320	640	640	64	134	64	102
68	128	136	256	272	512	82	106	82	62
152	236	304	472	608	944	122	103	122	74
76	116	152	232	304	464	92	82	92	114
60	120	120	240	240	480	68	109	68	98
84	144	168	288	336	576	86	88	86	76
72	280	144	560	288	1120	64	84	64	92
80	204	160	408	320	816	109	108	109	78
128	228	256	456	512	912	102	100	102	90
120	220	240	440	480	880	80	88	80	114
144	224	288	448	576	896	80	124	80	76
48	252	96	504	192	1008	108	97	108	74
60	184	120	368	240	736	62	104	62	92
44	232	88	464	176	928	80	120	80	62
96	192	192	384	384	768	60	108	60	116
44	216	88	432	176	864	98	103	98	76
52	80	104	160	208	320	90	66	90	88
84	88	168	176	336	352	100	67	100	120
76	92	152	184	304	368	85	92	85	72
80	100	160	200	320	400	53	86	53	98
132	240	264	480	528	960	64	71	64	98
140	180	280	360	560	720	64	92	64	94
124	88	248	176	496	352	52	108	52	86
96	184	192	368	384	736	90	66	90	120
112	140	224	280	448	560	78	64	78	128
112	164	224	328	448	656	98	102	98	88
88	136	176	272	352	544	76	92	76	102
132	156	264	312	528	624	92	94	92	86
100	120	200	240	400	480	84	102	84	114
80	136	160	272	320	544	76	94	76	90
112	108	224	216	448	432	86	104	86	86
112	112	224	224	448	448	100	106	100	102
40		80							
148		296							
204		408							
136		272							

Table A.6 Shear Vane Results for Lugnaskeehan(K&L) & Hollyford(M&N) Plots

Plot K		Plot L		Plot M		Plot N	
Control	Ext. Rack	Control	Ext. Rack	Control	Ext. Rack	Control	Ext. Rack
70	80	70	70	68	52	68	63
36	42	36	38	48	42	48	62
68	48	68	58	40	54	40	46
44	58	44	42	58	58	58	38
58	68	58	66	36	90	36	54
42	56	42	50	30	78	30	60
30	56	30	40	46	64	46	44
32	40	32	48	60	78	60	90
36	40	36	70	52	58	52	60
48	44	48	96	50	44	50	98
58	74	58	94	30	38	30	64
54	46	54	64	30	74	30	80
68	80	68	76	56	76	56	30
24	82	24	48	46	34	46	36
44	46	44	60	28	56	28	50
26	40	26	32	60	56	60	90
62	106	62	70	44	52	44	72
54	44	54	30	34	58	34	78
52	58	52	48	36	84	36	80
60	46	60	46	62	76	62	66
45	62	45	24	72	80	72	104
52	54	52	74	54	44	54	44
100	78	100	60	50	84	50	30
20	90	20	75	52	80	52	20
22	136	22	54	28	48	28	28
34	78	34	46	30	52	30	40
36	24	36	60	48	38	48	56
26	26	26	26	64	40	64	54
80	40	80	50	26	56	26	24
60	32	60	48	34	36	34	44
44	36	44	32	46	38	46	48
25	24	25	26	70	60	70	56
				54		54	70
				52		52	
				48		48	
				60		60	
				28		28	
				35		35	
				40		40	
				42		42	

Table A.7 Cone Penetrometer Measurements(Kg f) for Plot A in Lissadell

Depth	Sample 1						Sample 2					
Level	1	2	3	4	5	**Mean**	1	2	3	4	5	Mean
1	3	3	2	2	3	**3**	1	3	1	22	44	**14**
2	11	6	4	5	7	**7**	5	4	6	33	48	**19**
3	12	20	10	3	10	**11**	9	8	8	7	5	**7**
4	15	23	19	19	16	**18**	10	15	26	9	9	**14**
5	18	22	27	23	19	**22**	17	22	30	13	15	**19**
6	25	23	24	25	25	**24**	20	28	44	16	20	**26**
7	26	22	22	29	29	**26**	26	34	40	38	27	**33**
8	26	34	25	50	33	**34**	29	45	50	35	24	**37**
9	24	36	26	50	35	**34**	31	37	50	33	28	**36**
10	19	30	26	50	37	**32**	30	42	44	29	1	**29**
11	26	39	33	50	34	**36**	29	37	48	27	30	**34**
12	27	50	28	50	50	**41**	30	41	61	28	30	**38**
13	34	50	35	50	50	**44**	30	34	50	28	36	**36**
14	50	50	50	50	50	**50**	50	45	50	25	38	**42**
15	50	50	50	50	50	**50**	50	44	50	26	41	**42**

Depth	Sample 3						Sample 4					
Level	1	2	3	4	5	**Mean**	1	2	3	4	5	Mean
1	0	0	1	0	1	**0**	1	3	1	1	3	**2**
2	2	1	3	1	14	**4**	4	11	10	17	6	**10**
3	4	5	5	4	14	**6**	9	4	15	10	8	**9**
4	9	9	11	6	18	**11**	16	12	17	9	13	**13**
5	10	15	14	9	12	**12**	20	27	23	13	15	**20**
6	14	0	15	10	14	**11**	46	49	26	16	17	**31**
7	17	15	18	11	22	**17**	31	41	27	27	22	**30**
8	18	34	19	13	1	**17**	32	34	26	29	25	**29**
9	20	34	27	15	28	**25**	45	35	27	30	32	**34**
10	1	35	27	15	26	**21**	50	32	39	31	50	**40**
11	21	27	29	18	29	**25**	50	34	30	32	44	**38**
12	24	31	39	50	29	**35**	50	39	34	36	50	**42**
13	27	36	49	50	39	**40**	50	40	39	50	50	**46**
14	50	50	50	50	50	**50**	50	40	50	50	50	**48**
15	50	50	50	50	50	**50**	50	46	50	50	50	**49**

Depth	Sample 5						Sample 6					
Level	1	2	3	4	5	**Mean**	1	2	3	4	5	Mean
1	23	2	0	0	35	**12**	1	2	31	2	31	**13**
2	26	1	2	3	35	**13**	45	3	34	4	29	**23**
3	7	5	17	14	43	**17**	3	5	49	6	30	**19**
4	13	8	14	17	6	**12**	3	8	5	12	30	**12**
5	17	9	15	24	8	**15**	5	11	10	12	29	**13**
6	17	11	16	19	10	**15**	10	13	10	13	16	**12**
7	29	15	16	50	12	**24**	12	15	11	17	24	**16**
8	35	14	20	44	14	**25**	2	20	11	18	28	**16**
9	46	15	18	38	15	**26**	18	22	18	18	50	**25**
10	43	16	20	40	16	**27**	15	18	20	19	50	**24**
11	1	50	20	40	22	**27**	19	18	22	20	40	**24**
12	26	50	19	44	1	**28**	21	20	26	21	47	**27**
13	28	50	20	45	27	**34**	23	20	28	45	34	**30**
14	26	50	31	46	28	**36**	26	33	28	1	46	**27**
15	25	50	50	2	26	**31**	32	47	32	37	31	**36**

Table A.8 Cone Penetration Control Measurements (Kg f) for Plots A & B

Depth Level	Sample 1					Mean	Sample 2					Mean
	1	2	3	4	5		1	2	3	4	5	
1	24	18	0	2	40	**17**	26	32	2	32	0	**18**
2	27	4	4	3	7	**9**	37	35	6	33	2	**23**
3	5	9	1	5	10	**6**	36	37	1	8	6	**18**
4	6	14	7	9	11	**9**	16	38	15	10	12	**18**
5	9	14	8	13	14	**12**	20	18	17	10	14	**16**
6	10	14	8	0	19	**10**	24	25	30	12	15	**21**
7	11	17	16	14	25	**17**	19	34	20	14	16	**21**
8	14	16	15	14	26	**17**	25	30	18	14	14	**20**
9	14	19	14	18	27	**18**	29	34	18	17	17	**23**
10	13	22	17	23	26	**20**	32	35	24	21	20	**26**
11	15	22	20	34	32	**25**	35	39	21	19	20	**27**
12	17	22	22	44	34	**28**	36	33	23	18	21	**26**
13	18	17	23	41	45	**29**	2	33	26	18	30	**22**
14	18	31	24	50	50	**35**	44	40	27	21	37	**34**
15	21	50	22	50	50	**39**	49	40	21	25	31	**33**

Depth Level	Sample 3					Mean	Sample 4					Mean
	1	2	3	4	5		1	2	3	4	5	
1	1	0	1	1	2	**1**	1	1	1	1	33	**7**
2	4	2	4	0	8	**4**	6	4	7	4	39	**12**
3	9	4	7	8	39	**13**	13	12	9	7	10	**10**
4	18	5	11	12	39	**17**	17	14	15	9	9	**13**
5	17	8	27	16	24	**18**	18	12	15	12	9	**13**
6	17	15	42	21	22	**23**	17	20	40	14	8	**20**
7	19	15	37	27	28	**25**	25	30	44	17	16	**26**
8	20	16	27	43	33	**28**	20	33	27	19	20	**24**
9	24	1	43	30	25	**26**	21	30	28	31	26	**27**
10	30	14	45	50	35	**35**	25	21	29	50	34	**32**
11	32	13	50	50	37	**36**	26	25	30	50	33	**33**
12	28	15	50	50	29	**34**	28	43	42	30	29	**34**
13	1	19	50	50	2	**24**	38	50	34	38	31	**38**
14	42	49	50	50	31	**44**	50	50	50	37	30	**43**
15	50	50	50	50	29	**46**	50	50	50	33	29	**42**

Depth Level	Sample 5					Mean	Sample 6					Mean
	1	2	3	4	5		1	2	3	4	5	
1	42	40	37	1	38	**32**	1	17	27	1	44	**18**
2	33	36	2	3	37	**22**	6	16	22	2	50	**19**
3	33	32	6	7	33	**22**	5	16	18	6	17	**12**
4	33	34	11	12	27	**23**	8	20	23	13	21	**17**
5	33	39	20	18	22	**26**	9	25	31	22	17	**21**
6	12	1	19	19	1	**10**	8	22	30	33	17	**22**
7	11	13	19	20	17	**16**	12	10	15	47	15	**20**
8	14	40	23	23	20	**24**	18	8	16	31	2	**15**
9	13	33	28	30	29	**27**	19	9	24	22	13	**17**
10	17	43	30	38	33	**32**	22	13	25	21	15	**19**
11	20	38	64	50	32	**41**	23	14	26	20	15	**20**
12	23	37	45	50	36	**38**	22	38	24	23	19	**25**
13	22	36	41	50	40	**38**	29	31	25	18	34	**27**
14	26	38	34	50	41	**38**	25	29	25	19	33	**26**
15	26	39	35	50	43	**39**	43	20	24	26	44	**31**

Table A.9 Cone Penetrometer Measurements (Kg f) for Plot B

Depth Level	Sample 1					Mean	Sample 2					Mean
	1	2	3	4	5		1	2	3	4	5	
1	1	49	2	14	6	14	1	1	1	17	2	4
2	9	9	7	14	8	9	2	2	7	22	6	8
3	13	11	14	8	12	12	8	7	7	38	8	14
4	14	16	14	7	10	12	17	11	13	7	9	11
5	15	16	19	16	15	16	15	14	17	11	10	13
6	15	18	19	26	20	20	19	27	18	14	13	18
7	17	20	19	17	18	18	33	25	25	20	19	24
8	17	21	21	11	16	17	28	23	25	25	15	23
9	20	21	24	11	16	18	29	26	25	25	18	25
10	18	23	29	15	23	22	34	30	31	24	50	34
11	33	36	49	14	30	32	50	32	31	30	50	39
12	41	34	50	16	48	38	50	36	38	31	50	41
13	30	49	16	21	30	29	50	35	40	1	50	35
14	34	48	50	23	38	39	50	36	38	20	50	39
15	34	50	50	21	50	41	50	42	50	14	50	41

Depth Level	Sample 3					Mean	Sample 4					Mean
	1	2	3	4	5		1	2	3	4	5	
1	1	2	37	34	1	15	1	15	1	40	22	16
2	2	6	37	35	2	16	10	14	1	48	0	15
3	7	8	37	39	5	19	13	9	7	14	6	10
4	9	11	38	30	8	19	13	14	13	20	7	13
5	11	18	37	30	20	23	17	29	19	27	10	20
6	13	23	35	30	18	24	20	21	24	28	11	21
7	16	31	23	18	19	21	30	22	23	28	2	21
8	24	1	28	18	19	18	36	22	31	36	14	28
9	27	30	29	20	22	26	31	23	32	32	21	28
10	28	37	31	21	50	33	34	27	34	34	26	31
11	34	50	31	21	37	35	34	27	39	35	18	31
12	38	50	1	23	2	23	30	27	42	37	16	30
13	35	50	37	43	34	40	37	35	50	36	18	35
14	42	50	37	50	35	43	33	39	50	35	16	35
15	50	50	40	36	43	44	37	31	50	40	17	35

Depth Level	Sample 5					Mean	Sample 6					Mean
	1	2	3	4	5		1	2	3	4	5	
1	33	1	2	22	50	22	50	0	0	32	24	21
2	1	5	9	24	16	11	1	4	1	36	26	14
3	10	12	14	28	16	16	14	15	15	43	29	23
4	9	11	11	28	14	15	17	15	19	9	28	18
5	11	14	19	11	12	13	20	30	19	10	34	23
6	40	18	15	20	17	22	21	26	36	14	13	22
7	30	19	20	19	18	21	22	33	32	24	19	26
8	27	0	21	16	22	17	21	1	50	28	19	24
9	29	27	1	16	26	20	21	37	44	23	19	29
10	35	35	26	16	25	27	24	42	2	24	20	22
11	33	31	24	21	25	27	24	36	43	24	24	30
12	30	50	39	21	25	33	34	41	47	33	30	37
13	27	50	32	18	25	30	45	40	50	50	24	42
14	25	46	27	22	38	32	50	38	50	32	24	39
15	22	11	50	32	34	30	50	50	50	31	24	41

Table A. 10 Cone Penetration Measurement (Kg f) for Plot C

Depth Level	Sample 1					Mean	Sample 2					Mean
	1	2	3	4	5		1	2	3	4	5	
1	2	33	25	24	2	17	23	41	34	28	24	30
2	1	30	24	24	5	17	2	0	39	35	30	21
3	18	6	25	29	11	18	27	7	32	4	23	19
4	40	9	27	31	10	23	25	9	42	5	22	21
5	50	11	28	25	17	26	24	12	21	9	27	19
6	32	15	26	24	19	23	28	14	10	12	10	15
7	36	21	15	26	17	23	24	15	21	22	13	19
8	47	25	2	38	20	26	23	20	27	22	13	21
9	50	23	20	41	19	31	26	26	20	20	15	21
10	50	45	19	38	23	35	27	35	26	24	17	26
11	50	50	18	38	28	37	28	21	27	24	19	24
12	50	35	19	28	26	32	28	42	22	31	26	30
13	50	37	21	26	25	32	26	39	21	39	20	29
14	50	37	20	25	50	36	22	37	21	29	22	26
15	50	38	22	26	50	37	22	38	20	25	23	26

Depth Level	Sample 3					Mean	Sample 4					Mean
	1	2	3	4	5		1	2	3	4	5	
1	28	33	37	20	11	26	3	45	36	0	0	17
2	42	36	40	1	11	26	5	4	24	3	3	8
3	7	38	40	21	11	23	11	7	37	7	11	15
4	9	39	40	13	12	23	22	10	14	8	13	13
5	14	36	36	15	19	24	23	14	13	10	0	12
6	16	15	12	15	18	15	19	19	25	12	18	19
7	18	14	12	15	20	16	18	22	38	33	22	27
8	21	19	13	18	17	18	20	20	41	27	24	26
9	27	20	17	19	20	21	21	26	27	24	25	25
10	20	22	25	18	19	21	26	23	29	25	1	21
11	19	23	22	16	21	20	27	22	32	29	50	32
12	27	24	32	16	24	25	36	23	36	45	50	38
13	26	32	39	18	16	26	43	35	29	50	50	41
14	21	35	33	19	19	25	45	22	38	50	50	41
15	32	36	36	16	17	27	50	27	38	50	50	43

Depth Level	Sample 5					Mean	Sample 6					Mean
	1	2	3	4	5		1	2	3	4	5	
1	2	0	32	1	28	13	2	1	2	1	48	11
2	6	1	0	1	1	2	5	2	4	6	2	4
3	20	9	35	3	34	20	4	5	9	8	1	5
4	31	9	10	8	39	19	6	7	16	11	9	10
5	37	10	12	27	34	24	7	9	13	11	12	10
6	38	9	15	26	42	26	9	10	20	13	13	13
7	39	11	17	26	14	21	15	17	22	15	12	16
8	41	12	18	37	14	24	16	20	19	19	12	17
9	50	16	23	38	21	30	16	21	23	21	13	19
10	45	25	23	20	29	28	16	16	23	25	15	19
11	49	29	18	29	36	32	26	16	25	29	23	24
12	40	50	22	50	31	39	37	16	23	46	24	29
13	37	36	32	50	34	38	24	14	27	50	25	28
14	45	45	28	50	25	39	33	19	26	50	38	33
15	38	38	39	50	22	37	25	50	23	50	42	38

Table A.11 Cone Penetrometer Control Measurements (Kg f) for Plot C & D

Depth	Sample 1						Sample 2					
Level	1	2	3	4	5	Mean	1	2	3	4	5	Mean
1	1	31	1	35	1	14	2	1	1	1	1	1
2	5	40	6	32	1	17	4	0	3	0	3	2
3	12	34	6	29	7	18	6	7	4	1	8	5
4	12	30	8	7	12	14	0	11	9	9	10	8
5	16	25	11	9	15	15	24	16	16	10	10	15
6	18	23	14	19	15	18	41	18	26	12	14	22
7	23	1	13	18	15	14	29	21	30	16	15	22
8	28	3	32	21	18	20	37	23	33	16	20	26
9	18	24	26	25	25	24	1	22	1	16	25	13
10	38	27	30	23	24	28	46	24	42	21	50	37
11	42	28	26	24	50	34	41	49	50	29	50	44
12	50	27	34	25	50	37	50	50	41	49	41	46
13	42	30	33	28	50	37	50	50	47	50	41	48
14	50	28	29	0	50	31	50	42	47	50	37	45
15	50	29	29	32	50	38	50	50	47	50	39	47

Depth	Sample 3						Sample 4					
Level	1	2	3	4	5	Mean	1	2	3	4	5	Mean
1	19	40	1	37	2	20	1	1	2	1	1	1
2	18	41	5	1	12	15	1	4	6	7	2	4
3	17	37	9	10	17	18	3	5	7	7	5	5
4	21	9	24	12	21	17	9	7	9	8	6	8
5	9	10	19	12	24	15	12	11	10	10	10	11
6	13	21	23	13	25	19	43	14	10	18	15	20
7	22	1	15	14	27	16	41	14	13	26	14	22
8	28	23	16	17	41	25	32	21	17	18	17	21
9	20	21	18	19	44	24	24	25	21	18	20	22
10	19	23	18	22	42	25	27	21	15	40	23	25
11	27	21	18	1	37	21	33	23	32	26	24	28
12	1	35	26	50	33	29	32	27	32	34	27	30
13	31	38	34	2	30	27	34	40	36	39	37	37
14	30	34	39	2	37	28	33	46	30	41	50	40
15	29	34	34	36	42	35	50	46	28	37	50	42

Depth	Sample 5						Sample 6					
Level	1	2	3	4	5	Mean	1	2	3	4	5	Mean
1	3	1	2	27	2	7	2	2	2	50	2	12
2	9	3	9	29	4	11	4	1	9	3	3	4
3	10	8	13	9	12	10	10	16	13	5	4	10
4	15	10	18	12	12	13	10	16	16	8	7	11
5	16	13	21	13	13	15	13	18	18	10	11	14
6	14	15	17	14	19	16	26	29	20	14	12	20
7	17	16	21	14	39	21	29	40	24	16	19	26
8	21	18	24	18	46	25	26	26	31	16	22	24
9	24	21	43	27	35	30	35	20	35	21	26	27
10	24	20	26	22	34	25	38	50	46	18	27	36
11	26	26	28	23	30	27	36	2	44	34	40	31
12	28	27	27	21	30	27	1	49	50	34	36	34
13	26	29	48	34	50	37	42	44	50	23	36	39
14	34	27	50	26	50	37	41	47	50	22	36	39
15	32	32	50	29	50	39	50	46	50	23	39	42

Table A.12 Cone Penetrometer Measurements (Kg f) for Plot D

Depth Level	Sample 1						Sample 2					
	1	2	3	4	5	**Mean**	1	2	3	4	5	Mean
1	3	3	1	44	2	**11**	38	1	1	30	0	**14**
2	7	8	7	1	4	**5**	33	4	5	29	2	**15**
3	1	8	7	4	5	**5**	36	3	7	0	6	**10**
4	13	8	9	8	8	**9**	9	4	10	4	8	**7**
5	15	9	10	9	15	**12**	11	5	10	7	9	**8**
6	23	10	13	10	13	**14**	12	6	13	14	12	**11**
7	25	11	14	13	13	**15**	14	34	18	19	30	**23**
8	38	11	14	14	13	**18**	21	30	39	17	22	**26**
9	28	16	18	18	20	**20**	33	19	39	20	30	**28**
10	34	31	50	50	31	**39**	30	17	37	21	35	**28**
11	37	50	46	46	36	**43**	29	26	38	27	42	**32**
12	50	50	48	48	39	**47**	29	27	38	25	42	**32**
13	50	50	43	43	42	**46**	33	22	41	25	44	**33**
14	50	50	50	50	46	**49**	30	25	42	28	50	**35**
15	50	50	50	50	50	**50**	31	28	42	27	50	**36**

Depth Level	Sample 3						Sample 4					
	1	2	3	4	5	**Mean**	1	2	3	4	5	Mean
1	1	38	3	1	1	**9**	2	2	3	1	20	**6**
2	5	9	10	8	1	**7**	1	9	6	2	17	**7**
3	8	11	15	15	2	**10**	6	12	10	6	50	**17**
4	10	14	17	15	10	**13**	14	15	17	10	18	**15**
5	16	15	19	14	16	**16**	18	20	16	17	16	**17**
6	28	17	1	16	22	**17**	16	26	21	16	16	**19**
7	38	19	23	39	30	**30**	21	35	26	19	16	**23**
8	35	25	25	40	29	**31**	19	35	1	21	20	**19**
9	45	19	34	41	29	**34**	33	37	33	23	22	**30**
10	47	24	42	38	29	**36**	41	38	50	24	22	**35**
11	36	25	50	37	29	**35**	34	39	50	28	20	**34**
12	50	24	50	35	33	**38**	43	37	50	28	22	**36**
13	50	24	50	35	39	**40**	9	37	50	26	41	**33**
14	50	49	50	38	37	**45**	14	36	50	47	50	**39**
15	50	38	50	38	40	**43**	50	35	50	50	50	**47**

Depth Level	Sample 5						Sample 6					
	1	2	3	4	5	**Mean**	1	2	3	4	5	Mean
1	42	1	3	1	38	**17**	2	3	2	0	3	**2**
2	6	5	6	3	3	**5**	14	1	1	3	9	**6**
3	7	7	7	7	5	**7**	10	11	8	6	14	**10**
4	10	9	9	6	11	**9**	13	16	8	10	19	**13**
5	13	19	13	8	14	**13**	12	21	13	17	20	**17**
6	16	27	16	11	18	**18**	23	23	21	26	29	**24**
7	25	41	18	19	39	**28**	24	24	24	21	38	**26**
8	21	38	25	37	50	**34**	22	24	20	28	40	**27**
9	24	23	1	35	43	**25**	28	24	24	35	39	**30**
10	24	37	39	29	32	**32**	43	29	32	50	39	**39**
11	27	48	50	42	28	**39**	50	32	28	50	37	**39**
12	28	50	50	44	25	**39**	50	37	26	50	42	**41**
13	29	50	50	48	24	**40**	50	24	28	50	50	**40**
14	23	50	50	50	41	**43**	50	50	25	50	50	**45**
15	23	50	50	50	37	**42**	50	50	45	50	50	**49**

Table A.13 Cone Penetrometer Measurements (Kg f) for Plot E

Depth Level	Sample 1					Mean	Sample 2					Mean
	1	2	3	4	5		1	2	3	4	5	
1	1	2	3	2	4	**2**	1	37	1	1	1	**8**
2	3	5	5	4	1	**4**	2	37	6	6	19	**14**
3	5	6	7	6	5	**6**	9	8	9	9	17	**10**
4	8	11	11	6	9	**9**	10	9	12	11	10	**10**
5	11	17	15	1	13	**11**	10	10	13	11	11	**11**
6	16	22	19	11	12	**16**	10	13	12	7	11	**11**
7	27	19	1	17	12	**15**	11	16	14	15	11	**13**
8	30	18	21	20	18	**21**	12	14	23	24	11	**17**
9	25	19	21	21	21	**21**	15	18	36	22	19	**22**
10	2	30	28	23	19	**20**	18	22	24	22	22	**22**
11	50	38	26	25	32	**34**	15	24	21	22	22	**21**
12	27	30	30	22	30	**28**	47	23	31	24	18	**29**
13	24	28	36	25	24	**27**	46	22	50	41	18	**35**
14	34	34	50	33	29	**36**	27	32	50	50	21	**36**
15	33	33	50	42	30	**38**	50	32	50	50	50	**46**

Depth Level	Sample 3					Mean	Sample 4					Mean
	1	2	3	4	5		1	2	3	4	5	
1	33	1	1	1	41	**15**	1	4	30	35	32	**20**
2	35	46	14	19	19	**27**	32	17	35	40	31	**31**
3	25	37	37	31	26	**31**	36	24	39	17	28	**29**
4	30	34	36	30	32	**32**	37	26	24	23	34	**29**
5	34	37	31	41	31	**35**	36	29	24	22	38	**30**
6	31	32	33	50	31	**35**	33	29	22	23	27	**27**
7	31	29	33	39	34	**33**	31	50	23	22	27	**31**
8	34	30	35	50	42	**38**	35	40	26	21	29	**30**
9	31	27	40	50	33	**36**	32	32	28	20	33	**29**
10	26	22	40	50	40	**36**	35	35	28	26	32	**31**
11	26	28	43	50	48	**39**	40	37	30	30	31	**34**
12	29	31	42	50	48	**40**	33	33	28	40	32	**33**
13	30	33	50	50	40	**41**	38	34	27	32	30	**32**
14	29	30	50	50	29	**38**	37	50	27	27	26	**33**
15	34	31	50	50	41	**41**	31	50	26	21	25	**31**

Depth Level	Sample 5					Mean	Sample 6					Mean
	1	2	3	4	5		1	2	3	4	5	
1	1	1	3	3	5	**3**	11	2	3	2	4	**4**
2	7	10	25	41	25	**22**	11	20	2	15	10	**12**
3	13	22	43	22	32	**26**	15	37	40	28	22	**28**
4	10	22	49	24	42	**29**	3	43	49	41	44	**36**
5	12	22	42	27	41	**29**	28	45	50	42	46	**42**
6	19	28	38	26	42	**31**	28	43	50	50	50	**44**
7	16	34	38	31	46	**33**	40	50	50	50	50	**48**
8	17	41	39	30	5	**26**	37	50	50	50	50	**47**
9	17	16	47	31	50	**32**	39	50	50	50	50	**48**
10	16	45	30	33	50	**35**	39	50	50	50	50	**48**
11	19	29	38	32	50	**34**	50	50	50	50	50	**50**
12	25	33	35	30	50	**35**	50	50	50	50	50	**50**
13	32	29	38	32	50	**36**	50	50	50	50	50	**50**
14	42	34	36	33	50	**39**	50	50	50	50	50	**50**
15	50	35	37	46	50	**44**	50	50	50	50	50	**50**

Table A.14 Cone Penetrometer Control Measurements (Kg f) for Plot E

Depth	Sample 1						Sample 2					
Level	1	2	3	4	5	Mean	1	2	3	4	5	Mean
1	2	2	1	2	31	8	2	1	2	2	2	2
2	11	8	7	2	8	7	10	8	10	8	7	9
3	17	20	13	13	19	16	10	13	13	15	14	13
4	18	26	20	15	22	20	14	13	16	13	19	15
5	17	28	22	16	25	22	12	15	18	14	28	17
6	29	29	23	20	25	25	16	16	18	19	38	21
7	32	31	35	26	25	30	2	18	25	20	45	22
8	25	33	42	25	17	28	25	20	28	30	43	29
9	2	41	45	32	17	27	25	21	19	30	48	29
10	15	30	50	49	25	34	27	40	35	30	47	36
11	35	45	38	33	16	33	34	46	33	30	48	38
12	32	50	50	37	23	38	41	44	36	50	47	44
13	36	36	50	39	25	37	47	41	50	50	42	46
14	50	50	50	43	27	44	50	50	50	50	50	50
15	50	50	50	50	50	50	50	50	50	50	50	50

Depth	Sample 3						Sample 4					
Level	1	2	3	4	5	Mean	1	2	3	4	5	Mean
1	2	5	1	1	0	2	3	21	27	22	25	20
2	2	23	2	3	5	7	8	19	26	14	25	18
3	22	40	17	26	16	24	16	25	31	15	29	23
4	29	35	23	28	20	27	17	27	17	16	32	22
5	37	36	32	32	23	32	16	34	16	16	29	22
6	37	31	37	33	27	33	15	28	19	22	28	22
7	41	37	44	37	28	37	16	22	21	23	10	18
8	46	34	47	40	30	39	19	19	17	24	11	18
9	41	42	50	46	30	42	21	20	22	26	21	22
10	40	44	50	41	26	40	22	27	22	27	20	24
11	42	42	50	38	30	40	22	27	22	24	26	24
12	37	44	50	41	33	41	22	30	21	27	25	25
13	45	35	50	40	50	44	22	27	20	30	26	25
14	45	50	50	50	50	49	23	26	20	31	26	25
15	50	50	50	50	50	50	21	23	21	24	22	22

Depth	Sample 5						Sample 6					
Level	1	2	3	4	5	Mean	1	2	3	4	5	Mean
1	1	27	24	26	36	23	30	31	15	27	25	26
2	27	25	25	24	37	28	31	30	17	27	26	26
3	24	23	24	18	31	24	28	27	16	26	27	25
4	12	24	24	16	34	22	30	27	18	27	28	26
5	11	22	25	15	30	21	32	25	19	26	24	25
6	12	26	22	18	28	21	31	23	20	26	23	25
7	24	14	4	28	17	17	31	29	21	28	27	27
8	31	17	4	27	15	19	44	32	19	32	29	31
9	28	19	3	27	15	18	41	33	20	33	32	32
10	32	23	4	28	17	21	38	33	18	32	33	31
11	34	22	19	26	18	24	36	37	15	31	29	30
12	39	23	25	27	22	27	36	37	13	29	26	28
13	35	23	24	27	27	27	32	45	16	30	22	29
14	33	23	23	29	25	27	29	31	19	27	23	26
15	31	27	25	32	29	29	32	37	17	30	28	29

Table A.15 Cone Penetrometer Measurements (Kg f) for Plot F

Depth	Sample 1						Sample 2					
Level	1	2	3	4	5	**Mean**	1	2	3	4	5	**Mean**
1	24	33	19	28	3	**21**	27	4	21	23	20	**19**
2	24	29	19	32	23	**25**	23	27	21	24	21	**23**
3	25	28	23	27	24	**25**	20	24	25	27	20	**23**
4	25	26	23	24	23	**24**	20	21	29	26	20	**23**
5	23	27	21	23	19	**23**	21	25	28	24	20	**24**
6	24	28	22	30	20	**25**	22	25	13	25	20	**21**
7	27	20	27	20	20	**23**	23	21	14	16	10	**17**
8	25	19	22	14	20	**20**	20	23	14	20	15	**18**
9	28	18	22	18	24	**22**	17	24	16	26	17	**20**
10	30	21	25	19	24	**24**	16	21	17	25	17	**19**
11	25	23	25	26	27	**25**	16	22	19	21	25	**21**
12	18	24	25	29	32	**26**	16	25	21	25	18	**21**
13	19	23	29	27	36	**27**	20	23	19	23	23	**22**
14	16	24	26	27	2	**19**	23	23	28	21	23	**24**
15	22	27	24	27	33	**27**	23	28	21	24	24	**24**

Depth	Sample 3						Sample 3					
Level	1	2	3	4	5	**Mean**	1	2	3	4	5	**Mean**
1	4	50	3	44	2	**21**	24	19	20	31	25	**24**
2	40	42	3	41	4	**26**	22	16	16	30	22	**21**
3	39	25	16	47	7	**27**	23	19	16	27	23	**22**
4	32	29	21	41	9	**26**	22	21	19	27	24	**23**
5	26	21	23	36	15	**24**	23	21	24	27	25	**24**
6	24	25	23	28	20	**24**	23	26	18	26	25	**24**
7	32	42	26	27	15	**28**	21	21	16	28	23	**22**
8	37	50	29	30	14	**32**	23	25	12	28	23	**22**
9	30	50	29	34	13	**31**	24	25	20	29	26	**25**
10	29	50	33	34	15	**32**	28	32	36	31	33	**32**
11	36	50	36	27	18	**33**	30	39	30	32	34	**33**
12	36	50	22	32	17	**31**	30	34	39	30	35	**34**
13	36	50	36	39	15	**35**	21	27	30	30	28	**27**
14	43	49	50	46	41	**46**	19	27	24	30	26	**25**
15	50	46	50	46	50	**48**	21	23	21	30	25	**24**

Table A.16 Cone Penetrometer Measurements (Kg f) for Plot G

Depth	Sample 1						Sample 2					
Level	1	2	3	4	5	**Mean**	1	2	3	4	5	**Mean**
1	24	37	24	23	27	**27**	19	24	22	44	38	**29**
2	24	38	23	20	25	**26**	21	22	22	33	35	**27**
3	23	37	25	20	26	**26**	21	22	26	33	8	**22**
4	24	33	24	22	25	**26**	21	22	28	29	10	**22**
5	21	35	23	22	25	**25**	22	20	28	34	13	**23**
6	24	20	22	23	25	**23**	21	23	31	38	22	**27**
7	22	23	20	22	27	**23**	9	14	17	14	32	**17**
8	23	32	23	24	29	**26**	12	13	10	15	42	**18**
9	23	35	23	27	21	**26**	15	15	22	18	47	**23**
10	25	24	28	25	24	**25**	13	17	19	18	34	**20**
11	26	42	31	27	25	**30**	18	21	20	18	45	**24**
12	23	34	31	28	28	**29**	19	25	21	18	50	**27**
13	18	38	34	24	27	**28**	21	24	22	20	41	**26**
14	22	42	27	25	28	**29**	21	20	27	22	42	**26**
15	23	40	28	25	27	**29**	22	22	22	27	50	**29**

Depth	Sample 3						Sample 4					
Level	1	2	3	4	5	**Mean**	1	2	3	4	5	**Mean**
1	2	2	3	5	2	**3**	17	9	5	36	28	**19**
2	6	6	10	9	8	**8**	17	13	11	33	26	**20**
3	9	7	27	10	10	**13**	16	16	13	6	27	**16**
4	11	9	28	11	10	**14**	17	18	13	8	26	**16**
5	12	10	23	17	21	**17**	14	19	24	11	26	**19**
6	13	14	23	28	22	**20**	17	20	25	20	26	**22**
7	38	17	30	26	20	**26**	15	45	23	30	28	**28**
8	44	17	27	25	20	**27**	16	51	23	40	30	**32**
9	38	16	26	27	21	**26**	16	45	24	45	22	**30**
10	34	16	26	30	26	**26**	18	41	29	32	25	**29**
11	47	18	26	31	43	**33**	19	48	46	43	26	**36**
12	47	24	33	38	36	**36**	16	50	39	48	29	**36**
13	45	25	50	48	45	**43**	11	50	48	39	28	**35**
14	49	50	50	43	50	**48**	15	50	50	45	29	**38**
15	50	40	50	43	50	**47**	21	50	50	49	35	**41**

Table A.17 Cone Penetrometer Control Measurements (Kg f) for Plots F , G & H

Depth Level	Sample 1					**Mean**	Sample 2					Mean
	1	2	3	4	5		1	2	3	4	5	
1	3	21	27	22	25	**20**	1	27	24	26	36	**23**
2	8	19	26	14	25	**18**	27	25	25	24	37	**28**
3	16	25	31	15	29	**23**	24	23	24	18	31	**24**
4	17	27	17	16	32	**22**	12	24	24	16	34	**22**
5	16	34	16	16	29	**22**	11	22	25	15	30	**21**
6	15	28	19	22	28	**22**	12	26	22	18	28	**21**
7	16	22	21	23	10	**18**	24	14	4	28	17	**17**
8	19	19	17	24	11	**18**	31	17	4	27	15	**19**
9	21	20	22	26	21	**22**	28	19	3	27	15	**18**
10	22	27	22	27	20	**24**	32	23	4	28	17	**21**
11	22	27	22	24	26	**24**	34	22	19	26	18	**24**
12	22	30	21	27	25	**25**	39	23	25	27	22	**27**
13	22	27	20	30	26	**25**	35	23	24	27	27	**27**
14	23	26	20	31	26	**25**	33	23	23	29	25	**27**
15	21	23	21	24	22	**22**	31	27	25	32	29	**29**

Depth Level	Sample 3					**Mean**	Sample 4					Mean
	1	2	3	4	5		1	2	3	4	5	
1	30	31	15	27	25	**26**	26	21	21	26	21	**23**
2	31	30	17	27	26	**26**	20	17	20	28	20	**21**
3	28	27	16	26	27	**25**	21	17	19	28	21	**21**
4	30	27	18	27	28	**26**	21	19	18	27	20	**21**
5	32	25	19	26	24	**25**	22	22	21	30	21	**23**
6	31	23	20	26	23	**25**	24	22	21	15	18	**20**
7	31	29	21	28	27	**27**	16	19	24	19	29	**21**
8	44	32	19	32	29	**31**	16	20	24	19	30	**22**
9	41	33	20	33	32	**32**	22	23	27	19	22	**23**
10	38	33	18	32	33	**31**	27	23	23	18	17	**22**
11	36	37	15	31	29	**30**	27	22	24	29	20	**24**
12	36	37	13	29	26	**28**	26	23	24	21	20	**23**
13	32	45	16	30	22	**29**	30	23	22	33	20	**26**
14	29	31	19	27	23	**26**	29	23	21	29	21	**25**
15	32	37	17	30	28	**29**	24	22	23	29	22	**24**

Depth Level	Sample 5					**Mean**	Sample 6					Mean
	1	2	3	4	5		1	2	3	4	5	
1	2	1	2	3	12	**4**	22	17	34	26	26	**25**
2	10	6	9	13	17	**11**	23	10	34	28	25	**24**
3	17	13	21	11	18	**16**	29	11	7	28	20	**19**
4	22	14	21	13	26	**19**	29	10	12	29	21	**20**
5	39	15	26	14	17	**22**	30	23	14	29	25	**24**
6	31	13	34	19	16	**23**	31	23	21	28	27	**26**
7	10	16	36	21	17	**20**	15	9	22	20	18	**17**
8	47	18	36	24	19	**29**	16	13	18	17	17	**16**
9	42	21	38	28	20	**30**	17	16	16	14	17	**16**
10	44	23	36	30	23	**31**	18	17	19	10	17	**16**
11	50	27	40	25	21	**33**	17	21	21	6	18	**17**
12	50	27	27	23	19	**29**	17	23	22	16	21	**20**
13	50	28	45	44	15	**36**	18	24	24	18	22	**21**
14	50	30	43	40	12	**35**	21	25	25	13	22	**21**
15	50	32	42	28	12	**33**	26	25	27	12	24	**23**

Table A.18 Cone Penetrometer Measurements (Kg f) for Plot H

Depth	Sample 1						Sample 2					
Level	1	2	3	4	5	**Mean**	1	2	3	4	5	Mean
1	5	5	0	2	8	**4**	47	1	37	3	41	**26**
2	7	12	0	3	12	**7**	7	1	43	12	50	**23**
3	20	15	22	5	16	**16**	11	13	14	12	50	**20**
4	34	20	21	15	18	**22**	13	12	12	18	30	**17**
5	38	27	28	21	22	**27**	21	14	20	19	15	**18**
6	37	30	29	25	23	**29**	24	16	28	18	16	**20**
7	39	31	43	29	28	**34**	26	24	25	23	17	**23**
8	42	34	44	38	31	**38**	21	21	23	22	19	**21**
9	49	37	45	37	35	**41**	25	28	24	25	18	**24**
10	50	39	50	40	45	**45**	24	29	24	27	26	**26**
11	50	35	50	48	45	**46**	29	46	30	35	35	**35**
12	50	31	50	50	48	**46**	31	45	35	37	35	**37**
13	50	30	50	50	50	**46**	36	50	36	40	33	**39**
14	50	30	50	50	50	**46**	37	39	35	38	34	**37**
15	50	30	50	50	50	**46**	34	37	34	50	34	**38**

Depth	Sample 3						Sample 4					
Level	1	2	3	4	5	**Mean**	1	2	3	4	5	Mean
1	1	2	37	2	4	**9**	41	3	11	5	3	**13**
2	0	6	34	6	8	**11**	38	10	15	9	6	**16**
3	8	7	34	10	8	**13**	38	15	19	13	10	**19**
4	6	14	34	14	8	**15**	38	13	21	15	12	**20**
5	10	24	21	19	13	**17**	25	17	25	19	20	**21**
6	11	27	23	15	19	**19**	27	19	26	20	23	**23**
7	14	31	19	21	21	**21**	23	15	31	25	25	**24**
8	33	29	24	25	22	**27**	28	20	34	28	20	**26**
9	33	30	27	23	29	**28**	31	23	38	32	24	**30**
10	10	50	30	19	29	**28**	34	26	48	42	23	**35**
11	45	50	33	22	26	**35**	37	29	48	42	28	**37**
12	40	50	29	30	25	**35**	33	25	50	45	30	**37**
13	43	50	32	41	30	**39**	36	28	50	47	35	**39**
14	41	50	36	26	37	**38**	40	32	50	47	36	**41**
15	70	50	39	31	39	**46**	45	40	50	50	45	**46**

Table A.19 Soil Potassium Results

Plot	Sample	Extraction Rack (ppm K)	Plot	Sample	Control (ppm K)
A	S1	141	A	S1	102
	S2	109		S2	110
	S3	84		S3	115
	S4	111	B	S1	80
B	S1	94		S2	80
	S2	104		S3	102
	S3	135	C	S1	111
	S4	95		S2	147
C	S1	139		S3	93
	S2	121	D	S1	129
	S3	116		S2	119
	S4	108		S3	94
D	S1	78	E	S1	67
	S2	98		S2	94
	S3	115		S3	51
	S4	72	F	S1	106
E	S1	75		S2	98
	S2	105		S3	93
	S3	119	G	S1	109
	S4	79		S2	79
F	S1	50		S3	44
	S2	103	H	S1	84
	S3	86		S2	92
	S4	92		S3	115
G	S1	55			
	S2	87			
	S3	78			
	S4	81			
H	S1	63			
	S2	83			
	S3	78			
	S4	85			

Table A.20 Total Nitrogen in Soil Results for Lissadell Plots

Plot	Sample	Extraction Rack (ppm N)	Plot	Sample	Control (ppm N)
A	S1	1.4	A	S1	0.0
	S2	1.5		S2	1.3
B	S1	1.8	B	S1	1.9
	S2	1.4		S2	2.2
C	S1	2.0	C	S1	1.6
	S2	2.2		S2	1.7
D	S1	2.0	D	S1	1.3
	S2	1.9		S2	1.5
E	S1	1.3	E	S1	1.2
	S2	1.7		S2	1.4
F	S1	1.1	F	S1	1.4
	S2	1.1		S2	1.1
G	S1	1.1	G	S1	2.3
	S2	2.0		S2	1.8
H	S1	1.4	H	S1	0.5
	S2	1.4		S2	1.6

Table A.21 Nitrate Results for Soil in Lissadell Plots

Plot	Extraction Rack (ppm N)	Plot	Control (ppm N)
A	2.1	A	1.2
B	2.2	B	2.0
C	1.9	C	1.9
D	1.0	D	1.0
E	1.5	E	0.9
F	1.1	F	1.2
G	1.2	G	1.1
H	1.1	H	1.3

Table A.22 Organic Carbon Results for Lissadell Control Samples

Plot	Sample	Control (% O. C)	Plot	Sample	Control (% O. C)
A	S1	5.36	E	S1	3.88
	S2	3.82		S2	3.80
	S3	5.12		S3	3.93
A	S1	5.38	E	S1	4.26
	S2	4.47		S2	4.23
	S3	5.04		S3	3.78
A	S1	5.46	E	S1	5.47
	S2	6.54		S2	4.92
	S3	6.19		S3	4.70
A	S1	5.07	E	S1	3.21
	S2	5.04		S2	3.23
	S3	4.97		S3	3.19
B	S1	4.78	F	S1	4.49
	S2	4.38		S2	4.36
	S3	4.34		S3	4.34
B	S1	5.15	F	S1	3.79
	S2	4.79		S2	3.73
	S3	5.03		S3	3.59
B	S1	5.75	F	S1	3.28
	S2	4.69		S2	2.94
	S3	4.75		S3	2.99
B	S1	3.80	F	S1	4.11
	S2	6.79		S2	3.27
	S3	5.09		S3	2.76
C	S1	4.60	G	S1	4.43
	S2	4.41		S2	4.07
	S3	4.37		S3	4.42
C	S1	6.95	G	S1	2.36
	S2	6.95		S2	3.54
	S3	7.44		S3	3.06
C	S1	5.68	G	S1	2.78
	S2	6.02		S2	4.38
	S3	5.91		S3	3.74
C	S1	6.15	G	S1	4.56
	S2	5.07		S2	4.01
	S3	5.23		S3	3.95
D	S1	4.78	H	S1	4.45
	S2	4.25		S2	7.34
	S3	6.51		S3	3.83
D	S1	7.71	H	S1	4.93
	S2	7.11		S2	4.63
	S3	6.50		S3	4.73
D	S1	6.15	H	S1	5.31
	S2	6.19		S2	5.15
	S3	6.11		S3	5.17
D	S1	4.27	H	S1	5.72
	S2	5.65		S2	5.84
	S3	5.52		S3	5.70

Table A.23 Organic Carbon Results for Lissadell Extraction Rack Samples

Plot	Sample	Control (% O. C)	Plot	Sample	Control (% O. C)
A	S1	5.94	E	S1	10.46
	S2	4.67		S2	3.63
	S3	4.96		S3	3.39
A	S1	5.84	E	S1	3.45
	S2	5.37		S2	3.03
	S3	5.51		S3	3.02
A	S1	5.04	E	S1	4.04
	S2	5.37		S2	3.57
	S3	6.23		S3	3.85
A	S1	5.78	E	S1	4.63
	S2	6.11		S2	2.92
	S3	5.75		S3	2.78
B	S1	5.52	F	S1	4.11
	S2	5.72		S2	3.50
	S3	5.60		S3	3.06
B	S1	5.85	F	S1	2.01
	S2	2.28		S2	3.02
	S3	8.69		S3	2.98
B	S1	6.43	F	S1	3.87
	S2	6.20		S2	3.38
	S3	6.73		S3	3.54
B	S1	6.58	F	S1	3.51
	S2	6.10		S2	3.08
	S3	6.72		S3	3.19
C	S1	5.21	G	S1	2.65
	S2	5.31		S2	2.67
	S3	6.03		S3	2.95
C	S1	6.72	G	S1	4.33
	S2	6.71		S2	3.83
	S3	5.32		S3	3.54
C	S1	6.97	G	S1	3.35
	S2	7.01		S2	4.03
	S3	7.13		S3	3.79
C	S1	4.15	G	S1	4.51
	S2	4.74		S2	4.15
	S3	4.06		S3	5.93
D	S1	4.78	H	S1	4.45
	S2	4.25		S2	7.34
	S3	6.51		S3	3.83
D	S1	7.71	H	S1	4.93
	S2	7.11		S2	4.63
	S3	6.50		S3	4.73
D	S1	6.15	H	S1	5.31
	S2	6.19		S2	5.15
	S3	6.11		S3	5.17
D	S1	4.27	H	S1	5.72
	S2	5.65		S2	5.84
	S3	5.52		S3	5.70

Table A.24 Organic Matter Results for Lissadell Plots

Plot	Sample	Extraction Rack (% O. M.)	Plot	Sample	Control (% O. M.)
A	S1	16.90	A	S1	14.68
	S2	13.09		S2	15.91
	S3	16.29		S3	16.12
	S4	13.90		S4	15.13
B	S1	12.28	B	S1	15.14
	S2	13.07		S2	14.41
	S3	14.22		S3	14.47
	S4	12.89		S4	14.37
C	S1	15.00	C	S1	18.58
	S2	15.77		S2	20.82
	S3	15.81		S3	16.33
	S4	15.46		S4	19.35
D	S1	12.09	D	S1	17.49
	S2	16.79		S2	18.14
	S3	15.05		S3	12.03
	S4	12.46		S4	16.01
E	S1	10.68	E	S1	12.30
	S2	11.92		S2	11.07
	S3	11.62		S3	16.52
	S4	9.27	F	S1	7.69
F	S1	12.35		S2	11.43
	S2	10.88		S3	11.85
	S3	9.76	G	S1	16.90
	S4	12.99		S2	15.56
G	S1	14.26		S3	13.78
	S2	10.08	H	S1	14.63
	S3	10.79		S2	16.45
	S4	3.07		S3	21.15
H	S1	2.94			
	S2	14.50			
	S3	15.73			
	S4	15.10			

Table A.25 Available Phosphorus Results from Lissadell Samples

Plot	Sample	Control (ppm P)	Plot	Sample	Extraction Rack (ppm P)
A	S1	11.53	A	S1	2.45
	S2	16.32		S2	6.77
	S3	6.12		S3	8.14
	S4	13.00	B	S1	7.42
B	S1	6.83		S2	8.69
	S2	7.29		S3	6.01
	S3	9.37	C	S1	5.17
	S4	4.86		S2	14.28
C	S1	11.98		S3	7.00
	S2	9.54	D	S1	5.35
	S3	5.74		S2	3.06
	S4	3.98		S3	2.53
D	S1	4.78	E	S1	3.94
	S2	5.06		S2	2.89
	S3	11.38		S3	0.74
	S4	3.53	F	S1	8.31
E	S1	7.67		S2	4.37
	S2	9.58		S3	2.27
	S3	11.59	G	S1	4.38
	S4	7.26		S2	2.44
F	S1	3.56		S3	2.15
	S2	11.86	H	S1	3.28
	S3	5.14		S2	2.84
	S4	6.69		S3	10.16
G	S1	3.24			
	S2	4.02			
	S3	2.50			
	S4	2.18			
H	S1	3.14			
	S2	2.70			
	S3	2.44			
	S4	3.73			

Table A.26 Results of Soil pH Measurements from Lissadell

Plot	Sample	Extraction Rack	Plot	Sample	Control
A	S1	5.0	A	S1	4.5
	S2	4.9		S2	4.5
B	S1	4.2	B	S1	4.3
	S2	4.2		S2	4.3
C	S1	4.4	C	S1	4.5
	S2	4.5		S2	4.5
D	S1	4.7	D	S1	4.6
	S2	4.8		S2	4.6
E	S1	4.3	E	S1	4.3
	S2	4.2		S2	4.3
F	S1	4.4	F	S1	4.3
	S2	4.2		S2	4.3
G	S1	4.5	G	S1	4.5
	S2	4.7		S2	4.5
H	S1	4.5	H	S1	4.4
	S2	4.6		S2	4.4

Table A.27 Water Infiltration Results for Lissadell Plots

Plot	Sample	Extraction Rack (cm/min.)	Plot	Sample	Control (cm/min.)
A	S1	0.07	A	S1	0.39
	S2	0.29		S2	0.37
	S3	0.23		S3	0.34
	S4	0.15	B	S1	0.39
B	S1	0.21		S2	0.37
	S2	0.18		S3	0.34
	S3	0.12	C	S1	0.22
C	S1	0.10		S2	0.34
	S2	0.07	D	S1	0.22
	S3	0.16		S2	0.34
	S4	0.06	E	S1	5.75
D	S1	0.03	F	S1	5.50
	S2	0.18	G	S1	5.65
	S3	0.22	H	S1	0.85
E	S1	0.00	I	S1	0.27
	S2	0.03		S2	0.43
	S3	0.03	J	S1	0.27
F	S1	0.02		S2	0.43
	S2	0.02			
	S3	0.00			
G	S1	0.73			
	S2	0.00			
	S3	0.01			
	S4	0.01			
H	S1	0.01			
	S2	0.01			
	S3	0.01			
	S4	0.03			
I	S1	0.41			
	S2	0.32			
	S3	0.46			
J	S1	0.31			
	S2	0.42			
	S3	0.26			

Table A.28 Soil Microbiological Results for Fungi at Lissadell

Sample	Details	Serial Dilutions			
		cfu's@ 10-4	cfu's@10-3	cfu's@10-2	cfu's@10-1
Plot D		8	10	179	TNTC
		2	15	150	
		5	19	200	
	Mean	5	15	176	
	Total Count			17600	
Plot E		20	13	70	TNTC
		20	21	113	
		36	38	45	
	Mean	25	24	76	
	Total Count			7600	
Plot F		23	43	TNTC	TNTC
		9	26		
		20	41		
	Mean	17	37		
	Total Count		37000		
Plot G		2	6	48	TNTC
		1	14	55	
		2	7	41	
	Mean	2	9	48	
	Total Count			4800	
Plot H		2	13	145	TNTC
		6	23	170	
		8	15	135	
	Mean	5	17	150	
	Total Count			15000	
Control 1		1	3	26	TNTC
		0	91	42	
		2	6	40	
	Mean	1	33	36	
	Total Count			3600	
Control 2		2	5	32	TNTC
		0	4	54	
		1	7	28	
	Mean	1	5	38	
	Total Count			3800	
Control 3		8	17	63	TNTC
		1	14	64	
		1	29	68	
	Mean	3	20	65	
	Total count			6500	
Control 4		7	26	96	TNTC
		6	23	68	
		11	33	111	
	Mean	8	27	92	
	Total Count			9200	
Control 5		8	25	90	TNTC
		15	35	35	
		4	28	55	
	Mean	9	29	60	
	Total Count			6000	

TNTC - To Numerous To Count

Table A.29 Soil Microbiological Results for Nitrifying Bacteria at Lissadell

Sample	**Details**	**Serial Dilutions**			
		cfu's@ 10-4	**cfu's@10-3**	**cfu's@10-2**	**cfu's@10-1**
Plot D		0	0	0	
		0	0	0	
		0	0	0	
	Mean	0	0	0	
	Total Count			**0**	
Plot E		1	16	69	TNTC
		1	38	54	
		0	26	79	
	Mean	1	27	67	
	Total Count			**6700**	
Plot F		1	5	65	TNTC
		0	11	66	
		0	3	49	
	Mean	0	6	60	
	Total Count			**6000**	
Plot G		0	0	17	65
		0	0	10	66
		0	1	11	93
	Mean	0	0	13	75
	Total Count				**750**
Plot H		0	5	43	TNTC
		0	0	32	
		0	9	30	
	Mean	0	5	35	
	Total Count			**3500**	
Control 1		0	6	95	TNTC
		0	0	95	
		1	0	21	
	Mean	0	2	70	
	Total Count			**7000**	
Control 2		0	0	0	96
		2	0	36	88
		0	0	33	29
	Mean	1	0	23	71
	Total Count				**710**
Control 3		0	0	28	53
		0	4	16	39
		1	0		31
	Mean	0	1	22	41
	Total count				**410**
Control 4		0	6	38	TNTC
		0	6	81	
		0	3	70	
	Mean	0	5	63	
	Total Count			**6300**	
Control 5		0	4	30	TNTC
		0	5	25	
		0	3	42	
	Mean	0	3	32	
	Total Count			**3200**	

Table A.30 Soil Microbiological Results for Total Aerobes at Lissadell

Sample	Details	Serial Dilutions			
		cfu's@ 10-4	cfu's@10-3	cfu's@10-2	cfu's@10-1
Plot D		27	92	TNTC	TNTC
		11	57		
		12	64		
	Mean	17	71		
	Total Count		71000		
Plot E		34	TNTC	TNTC	TNTC
		96			
		32			
	Mean	54			
	Total Count	540000			
Plot F		29	179	TNTC	TNTC
		18	184		
		23	146		
	Mean	23	170		
	Total Count		170000		
Plot G		30	142	TNTC	TNTC
		16	118		
		14	125		
	Mean	20	128		
	Total Count		128000		
Plot H		8	80	TNTC	TNTC
		25	135		
		31	145		
	Mean	21	120		
	Total Count		120000		
Control 1		8	43	57	TNTC
		4	10	146	
		4	15	151	
	Mean	5	23	118	
	Total Count			11800	
Control 2		7	73	TNTC	TNTC
		18	46		
		5	55		
	Mean	10	58		
	Total Count		58000		
Control 3		1	97	TNTC	TNTC
		18	57		
		19	57		
	Mean	13	70		
	Total count		70000		
Control 4		7	66	TNTC	TNTC
		17	55		
		11	68		
	Mean	12	63		
	Total Count		63000		
Control 5		4	65	TNTC	TNTC
		15	32		
		23	53		
	Mean	14	50		
	Total Count		50000		

Table A.31 Soil Moisture Results for Lissadell

Details	Sample	W1 (Dish)	W2 (Dish + sample)	W3 - (W2 dry)	% Moisture Content	% Moisture (Mean)
Moisture Content - Harvester Trials						
Plot I	1	73.758	112.026	95.575	42.99	
		75.604	107.617	94.464	41.09	42.04
	2	75.176	103.468	94.343	32.25	
		76.366	105.598	97.002	29.41	30.83
	3	75.401	103.641	94.907	30.93	
		74.268	103.844	94.043	33.14	32.03
	4	75.644	110.81	98.038	36.32	
		39.162	66.274	56.253	36.96	36.64
Plot J	5	78.101	105.12	102.537	9.56	
		76.095	108.66	99.469	28.22	18.89
	6	75.717	110.132	99.963	29.55	
		38.155	62.789	55.115	31.15	30.35
	7	38.802	65.34	58.464	25.91	
		39.21	72.605	64.338	24.76	25.33
	8	38.639	62.215	55.003	30.59	
		76.595	108.226	98.363	31.18	30.89
Moisture Content - Ponsse Trials						
Plot A	9	75.395	113.241	102.724	27.79	
		73.135	101.825	93.387	29.41	28.60
	10	76.972	105.512	98.187	25.67	
		75.822	108.958	100.073	26.81	26.24
	11	75.178	103.76	94.042	34.00	
		75.778	100.746	91.945	35.25	34.62
Plot B	12	37.264	59.162	53.333	26.62	
		39.167	70.301	62.137	26.22	26.42
	13	75.614	98.665	88.449	44.32	
		74.277	101.631	93.088	31.23	37.78
	14	75.653	103.703	96.221	26.67	
		76.102	98.726	90.169	37.82	32.25
Plot C	15	73.767	97.451	89.624	33.05	
		75.409	103.322	94.09	33.07	33.06
	16	78.111	107.311	98.293	30.88	
		76.376	98.681	91.548	31.98	31.43
	17	76.602	100.179	91.676	36.06	
		73.142	97.962	87.963	40.29	38.18
Plot D	18	39.212	60.848	54.479	29.44	
		75.401	104.404	97.393	24.17	26.81
	19	75.83	96.32	87.772	41.72	
		38.812	59.124	52.031	34.92	38.32
	20	76.978	97.54	90.368	34.88	
		38.16	61.492	52.47	38.67	36.77
Moisture Content - Norcar 480 Trials						
Plot E		73.7493	90.4646	86.0272	26.55	
		74.2588	88.0336	85.0225	21.86	
		75.3901	92.1426	87.7787	26.05	
Plot F		76.8133	91.506	87.4375	27.69	
		76.0859	89.3127	86.1516	23.90	
		75.7611	89.3933	86.3916	22.02	
Plot G		75.1618	86.3201	82.8582	31.03	
		76.9632	91.1099	86.6986	31.18	
Plot H		75.5972	87.8716	84.9586	23.73	
		78.0931	90.0868	87.2597	23.57	

Table A.32 Soil Moisture Content for Hollyford and Lugnaskeehan Trials

Details	**Sample**	**W1** **(Dish)**	**W2** **(Dish + sample)**	**W3 -** **(W2 dry)**	**% Moisture Content**	**% Moisture (Mean)**
Moisture Content - Norcar 490 Trials at Hollyford						
Plot M	1	74.9161	102.6337	92.1916	37.67	
	2	75.6059	93.8048	85.01045	48.32	
	3	74.8153	94.8475	84.7711	50.30	
	4	75.9432	95.1963	83.4905	60.80	49.27
Plot N	5	78.5421	108.7263	100.3243	27.84	
	6	46.8958	62.8387	54.4387	52.69	
	7	45.9848	69.5064	59.5135	42.48	
	8	9.2961	18.5794	13.0929	59.10	45.53
Moisture Content - Ponsse S10 Trials at Lugnaskeehan						
Plot K	1	75.9467	99.7412	92.8173	29.10	
	2	78.2516	96.7005	85.9153	58.46	
	3	74.2684	91.954	82.4695	53.63	
	4	75.6106	90.9313	82.4180	55.57	
	5	60.875	74.5201	69.6232	35.89	
	6	55.1261	66.2353	60.7886	49.03	46.95
Plot L	7	55.533	67.7332	61.5932	50.33	
	8	36.8945	44.6305	40.0518	59.19	
	9	40.6258	54.2549	50.5286	27.34	
	10	40.8662	51.5046	45.9443	52.27	
	11	39.6299	54.7754	44.3135	69.08	
	12	39.979	51.5825	44.789	58.55	52.79

Appendix B

Table B.1 Statistical Analysis (t-Test) of Bulk Density Values for the Lissadell Plots

Plot A: Ponsse S10, Band Tracks, No Brash.

t-Test: (0.01)	Control	Ext. Rack A
Mean	**0.85**	**0.94**
Variance	0.0077	0.0037
df	6.7387	
t	**-2.0332**	
P(T<=t) one-tail	0.0441	
t Critical one-tail	**3.1427**	
P(T<=t) two-tail	0.0883	
t Critical two-tail	**3.7074**	

Conclusion:

No increase in bulk density at 0.01 level of significance

t-Test: (0.05)	Control	Ext. Rack A
Mean	**0.85**	**0.94**
Variance	0.0077	0.0037
df	6.7387	
t	**-2.0332**	
P(T<=t) one-tail	0.0441	
t Critical one-tail	**1.9432**	
P(T<=t) two-tail	0.0883	
t Critical two-tail	**2.4469**	

Conclusion:

An increase in bulk density at 0.05 level of significance.

Plot B: Ponsse S10, Band Tracks, Brash.

t-Test: (0.01)	Control	Ext. Rack B
Mean	**0.90**	**0.98**
Variance	0.0061	0.0025
df	6.5787	
t	**-2.0189**	
P(T<=t) one-tail	0.0450	
t Critical one-tail	**3.1427**	
P(T<=t) two-tail	0.0900	
t Critical two-tail	**3.7074**	

Conclusion:

No increase in bulk density at 0.01 level of significance

t-Test: (0.05)	Control	Ext. Rack B
Mean	**0.90**	**0.98**
Variance	0.0061	0.0025
df	6.5787	
t	**-2.0189**	
P(T<=t) one-tail	0.0450	
t Critical one-tail	**1.9432**	
P(T<=t) two-tail	0.0900	
t Critical two-tail	**2.4469**	

Conclusion:

An increase in bulk density at 0.05 level of significance.

Plot C: Ponsse S10, Tyres, Brash

t-Test: (0.01)	Control	Ext. Rack C
Mean	**0.83**	**1.05**
Variance	0.0107	0.0117
df	8.7821	
t	**-3.3158**	
P(T<=t) one-tail	0.0053	
t Critical one-tail	**2.8965**	
P(T<=t) two-tail	0.0106	
t Critical two-tail	**3.3554**	

Conclusion:

An increase in bulk density at 0.01 level of significance

t-Test: (0.05)	Control	Ext. Rack C
Mean	**0.83**	**1.05**
Variance	0.0107	0.0117
df	8.7821	
t	**-3.3158**	
P(T<=t) one-tail	0.0053	
t Critical one-tail	**1.8595**	
P(T<=t) two-tail	0.0106	
t Critical two-tail	**2.3060**	

Conclusion:

An increase in bulk density at 0.05 level of significance.

Plot D: Ponsse S10, Tyres,No Brash.

t-Test: (0.01)	Control	Ext. Rack D
Mean	**0.79**	**1.03**
Variance	0.0204	0.0054
df	5.7244	
t	**-3.4201**	
P(T<=t) one-tail	0.0094	
t Critical one-tail	**3.3649**	
P(T<=t) two-tail	0.0188	
t Critical two-tail	**4.0321**	

Conclusion:

An increase in bulk density at 0.01 level of significance

t-Test: (0.05)	Control	Ext. Rack D
Mean	**0.79**	**1.03**
Variance	0.0204	0.0054
df	5.7244	
t	**-3.4201**	
P(T<=t) one-tail	0.0094	
t Critical one-tail	**2.0150**	
P(T<=t) two-tail	0.0188	
t Critical two-tail	**2.5706**	

Conclusion:

An increase in bulk density at 0.05 level of significance.

Appendix B

Plot E: Norcar 480, Band Tracks, No Brash

t-Test: (0.01)	Control	Ext. Rack E
Mean	**0.88**	**1.10**
Variance	0.0139	0.0100
df	7.9575	
t	**-3.2968**	
P(T<=t) one-tail	0.0066	
t Critical one-tail	**2.9979**	
P(T<=t) two-tail	0.0132	
t Critical two-tail	**3.4995**	

Conclusion:

An increase in bulk density at 0.01level of significance

t-Test: (0.05)	Control	Ext. Rack E
Mean	**0.88**	**1.10**
Variance	0.0139	0.0100
df	7.9575	
t	**-3.2968**	
P(T<=t) one-tail	0.0066	
t Critical one-tail	**1.8946**	
P(T<=t) two-tail	0.0132	
t Critical two-tail	**2.3646**	

Conclusion:

An increase in bulk density at 0.05 level of significance.

Plot F: Norcar 480, Band Tracks, Brash

t-Test: (0.01)	Control	Ext. Rack F
Mean	**0.92**	**1.11**
Variance	0.0068	0.0078
df	8.8457	
t	**-3.6073**	
P(T<=t) one-tail	0.0035	
t Critical one-tail	**2.8965**	
P(T<=t) two-tail	0.0069	
t Critical two-tail	**3.3554**	

Conclusion:

An increase in bulk density at 0.01level of significance

t-Test: (0.05)	Control	Ext. Rack F
Mean	**0.92**	**1.11**
Variance	0.0068	0.0078
df	8.8457	
t	**-3.6073**	
P(T<=t) one-tail	0.0035	
t Critical one-tail	**1.8595**	
P(T<=t) two-tail	0.0069	
t Critical two-tail	**2.3060**	

Conclusion:

An increase in bulk density at 0.05 level of significance.

Plot G: Norcar 480, Tyres, Brash

t-Test:	Control	Ext. Rack G
Mean	**0.90**	**1.02**
Variance	0.0038	0.0088
df	10.9061	
t	**-2.8781**	
P(T<=t) one-tail	0.0082	
t Critical one-tail	**2.7638**	
P(T<=t) two-tail	0.0164	
t Critical two-tail	**3.1693**	

Conclusion:

An increase in bulk density at 0.01level of significance

t-Test: (0.05)	Control	Ext. Rack G
Mean	**0.87**	**1.05**
Variance	0.0096	0.0105
df	8.9586	
t	**-3.2262**	
P(T<=t) one-tail	0.0061	
t Critical one-tail	**1.8595**	
P(T<=t) two-tail	0.0121	
t Critical two-tail	**2.3060**	

Conclusion:

An increase in bulk density at 0.05 level of significance.

Plot H: Norcar 480, Tyres, No Brash.

t-Test: (0.01)	Control	Ext. Rack H
Mean	**0.87**	**1.05**
Variance	0.0096	0.0105
df	8.9586	
t	**-3.2262**	
P(T<=t) one-tail	0.0061	
t Critical one-tail	**2.8965**	
P(T<=t) two-tail	0.0121	
t Critical two-tail	**3.3554**	

Conclusion:

An increase in bulk density at 0.01level of significance

t-Test: (0.05)	Control	Ext. Rack H
Mean	**0.90**	**1.02**
Variance	0.0038	0.0088
df	10.9061	
t	**-2.8781**	
P(T<=t) one-tail	0.0082	
t Critical one-tail	**1.8125**	
P(T<=t) two-tail	0.0164	
t Critical two-tail	**2.2281**	

Conclusion:

An increase in bulk density at 0.05 level of significance.

Plot I: Teva Harvester with Brash

t-Test: (0.01)	Control	Trial I
Mean	**0.80**	**0.81**
Variance	0.0044	0.0067
df	13.4467	
t	**-0.2211**	
P(T<=t) one-tail	0.4142	
t Critical one-tail	**2.6503**	
P(T<=t) two-tail	0.8285	
t Critical two-tail	**3.0123**	
Conclusion:		
No increase in bulk density at 0.01 level of significance		

t-Test: (0.05)	Control	Trial I
Mean	**0.80**	**0.81**
Variance	0.0044	0.0067
df	13.4467	
t	**-0.2211**	
P(T<=t) one-tail	0.4142	
t Critical one-tail	**1.7709**	
P(T<=t) two-tail	0.8285	
t Critical two-tail	**2.1604**	
Conclusion:		
No increase in bulk density at 0.05 level of significance.		

Plot J: Teva Harvester with No Brash

t-Test: (0.01)	Control	Trial J
Mean	**0.88**	**0.87**
Variance	0.0042	0.0074
df	12.7790	
t	**0.1632**	
P(T<=t) one-tail	0.4365	
t Critical one-tail	**2.6810**	
P(T<=t) two-tail	0.8731	
t Critical two-tail	**3.0545**	
Conclusion:		
No increase in bulk density at 0.01 level of significance		

t-Test: (0.05)	Control	Trial J
Mean	**0.88**	**0.87**
Variance	0.0042	0.0074
df	12.7790	
t	**0.1632**	
P(T<=t) one-tail	0.4365	
t Critical one-tail	**1.7823**	
P(T<=t) two-tail	0.8731	
t Critical two-tail	**2.1788**	
Conclusion:		
No increase in bulk density at 0.05 level of significance.		

Table B.2 Statistical Analysis (t-Test) of Bulk Density Values for the Lugnaskeehan Plots

Plot K: Ponsse S10, Band Tracks, Brash

t-test: (0.01)	Ext. Rack K	Control
Mean	**0.36**	**0.34**
Variance	0.0170	0.0273
df	13.2705	
t	**0.3597**	
P(T<=t) one-tail	0.3624	
t Critical one-tail	**2.6503**	
P(T<=t) two-tail	0.7248	
t Critical two-tail	**3.0123**	
Conclusion:		
No Difference in bulk density at 0.01 level of significance.		

t-test: (0.05)	Ext. Rack K	Control
Mean	**0.36**	**0.34**
Variance	0.0170	0.0273
df	13.2705	
t	**0.3597**	
P(T<=t) one-tail	0.3624	
t Critical one-tail	**1.7709**	
P(T<=t) two-tail	0.7248	
t Critical two-tail	**2.1604**	
Conclusion:		
No difference in bulk density at 0.05 level of significance.		

Plot L: Ponsse S10, Band Tracks, No Brash.

t-test: (0.01)	Ext. rack L	Control
Mean	**0.39**	**0.34**
Variance	0.0184	0.0273
df	13.4835	
t	**0.6703**	
P(T<=t) one-tail	0.2572	
t Critical one-tail	**2.6503**	
P(T<=t) two-tail	0.5144	
t Critical two-tail	**3.0123**	
Conclusion:		
No Difference in bulk density at 0.01 level of significance.		

t-test: (0.05)	Ext. Rack L	Control
Mean	**0.39**	**0.34**
Variance	0.0184	0.0273
df	13.4835	
t	**0.6703**	
P(T<=t) one-tail	0.2572	
t Critical one-tail	**1.7709**	
P(T<=t) two-tail	0.5144	
t Critical two-tail	**2.1604**	
Conclusion:		
No Difference in bulk density at 0.05 level of significance.		

Table B.3 Statistical Analysis (t-Test) of Bulk Density Values for the Hollyford Plots

Plot M: Norcar 490, Band Tracks, Brash.

t-test: (0.01)	Ext. Rack M	Control	t-Test:(0.05)	Ext. Rack M	Control
Mean	**0.68**	**0.61**	**Mean**	**0.68**	**0.61**
Variance	0.0277	0.0572	Variance	0.0277	0.0572
df	12.4433		df	12.4433	
t	**0.6709**		**t**	**0.6709**	
P(T<=t) one-tail	0.2575		P(T<=t) one-tail	0.2575	
t Critical one-tail	**2.6810**		**t Critical one-tail**	**1.7823**	
P(T<=t) two-tail	0.5150		P(T<=t) two-tail	0.5150	
t Critical two-tail	**3.0545**		**t Critical two-tail**	**2.1788**	
Conclusion:			**Conclusion:**		
No difference in bulk density at 0.01 level of significance.			No difference in bulk density at 0.01 level of significance.		

Plot N: Norcar 490, Band Tracks, No Brash.

t-Test: (0.01)	Ext. Rack N	Control	t-Test: (0.05)	Ext. Rack N	Control
Mean	**0.94**	**0.61**	**Mean**	**0.94**	**0.61**
Variance	0.0774	0.0572	Variance	0.0774	0.0572
df	13.6909		df	13.6909	
t	**2.5688**		t	**2.5688**	
P(T<=t) one-tail	0.0117		P(T<=t) one-tail	0.0117	
t Critical one-tail	**2.6503**		**t Critical one-tail**	**1.7709**	
P(T<=t) two-tail	0.0233		P(T<=t) two-tail	0.0233	
t Critical two-tail	**3.0123**		**t Critical two-tail**	**2.1604**	
Conclusion:			**Conclusion:**		
No difference in bulk density at 0.01 level of significance.			A difference in bulk density at 0.05 level of significance.		

Table B.4 Statistical Analysis (z-Test & t-Test) of Shear Strength Values at Lissadell Plots

Plot A: Ponsse S10, Band Tracks, No Brash.

z-Test (0.01)	Ext. Rack A	Control
Mean	93.06	76.31
Known Variance	559.4798	278.479387
Hypothesized Mean Difference	0	
z	**3.2732**	
P(Z<=z) one-tail	0.0003	
z Critical one-tail	**2.5758**	
P(Z<=z) two-tail	0.0005	
z Critical two-tail	**2.3263**	

t-Test (0.01)	Ext. Rack A	Control
Mean	93.06	76.31
Variance	559.4798	278.4798
df	55.7328	
t	**3.2732**	
P(T<=t) one-tail	0.0009	
t Critical one-tail	**2.3961**	
P(T<=t) two-tail	0.0018	
t Critical two-tail	**2.6682**	

Conclusion: An increase in shear strength at 0.01 level of significance.

Plot B: Ponsse S10, Band Tracks, Brash.

z-Test (0.01)	Control	Ext. Rack B
Mean	**70.06**	**84.33**
Known Variance	348.2540	363.5429
Hypothesized Mean Difference	0	
z	**-3.1155**	
P(Z<=z) one-tail	0.0005	
z Critical one-tail	**2.5758**	
P(Z<=z) two-tail	0.0009	
z Critical two-tail	**2.3263**	

t-Test (0.01)	Ext. Rack B	Control 4
Mean	**84.33**	**70.06**
Variance	363.5429	348.2540
df	65.3699	32
t	**3.1155**	
P(T<=t) one-tail	0.0014	
t Critical one-tail	**2.3851**	
P(T<=t) two-tail	0.0027	
t Critical two-tail	**2.6536**	

Conclusion: A difference in shear strength at 0.01 level of significance.

Plot C: Ponsse S10, Tyres, Brash.

z-Test (0.01)	Ext. Rack C	Control
Mean	**82.43**	**65.72**
Known Variance	320.863	361.628
Hypothesized Mean Difference	0	
z	**3.7398**	
P(Z<=z) one-tail	0.0000	
z Critical one-tail	**2.5758**	
P(Z<=z) two-tail	0.0001	
z Critical two-tail	**2.3263**	

t-Test (0.01)	Ext. Rack C	Control
Mean	**82.43**	**65.72**
Variance	320.863	361.628
df	64.2515	
t	**3.7398**	
P(T<=t) one-tail	0.0002	
t Critical one-tail	**2.3860**	
P(T<=t) two-tail	0.0004	
t Critical two-tail	**2.6549**	

Conclusion: An increase in shear strength at 0.01 level of significance.

Plot D: Ponsse S10, Tyres, No Brash

z-Test	Ext. Rack D	Control
Mean	**92.56**	**73.69**
Known Variance	950.539683	369.0605
Hypothesized Mean Difference	0	
z	**3.0633**	
P(Z<=z) one-tail	0.0005	
z Critical one-tail	**2.5758**	
P(Z<=z) two-tail	0.0011	
z Critical two-tail	**2.3263**	

t-Test	Ext. Rack D	Control
Mean	**92.56**	**73.69**
Variance	950.5397	369.0605
df	59.4478	
t	**3.0633**	
P(T<=t) one-tail	0.0016	
t Critical one-tail	**2.3912**	
P(T<=t) two-tail	0.0033	
t Critical two-tail	**2.6618**	

Conclusion: An increase in shear strength at 0.01 level of significance.

Appendix B

Plot E: Norcar 480, Band Tracks, No Brash.

z-Test (0.01)	Ext. Rack E	Control
Mean	**155.25**	**99.89**
Known Variance	1541.613	1473.359
Hypothesized Mean Difference	0	
z	**5.8649**	
P(Z<=z) one-tail	0.0000	
z Critical one-tail	**2.5758**	
P(Z<=z) two-tail	0.0000	
z Critical two-tail	**2.3263**	

t-Test (0.01)	Ext. Rack E	Control
Mean	**155.25**	**99.89**
Variance	1541.612903	1473.35873
df	64.69149534	
t	**5.8649**	
P(T<=t) one-tail	0.0000	
t Critical one-tail	**2.3860**	
P(T<=t) two-tail	0.0000	
t Critical two-tail	**2.6549**	

Conclusion: An increase in shear strength at 0.01 level of significance.

Plot F: Norcar 480, Band Tracks, Brash.

z-Test (0.01)	Ext. Rack F	Control
Mean	**164.38**	**99.89**
Known Variance	3147.726	1473.359
Hypothesized Mean Difference	0	
z	**5.4639**	
P(Z<=z) one-tail	0.0000	
z Critical one-tail	**2.5758**	
P(Z<=z) two-tail	0.0000	
z Critical two-tail	**2.3263**	

t-Test (0.01)	Ext. Rack F	Control
Mean	**164.38**	**99.89**
Variance	3147.726	1473.359
df	53.8983	
t	**5.4639**	
P(T<=t) one-tail	0.0000	
t Critical one-tail	**2.3988**	
P(T<=t) two-tail	0.0000	
t Critical two-tail	**2.6718**	

Conclusion: An increase in shear strength at 0.01 level of significance.

Plot G: Norcar 480, Tyres, Brash.

z-Test (0.01)	Ext. Rack G	Control
Mean	**133.63**	**99.89**
Known Variance	1472.887	1473.359
Hypothesized Mean Difference	0	
z	**3.6178**	
P(Z<=z) one-tail	0.0001	
z Critical one-tail	**2.5758**	
P(Z<=z) two-tail	0.0001	
z Critical two-tail	**2.3263**	

t-Test (0.01)	Ext. Rack G	Control
Mean	**133.63**	**99.89**
Variance	1472.887	1473.359
df	65.0709	
t	**3.6178**	
P(T<=t) one-tail	0.0003	
t Critical one-tail	**2.3851**	
P(T<=t) two-tail	0.0006	
t Critical two-tail	**2.6536**	

Conclusion: An increase in shear strength at 0.01 level of significance.

Plot H: Norcar 480, Tyres, No Brash.

z-Test (0.01)	Rack 10	Control
Mean	**159.56**	**112.38**
Known Variance	1609.222	787.210
Hypothesized Mean Difference	0	
z	**5.4528**	
P(Z<=z) one-tail	0.0000	
z Critical one-tail	**2.5758**	
P(Z<=z) two-tail	0.0000	
z Critical two-tail	**2.3263**	

t-Test (0.01)	Rack 10	Control
Mean	**159.56**	**112.38**
Variance	1609.222	766.306
df	55.0667	
t	**5.4767**	
P(T<=t) one-tail	0.0000	
t Critical one-tail	**2.3961**	
P(T<=t) two-tail	0.0000	
t Critical two-tail	**2.6682**	

Conclusion: An increase in shear strength at 0.01 level of significance.

Plot I: Teva Harvester with Brash

z-Test (0.01)	Ext. Rack I	Control
Mean	**95.8**	**82.7**
Known Variance	284.903	294.878
Observations	32	32
Hypothesized Mean Difference	0	
z	**3.0761**	
P(Z<=z) one-tail	0.0005	
z Critical one-tail	**2.5758**	
P(Z<=z) two-tail	0.0010	
z Critical two-tail	**2.3263**	

z-Test (0.05)	Ext. Rack I	Control
Mean	**95.8**	**82.7**
Known Variance	284.903	294.878
Observations	32	32
Hypothesized Mean Difference	0	
z	**3.0761**	
P(Z<=z) one-tail	0.0005	
z Critical one-tail	**1.9600**	
P(Z<=z) two-tail	0.0010	
z Critical two-tail	**1.6449**	

Conclusion: An increase in shear strength at 0.01or 0.05 level of significance.

Plot J: Teva Harvester with No Brash

z-Test (0.01)	Ext. Rack J	Control
Mean	92.75	82.66
Known Variance	298.2581	294.878
Observations	32	32
Hypothesized Mean Difference	0	
z	**2.3445**	
P(Z<=z) one-tail	0.0048	
z Critical one-tail	**2.5758**	
P(Z<=z) two-tail	0.0095	
z Critical two-tail	**2.3263**	

z-Test (0.05)	Ext. Rack J	Control
Mean	92.75	82.66
Known Variance	298.2581	294.878
Observations	32	32
Hypothesized Mean Difference	0	
z	**2.3445**	
P(Z<=z) one-tail	0.0048	
z Critical one-tail	**1.9600**	
P(Z<=z) two-tail	0.0095	
z Critical two-tail	**1.6449**	

Conclusion: An increase in shear strength at 0.05 level of significance but not at 0.01.

Table B.5 Statistical Analysis (z-Test & t-Test) of Shear Strength Values at Lugnaskeehan Plots

Plot K: Ponsse S10, Band Tracks, Brash

z-Test (0.01)	Ext. Rack K	Control
Mean	**53.7813**	**47.1875**
Known Variance	1	1
Hypothesized Mean Differe	0	
z	**26.3750**	
P(Z<=z) one-tail	0	
z Critical one-tail	**2.5758**	
P(Z<=z) two-tail	0	
z Critical two-tail	**2.3263**	

t-Test (0.01)	Ext. Rack K	Control
Mean	**53.7813**	**47.1875**
Variance	346.3054	342.3508
df	61.9980	
t	**1.4214**	
P(T<=t) one-tail	0.0802	
t Critical one-tail	**2.3890**	
P(T<=t) two-tail	0.1603	
t Critical two-tail	**2.6589**	

Conclusion: Increase in shear strength at 0.01 level of significance, for z-Test only

Plot L: Ponsse S10, Band Tracks, No Brash.

z-Test (0.01)	Ext. Rack L	Control
Mean	57.3125	47.1875
Known Variance	1	1
Hypothesized Mean Difference	0	
z	**40.5000**	
P(Z<=z) one-tail	0	
z Critical one-tail	**2.5758**	
P(Z<=z) two-tail	0	
z Critical two-tail	**2.3263**	

t-Test (0.01)	Ext. Rack L	Control
Mean	57.3125	47.1875
Variance	616.4153	342.3508
df	57.3166	
t	**1.8498**	
P(T<=t) one-tail	0.0348	
t Critical one-tail	**2.3936**	
P(T<=t) two-tail	0.0695	
t Critical two-tail	**2.6649**	

Conclusion: Increase in shear strength at 0.01 level of significance, for z-Test only

Table B.6 Statistical Analysis (z-Test & t-Test) of Shear Strength Values for the Hollyford Plots

Plot M: Norcar 490, Band Tracks, Brash.

z-Test (0.01)	Ext. Rack M	Control	t-Test (0.01)	Ext. Rack M	Control
Mean	**56.9394**	**46.1750**	**Mean**	**56.9394**	**46.1750**
Known Variance	1	1	Variance	462.3712	167.2763
Hypothesized Mean Difference	0		df	50.2776	
z	**45.7736**		**t**	**2.5237**	
P(Z<=z) one-tail	0		P(T<=t) one-tail	0.0074	
z Critical one-tail	**2.5758**		**t Critical one-tail**	**2.4033**	
P(Z<=z) two-tail	0		P(T<=t) two-tail	0.0148	
z Critical two-tail	**2.3263**		**t Critical two-tail**	**2.6778**	

Conclusion: Increase in shear strength at 0.01 Level of significance. Increase is marginal from t-Test.

Plot N: Norcar 490, Band Tracks, No Brash.

z-Test (0.01)	Ext. Rack N	Control	t-Test (0.01)	Ext. Rack N	Control
Mean	**58.6875**	**46.1750**	**Mean**	**58.6875**	**46.1750**
Known Variance	1.0000	1.0000	Variance	275.5121	167.2763
Hypothesized Mean Difference	0.0000		df	57.6223	
z	**52.7573**		**t**	**3.4985**	
P(Z<=z) one-tail	0.0000		P(T<=t) one-tail	0.0005	
z Critical one-tail	**2.5758**		**t Critical one-tail**	**2.3936**	
P(Z<=z) two-tail	0.0000		P(T<=t) two-tail	0.0009	
z Critical two-tail	**2.3263**		**t Critical two-tail**	**2.6649**	

Conclusion: Increase in shear strength values at 0.01 level of significance