An examination of the current slope gradients being experienced by ground-based forest machines in New Zealand plantation forests.

A thesis submitted in fulfilment

of the requirements for the

Degree of Master of Forestry Science

by

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2012

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Acknowledgements

The author wishes to thank Associate Professor Rien Visser and Dr Justin Morgenroth for their assistance in the development and undertaking of this thesis. Thank you to Dr Bruce Talbot at the Forest and Landscape research institute, Norway (skog og landskap) for his help during my time in Norway. In addition, thank you to Professor Karl Stampfer, Dr Martin Kühmaier, Dr Franz Holzleitner, Christian Rottensteiner and others at the Institute of Forest Engineering, University of Bodenkultur for their help during my time in Austria and the additional data collected on my behalf. Thanks also to Jessie Garland for her continued support with editing during the final stages of this thesis.

I would also like to acknowledge the financial support I received from the New Zealand School of Forestry University of Canterbury and Future Forest Research (FFR), without which this work would not have been possible.

Abstract

Harvesting is typically one of the largest cost components within a plantation forest rotation. A large proportion of New Zealand’s future harvest will be on steep terrain. Currently steep terrain harvesting is characterised by lower productivity and higher cost. It also has higher levels of manual or motor manual tasks such as setting chokers or tree felling, with a corresponding higher safety risk. The utilisation of ground-based machines on steep terrain has the potential to decrease harvest costs and improve safety. There is currently a push in New Zealand to increase the operating range. This is being done with a poor understanding of the slopes on which machines are currently operating and little understanding of the new risks steeper slopes might introduce. To better understand the true range of slopes on which forest machines are operating, a digital accelerometer was attached to 22 forest machines and provided real-time measurements of slope. The evaluated machines were grouped into one of four machine types; felling (n=4), shovelling (n=5), skidder (n=9) or European (n=4). The machine types were then analysed with respect to their machine slope (actual) and terrain slope (predicted) based on a digital terrain map. Two methods of calculating terrain slope were used, method one was based on a triangular irregular network (TIN) file with method two based off a raster file. Linear regression indicated that there was a relationship between machine slope and terrain slope for all four machine types, with the exception of European based machines, using the TIN method of slope calculation. All variables showed a poor coefficient of determination with the highest adjusted R squared single variable explaining 17% of the variation. All machines operated on slopes that exceed the New Zealand approved code of practice guideline of 30% and 40% slope for wheeled and tracked machines respectively. New Zealand based machines were shown to exceed the guidelines for terrain slope much more frequently, and by a greater margin, than European based machines.

1. Introduction

Harvesting is typically the largest cost component within a forest rotation. As such, harvesting is currently the focus of a large amount of research and development, nationally and internationally, in an attempt to develop more cost effective methods of harvesting and extraction. At present logging rates in New Zealand range from $19.50 per tonne on average for ground-based to $32.10 per tonne on average for cable operations (Visser, 2011). The cost of harvesting is particularly important in New Zealand due to the most common plantation species, *Pinus radiata (D.Don)*, having relatively low margins, making it susceptible to negative returns at time of harvest (Berkett et al., 2011).

The New Zealand commercial forest estate is currently estimated at 1.72 million hectares, with an annual cut of 21.7 million m^3 (New Zealand Forest Owners Association, 2011). The latter is expected to increase over the next 15 years to more than 35 million m^3 per year (Manley, 2010). Analysis conducted by Future Forest Research (FFR) (Raymond, 2010) found that steep hill country, that with slopes 35% or greater, accounted for 44% of the total forest estate and this percentage is expected to rise to 58% by 2020. The area of steep terrain currently harvested annually is also expected to rise with the estimated 22400 hectares in 2010 increasing to 37800 hectares per year by 2020.

Much of New Zealand's forest base expansion during the early 1990s focused on the planting of lowest cost land. Erosion protection plantings during the last 25 years have been primarily on unstable terrain (Berkett et al., 2011; New Zealand Forest Owners Association, 2011). New plantings driven by carbon trading initiatives are again likely to be based on areas of low cost land. These forests are characterised by steep unstable terrain, limited existing infrastructure and remote locations with regard to markets for forest products.

There is currently a particular focus, both nationally and internationally, towards using ground-based machines for harvesting as well as extraction of timber on steep terrain. New Zealand based Future Forest Research currently has the goal of "no worker on the slope, no hand on the chainsaw" for their harvesting and logistics research theme. The shift to using ground-based machine on steep terrain is due to the lower operating costs per tonne of ground-based systems over cable based systems. There is also the potential to increase the productivity of cable harvest systems and increase safety through mechanisation. Unlike cable extraction, which requires an appropriate terrain shape to achieve adequate deflection for optimum efficiency, ground-based extraction has minimal requirements with respect to terrain. However, for proper evaluation/consideration of ground-based systems, there is a requirement for better knowledge and understanding regarding the terrain, conditions and machine experience during operation.

Ground-based extraction on steep terrain has the potential to increase the risk of an accident due to increased possibility of equipment rollover (McMahon, 2006). New Zealand's department of labour's approved code of practice for safety and health in forestry operations (ACOP guidelines) states that "Equipment shall not be operated on slopes that exceed the maximum specified by the manufacturer" (Occupational Safety and Health Service, 1999). The guidelines suggest a set of limits based on the vehicles method of propulsion when the manufacturer doesn't provide a maximum, whereby:

- "Rubber-tyred machines should not operate on slopes that exceed 30%".

- "Crawler tractors, feller bunchers, excavators, and other similar mobile plant should not operate on slopes that exceed 40%".

Issues with the ACOP guidelines arise from the fact that machine manufactures do not release or simply do not know the rollover thresholds for their particular machine. This means that the ACOP guidelines developed are required to be used by operators unless it can be shown that they can exceed them safely. There is however no side slope limitations listed within the guidelines and there is also no metric by which a slope is defined. This causes an issue as there is no single way to determine terrain slope and, thus, identify 'risk areas', making it difficult to define areas of suitability for ground-based machines.

Steep terrain is often unstable, uneven and covered in debris, creating the potential for machines, even those operating within the ACOP guidelines, to rollover. Ground-based machines working on steep slopes can use skid trails in an attempt to keep them on a safe operating slope and mitigate the effects the other factors have on the machine. In order to truly understand the type of slope on which New Zealand extraction machines are operating it was necessary that individual machines be monitored in order to better understand what impacts ground conditions have on the stability of these machines. Other possible factors that could influence machine slope such as soil bearing strength, moisture content, terrain surface (slash vs. no slash) and tree size were excluded from the study due the highly complex and difficult nature of measuring these factors.

2. Literature review

2.1. Ground-based harvesting

Currently New Zealand's steep terrain forests are typically harvested with a cable yarder system. Cable yarder systems are suited to steep terrain as the terrain shape typically provides adequate deflection for the yarders to operate effectively. A FFR benchmarking study showed that cable yarding systems account for 53% of the New Zealand forest estate operators with the vast majority of these on steep slopes. The remaining 47% are ground-based operators, but due to the relative productivity produce more, accounting for approximately 55% to 60% of the total wood harvested (Visser, 2010; Visser, 2011). Of the ground-based harvest systems, grapple skidders are the most common method of extraction (36%) with the remainder extracted using a tractor/arch (5%), cable skidder (3%) or forwarder (2%). The study also found that 90% of New Zealand's cable yarders surveyed in 2010 were operating on average slopes greater than 24% with 72% operating on steep slopes (≥35%). Only 10% of the ground-based extraction machines were operating on slopes greater than 25%.

Steep terrain felling in New Zealand is largely motor manual, but there is an increasing number of machines that are capable of operating on steep slopes for harvesting purposes. These machines can be used in conjunction with a cable extraction system and provide a number of benefits for cable systems, such as bunching, in order to increase productivity (Acuna et al., 2011; Evanson, 2010). The use of steep terrain felling is also deemed to be safer, depending on the grade that the machine is operating on, as the risk of a fatality from falling objects is seen to be significantly reduced (Axelsson, 1998).

New Zealand's current experience with machines on steep slopes is not well documented. While machines are being put on slopes that exceed the recommended limits, it is typically done using designated skid trails to reduce machine slope and allow cross slope operation without the risk of exceeding the side slope limitations of the machine. Literature has indicated that this is typically around 20% for skidders and tracked machines and lower for forwarders at 10% due to their higher centre of gravity when loaded.

2.2. Harvesting in New Zealand

Excavator based felling machines are often used on flat to moderate slopes (Figure 1 and Figure 2) particular in conjunction with grapple skidders, as the felling machine is able to pre-bunch for the skidder.

Figure 1: Volvo excavator felling in small piece size pine plantation. Note the rigid track based undercarriage and the housing that can rotate on top of the undercarriage.

An excavator consists of an undercarriage and house: the undercarriage is comprised of a rigid track frame, tracks and track rollers and drive wheels. The undercarriage is also often fitted with a blade. The housing consists of the cab, boom, engine, counterweight and fuel and oil tanks. The housing attaches to the undercarriage by means of a turntable, allowing the machine housing to swing independently of the undercarriage.

Figure 2: A typical New Zealand felling machine. These machines have a reinforced cab to meet forestry equipment regulations and often have a widened and lifted track base to increase clearance.

Excavator based felling machines often use the same processing head for felling and for processing logs at the landing, limiting the amount of equipment that the contractor needs to invest in, or the contractor buys a new processor head for the log processing and uses the old head for tree felling. Processor heads, however, are heavier than those dedicated to felling as well as being more expensive and less productive (Spinelli et al., 2009).

Figure 3: Felling head considerably lighter than the alternative processing head consisting of a grapple and a bar saw.

Figure 4: Processing head, note the large rollers that are absent on the felling head. The head is also fitted with knives (behind the rollers) for removing limbs and bark.

A dedicated felling head typically weighs 1200 to 2000kg (Figure 3) whereas a processing head (Figure 4) can weigh up to 5000 kg. The additional weight is a concern when operating on slopes, as the weight is situated at the very end of the boom, adding to the momentum the machine experiences as it rotates. The additional weight also means that a larger machine is needed, with a 35-40 tonne excavator recommended for the larger processing heads (85cm maximum diameter) whereas a 20 – 30 tonne machine is suggested for a felling head capable of the same diameter.

Ground-based timber extraction is done almost entirely with skidders, either cable or grapple skidders, with only a small percentage (6.5%) of forwarders being used (Visser, 2011). Skidders make up 93.5% of the ground-based extraction machines, with wheeled grapple skidders comprising 78.3% of this, followed by tracked skidders (10.9%) and wheeled cable skidders (4.3%). The preference for skidders in New Zealand is largely driven by whole tree harvesting. Wood is extracted as whole trees to a centralised landing where it is processed and then loaded onto road going trucks for extraction. This is in contrast to Europe where cut to length (CTL) systems are typically employed, resulting in very different requirements for their extraction machines.

The other potential area of expansion for ground-based machines is in the mechanisation of cable operations. A combination of ground-based felling or shovelling in conjunction with a cable extraction system is becoming more common in New Zealand, particularly in combination with grapple swing yarders. This technique of motor manual felling and shovelling into bunches, or mechanised felling and bunching, increases production as the yarder requires less line shifts and is able to pick up more than one log at a time with greater frequency (Acuna et al., 2011; Evanson, 2010). Acuna's study showed that the improvement in average volume per cycle increased from 1.3m^3 to 1.9m^3 when trees were bunched in a 1000 stems per hectare stand, with an average piece size of 0.8m^3. The use of bunching to increase productivity is thought to be best suited to small piece sized timber and high stocking, due to the payload limitations of the yarder and the distance needed to travel to the next tree. This significantly reduces its application in large parts of the country, given the national average piece size of 2.2m^3 (Visser, 2011) and, typically, 400 stems per hectare, which limits the productivity benefits on a cost basis. The other possible advantage of this system is in the potential for increased safety. This results from a reduction in the number of fatalities due to the most common tasks resulting in death being felling and breaking out (McMahon, 2006).

2.3. Ground-based Steep terrain harvesting

Steep terrain felling machines are more commonly used in Europe and North America, driven largely by safety and increased productivity. Some machines have been developed for the specific purpose of felling on steep terrain, such as the Komatsu 911 Snake harvester. This machine uses a Komatsu 911 wheeled harvester as its base, with the standard wheels being replaced by four independent trapezoidal tracks (Figure 5). Other vehicles such as the Kaiser and Menzi Muck walking excavators, which both use independently adjustable hydraulic wheeled legs, have also been adapted for harvesting through the addition of a harvesting head (Figure 6). The Konrad Highlander (Figure 7), a purpose built wheeled harvester (four or six wheel drive), uses extendable rear axles, allowing for increased stability due to a longer wheel base. More standard European harvesters such as the Ponsse Ergo 8 (Figure 8) and the Komatsu 941 (Figure 9) are also able to operate safely in moderate to steep terrain with little to no modifications (respective manufacture claims[1]). This is a result of the machines already large tractive footprint, bogie wheels and low centre of gravity, with the addition of bogie tracks to provide better traction when required.

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[1] http://www.ponsse.com/finnmetko/pdf/TuoteuutisetENG_lr.pdf - 23/05/12
http://www.komatsuforest.ca/Media/Pdf/CustomerMagazines/jf2_2007_eng.pdf - 23/05/12

Figure 5: Komatsu 911 Snake harvester operating in a mixed forest in Central Austria

Figure 8: Ponsse Ergo 8 with bogie tracks over all 4 pairs of bogies

Figure 6: Kaiser S2 4x4 Cross walking excavator with each wheel able to raise or lower individually[2]

Figure 9: Komatsu 941 harvest equipped with front bogie tracks and chains on the rear wheels

Figure 7: Konrad Highlander 6w - A purpose built steep terrain European harvester

Figure 10: John Deere 909KH self levelling harvester working tethered using a wire rope.

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[2] http://www.baumaschinenbilder.de/forum/attachment.php?attachmentid=29767&sid=03ef30bf302a302b993e5865c2cac10a – 23/05/2012

American based harvesting machines have largely focused on developing an improved ridged tracked excavator machine. These machines are similar to a normal construction excavator, with the addition of a self-levelling cab section which provides a more stable platform for the housing and a more comfortable working position for the operator (Figure 10). Some models also have a reduced counter-weight to reduce tail swing, allowing for more manoeuvrability in the forest.

European extraction of forest logs in context of ground-based systems is largely done using forwarders (Figure 11). This is a result of the CTL system developed in Scandinavia. The system works in combination with a harvester, by means of which the logs are all cut to a set length and placed in piles. The forwarder follows through the forest after the harvester and extracts the timber. This system is employed in Europe, due to their use of continuous cover forestry, which results from restrictions on the size of clear cut areas.

Figure 11: Forwarder operating on moderate slopes in Austria, note the log piles of equal length logs in this cut to length system. This machine was following through a stand that had been felled with a harvester and subsequently is driving on slash rather than the topsoil.

While cable extraction is also the preferred method in Europe when harvesting on steep slopes, there is an increasing move to using forwarders as an alternative method. Due to the roll over potential, a loaded forwarder is susceptible to rolling, even with small degrees of side slope. However, the forwarder remains stable if driving directly up and down slopes. Some contractors have also started securing their machine with a winch, allowing it to travel up and down the slopes more safely while still functioning as an effective forwarder (Stampfer, 2011).

2.4. Current issues with steep terrain harvesting

2.4.1. Safety

The safety aspect of steep terrain harvesting is an important consideration in the use of specialised machinery for felling and extraction. Both New Zealand and the rest of the world have recognised that forestry is an inherently dangerous job with fatality figures much higher than almost any other industry. Mechanisation of forest activities on steep terrain machines is seen as a possible solution to reducing fatalities and risk.

From 1988 to 2005 there was a total of 94 forestry related fatalities in New Zealand. Of these, 41% were related to felling, 14% breaking out and 12% extraction related (Table 1) (McMahon, 2006).

Table 1: Showing the number of fatalities in New Zealand forest sector from 1998 to 2005 with associated activity (McMahon, 2006).

Operation	Number	Percentage
Felling	39	41%
Breaking out	13	14%
Extraction	11	12%
Skid work	9	10%
Trimming	5	5%
Maintenance	5	5%
Road use	5	5%
Moving Plant	2	2%
Loading	3	3%
Helicopter op	1	1%
Unknown	1	1%

The data provided by McMahon (2006) shows that there is potential for reduction in the number of fatalities and injuries sustained. Felling, breaking-out and skid work are all primarily manual activities. Through the use of mechanisation and the additional protection the operator is provided with a safer working environment.

Motor manual tree fellers are subjected to numerous other hazards in addition to falling objects during a normal days work due their uncontrolled, all-weather, outdoor working environment. As such, non fatal injuries related to slipping, tripping and falling are prevalent. Dehydration is also a key factor that, although not a direct injury, can be attributed to a loss of concentration which results in the occurrence of an injury (Bentley et al., 2005; Slappendel et al., 1993). The use of mechanical felling machines lowers the physical workload on the worker, lessening fatigue and dehydration. The reduction in the amount of time on the ground also decreases the workers risk to terrain attributed injuries. The protection of a cab as well as the ability to directionally fell can significantly reduce the risk to the forest worker (Laflamme and Cloutier, 1988). Table 2 shows that some, if not all, of the felling related fatalities in New Zealand from 1988 to 2005 may have been prevented or reduced in severity through the use of a mechanised felling system.

Table 2: Showing a breakdown of felling fatalities by cause from 1988 to 2005 (McMahon, 2006)

Cause	Number	Percentage
Hang up / working in front of cut up tree	11	28%
Direction/Position (Description unclear)	9	23%
Hit by contacted tree/spar	5	13%
Retreat to incorrect position	4	10%
Hit by sailer	3	8%
Fell direction not anticipated	3	8%
Hit by tree felled by second party	2	5%
Driving tree	1	2%

In Canada in 1990 a study into the fatalities of workers showed that forestry had the second highest risk with 54.3 deaths in every 100,000 workers, second only to deep sea fishing (Hasselback and Neutel, 1990). The paper also summarised data from 11 states of the USA with similar results. However, in this case fatalities were much higher with 129 deaths per 100,000 workers. Another publication on forestry fatalities in the USA (Scott, 2004) summarised the forestry deaths and their related causes for the nine year period from 1992 to 2000. Again tree fellers made up the vast majority of fatalities with 63% of all fatalities, of a total of 780 deaths.

A European study in 2007 (Klun and Medved, 2007) showed the number of fatalities amongst professional and non-professional forest workers, segregated by country (Figure 12 and Figure 13). The data showed a large difference in the number of annual deaths both between countries and between professional and non professional forest workers. The difference between both of these factors and the continued reduction of deaths can be largely attributed to varying levels of mechanisation. In particular, Sweden showed very low fatality rates, having reached 98% mechanisation by 2001, as did Finland with 91% by the same period. This also gives a good indication of the advantage of not only good safety practices but also of higher degrees of mechanisation.

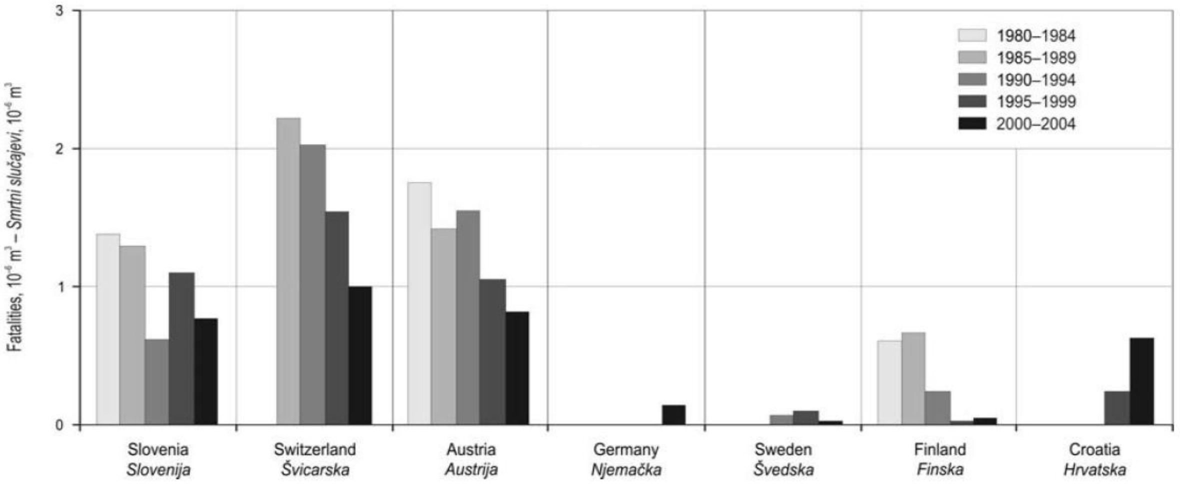

Figure 12: Showing the accident rates of various European countries over a 24 year period for professional forestry workers. (Klun and Medved, 2007)

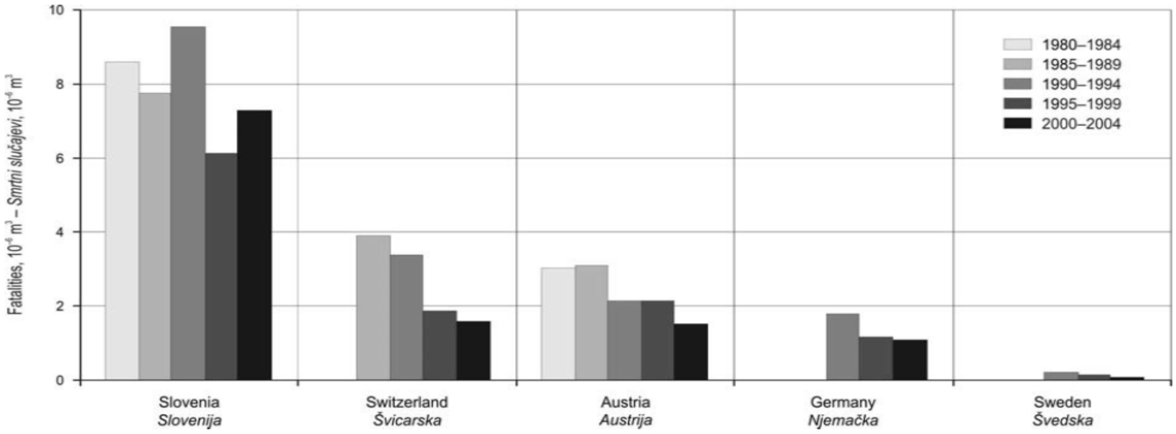

Figure 13: Showing the accident rates of various European countries over a 24 year period for non- professional forestry workers. (Klun and Medved, 2007)

A survey conducted in Sweden (Axelsson, 1998) showed a 73% reduction in accident frequency when using mechanised methods over chainsaw-based methods. A large proportion of the reduction in accidents can be attributed to the change from manual and motor manual delimbing to mechanised delimbing (Laflamme and Cloutier, 1988). A similar result was seen in West Virginia, United States, where ‘struck by’ injuries were 3.8 times greater prior to the introduction of feller-bunchers. (Bell, 2002). Bell recognised that, at the time of writing, there was limited application for reducing felling injuries/fatalities “in areas of very steep terrain where it is not possible to use these machines”.

New Zealand has the potential to further reduce risk through a change from motor manual felling, which is the commonly employed method for felling on steep terrain, to mechanised felling which limits the number of workers subjected to falling objects. The percentage of mechanised felling in New Zealand is currently well below its potential maximum with only 57% mechanisation of felling and 3% mechanised processing for grapple skidder based harvesting systems (Visser, 2011). It is assumed that if a machine is able to extract with a grapple skidder it should also be possible to use mechanised felling as well.

The trade-off with moving people off the ground and into machines is the potential increase in occurrences of other injuries or causes of death. These range from vehicle roll over deaths to a rise in the number of repair and maintenance and repetitive strain (RSI) related injuries due to the increase in machine numbers (Slappendel et al., 1993).

The number of deaths for workers employed in extraction is one area of concern with regards to operating ground-based machines on steep slopes. The major concern is vehicle roll-over, which was the only cause of death in this operational task from 1988 to 2005 in New Zealand (McMahon, 2006). During this period there were a total of 77 reported machine rollovers, with 12 (16%) of these resulting in fatalities (Sullman, 1998). However, due to the implementation of safety features on ground-based machines, such as rollover protection (ROB) and falling object protection (FOB), as well as safety restraint systems, the potential injury risk and chance of a fatality occurring during machine accidents has been significantly reduced (Eger and Kiencke, 2003; Sullman, 1998). Of the 11 operators that died from machine rollover for the period from 1988 to 2005, all 11 failed to wear their vehicle's safety restraints.

Due to the high risk of an injury occurring to the operator in the event of a rollover, a number of studies have been done to try and establish suitable methods of insuring that seatbelts are worn. Sullman (1998) showed that a 58% increase in seatbelt use was obtainable by providing an improved seatbelt design and installing a flashing light reminding the operator to fasten their seatbelt.

Vehicle maintenance related injuries are another potential safety risk that logically increases with the number of vehicles being operated. A study in Finland (Scott, 2004) showed that repair and maintenance related injuries were a significant contributor to days off work due to injury, with the main causes related to working within the forest environment. The major problems were cold in the winter, the necessity of working barehanded, the handling of oil and solvents, slips and falls from the machine, troublesome working postures and the handling of heavy machine parts during maintenance. The study showed that while the severity of the injuries was less than manual felling, the accident rate was still similar. Johansson and Pontén (2008) showed that in 20 large forest companies in Sweden 19% of accidents occurred during work with machines, the most significant cause of which was machine maintenance.

2.4.2. Environmental

The other big concern when using mechanised equipment on steep terrain is the possibility of increased environmental damage. Soil compaction, soil erosion, water quality, land slide risk, residual stand damage and regeneration damage all have the potential to increase through the use of heavy machinery (Tiernan et al., 2002).

2.4.2.1. Soil compaction

Soil compaction is a major concern with the use of heavy machinery on off-road surfaces. Soil compaction from heavy machine operation has been shown to significantly reduce tree growth through a number of factors such as: a decrease in soil penetration by seedlings, reduction in soil macroporosity, reduction in soil moisture and air due to compaction, damage to regeneration, damage to understory and forest floor mass and soil displacement (Demir et al., 2007; Horn et al., 2004; Makineci et al., 2007; Zenner et al., 2007). The decrease in pore space also decreases the amount of soil water which, in turn, increases overland flow (Garland, 1983; Horn et al., 2007). All these factors contribute to reducing the ability of the soil to productively grow trees and lessen the overall productivity of the site. Designated skid trails have the potential to minimize the amount of soil compaction within the harvest area by ensuring that machines impact the minimal amount of soil per unit area (Garland, 1983; Horn et al., 2007).

Rab (1994) showed that, on a logging site in the Victorian Central Highlands, South-Eastern Australia, 39% of the coupe area reached critical levels with regards to tree growth. This was a result of increased bulk density and a decrease in macroporosity and organic carbon. Water retention and absorption also decreased as a result of these factors, resulting in the occurrence of overland flow on over 72% of the total harvested area.

2.4.2.2. Erosion and water quality

Soil erosion is one of the key environmental issues surrounding the use of any sort of machine operating within a forest. It is a problem in itself, as it degrades the sites productivity, can be visually unappealing and seriously affects water quality. With this in mind, soil water quality will be discussed with erosion.

Roads, skid trails and landing sites are the most significant sources of soil erosion resulting from harvesting practices (David, 2000), with roads found to contribute up to 90% of the total sediment produced from a harvest site (EPA, 2005). The results of this erosion type, known as non point source erosion, are most often discussed as a consequence of an increase in suspended sediment in downstream rivers and streams (Grace III, 2002). While little can be done in practice about actual road construction impacts, beyond utilising best environmental management practices, their impact on a per hectare basis is dependent on the harvest system used. Appropriate planning is the most effective method for reducing the number of roads needed, their location and their subsequent impact on the environment.

Skid trails are typically used on steep terrain when operating a ground-based machine, to allow the machine to stay within its safe operating limits (Reisinger and Gallagher, 2001). However, this can result in significantly more erosion due to the large amount of earthwork required, heightened landslide risk and a rise in surface erosion from vegetation removal and forest floor disturbance (Horn et al., 2004; Reisinger and Gallagher, 2001; Zenner et al., 2007). Skid trails differ from forest roads in that they are not surfaced and have little or no planning in regard to their location, which can also result in significant increases in soil erosion.

Clearly, skid trails, particularly their construction, contribute heavily to overall soil erosion. The movement of the machine within the forest (off-road) factors into the amount of soil disturbance through track and wheel skidding (Figure 14) as do skidded logs (Figure 15) or the process of skidding logs to a landing. The damage done to the soil is dependent on the soil type and moisture levels as well as the configuration of the vehicle acting on it (wheels vs. tracks etc).

Figure 14: Steep terrain bogie tracks

Figure 15: Soil damage from skidder wheels and skidded logs

The exposed soil is prone to water erosion and can suffer more damaging events such as landslides, with poorly managed ground-based harvesting exposing bare soil on as much as 39% of the total harvest area (Modrý and Hubený, 2003).

The use of permanent skid trails has often been proposed as a method to reduce the amount of soil work and new skid trails required (Horn et al., 2007; Zenner et al., 2007). This is now a common practice in many parts of the world due to legislation designed to protect water ways through limiting the volume of earthworks. Facilitating this, light detection and ranging techniques (LIDAR) are now being used in forestry, which has the benefit of being able to detect old skid trails hidden under vegetation (Espinoza, 2007; Karatolios, 2008). This allows the harvest planner to identify and utilise existing skid trails rather than constructing new ones, thus reducing the amount of soil disturbance while also reducing costs.

The risk of landslides increases with slope and can be affected by forest activities such as vegetation removal, earthworks, water table and flow modification and the activities of heavy machinery (Johnson et al., 2007; Visser and Adams, 2002). Haul road and landing construction is the most significant of these factors, but the act of skidding and tracking (skid trails) for ground-based machines can also contribute significantly to the volume of soil eroded from harvest sites (Rice et al., 1972; Sheridan, 2003). Tracked skidding has been shown to produce significantly more bare soil per unit area than high lead or skyline systems and to increase the rate of surface erosion (Rice et al., 1972). The rate of erosion was dependent on soil type, with factors such as particle size and pore distribution significant due to their impacts on water movement and retention (Kitutu et al., 2009). High amounts of erosion are also possible with cable harvesting systems, as there are still landings and roads which add to the overall site erosion (Worrell et al., 2010). High leading has the highest rate of soil disturbance due to the lack of suspension and continuous log drags over the same area. This is of particular concern when downhill hauling as these trenchers converge on a single point (landing), which can cause problems during periods of high rainfall (Dissmeyer, 1985).

2.4.3. Cost and feasibility

The push towards ground-based machines primarily comes from the lower operating costs and higher productivity they bring, but these advantages decrease with increasing slope. The average logging rate for a cable yarder in New Zealand is $32.10 a tonne with an average productivity of 22.6 tonnes per scheduled hour. This compares with ground-based systems that have a logging rate of $19.50 a tonne and a productivity of 35.4 tonnes per hour (Visser, 2011). Analysis of the logging rate of cable and ground-based operations showed that the logging rate of ground-based machines was highly affected by the terrain slope, whereas cable yarding logging rates were largely unaffected.

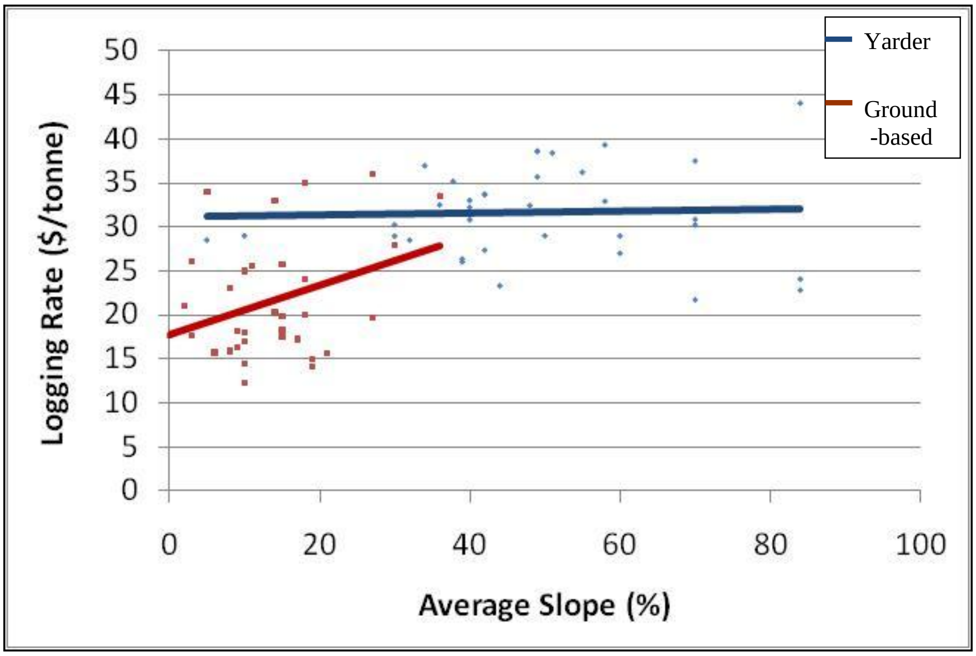

Figure 16: Logging rate of cable and ground-based extraction vs. slope (Visser, 2010)

The intercept of this data means that it would be more cost effective to use ground-based machines up to a maximum slope of 44% at which time the cost of cable harvesting would become cheaper per tonne (Figure 16). It is this cost and productivity difference that is driving the current shift towards putting ground-based machines onto steeper terrain, although, the capital investment required for a yarder compared to a skidder is also a significant driver.

It is generally acknowledged that cable extraction is a more environmentally friendly option compared to ground-based systems in steep terrain (Rice and Datzman, 1981). However, there are times when cable extraction is not a suitable option. This is typically as a result of cost rather than feasibility as a yarder can still operate on flat terrain using a simple high-lead system or using intermediate supports (Tiernan et al., 2002). A yarder is typically limited to operating within one gully in New Zealand as the use of intermediate spars is not common, due to the skill needed to implement these spars having been largely lost within New Zealand's forest industry. The poor strength of *Pinus radiata* is also seen as a factor. The cost of a yarder operation can be significant, particularly on woodlots or small harvest settings, due to one off costs, such as moving equipment on site, forming a much higher percentage of the total costs. These higher relative costs result in limited use of yarders over small settings, with a preference for ground-based equipment due to their lower moving cost and greater flexibility. The cost restriction of yarder crews on small settings has implications for New Zealand forest harvesting in the near future as a very large number of small-scale forests mature (Manley, 2010). The likelihood of these stands being of suitable scale to justify the cost of moving, setting up and operating a yarder seems unlikely. This large increase in small scale forests or woodlots is another key driver in the search for a more cost effective measure of harvesting on steep terrain in New Zealand.

This thesis will endeavour to improve the knowledge around the conditions that forestry machines operating on steep terrain encounter by determining the slopes the machines experience as well as the relationship between these and the slope of the ground surface. This information will be used to improve safety, reduce environmental impacts and reduce harvest cost. The information will aid in appropriate machine management by harvest planners prior to the beginning of harvesting and by forestry crews during the harvest operation.

3. Research Objectives

The research goals of this thesis are to improve our understanding of:

- Slope gradients that current forest machines experience when carrying out normal harvesting activities in New Zealand.
    - Such information to be included in this will be the average machine slope for each machine and machine type as well as time spent over the limit according to the ACOP guidelines.
- The relationship between the machine slope and the terrain slope it is working on.
    - In order to test this argument the null hypothesis was tested where:

      h_0: There is no difference between machine slope and terrain slope.

4. Methodology

4.1. Study area, site and machine selection

The study areas were split between New Zealand and Europe, with the majority of the research being conducted in New Zealand. The study areas in New Zealand included Canterbury, Nelson/Marlborough and Otago. Data collection started in April of 2011 through until the end of May, with continuation of data collection in the summer of 2011 to 2012. The exact location of the study sites was determined by the current operating locations of harvesting crews and equipment. The locations were selected with preference given to steep sites. The crew's equipment was an important consideration so as to ensure a good distribution of machine types in order to achieve the research objectives. The study areas in Europe were located in the Lillehammer region in Norway and the states of Carinthia and Lower Austria, Austria. Data collection in Norway and Austria was done during October and November of 2011.

The goal was to measure a minimum of three of each machine type in order to eliminate site based bias. There was no preference for machine make or model. The four machine types surveyed were:

- Excavator based felling machine
- Excavator based shovelling machine
- Wheeled articulating skidder
- Purpose built forestry machines based in Europe.

A total of 22 machines were sampled in the three countries (Table 3). All felling sites in New Zealand were large clear felled areas, while Norway used small clear felled areas. Both Austrian machines were operated in continuous cover/thinning based operations.

Table 3: List of machines studied their model and location

Machine type	Make and model	Location
Feller 1	Cat 325C	North Canterbury – New Zealand
Feller 2	Volvo FC3329C	Milton – New Zealand
Feller 3	Komatsu – model unknown	Nelson – New Zealand
Feller 4	Volvo FC3329C	Milton – New Zealand
Shovel 1	Hitachi 230	North Canterbury – New Zealand
Shovel 2	Cat 322C	Nelson – New Zealand
Shovel 3	Cat 325D	Nelson – New Zealand
Shovel 4	Sumitomo H300	Mosgiel – New Zealand
Shovel 5	Volvo – model unknown	Nelson – New Zealand
Skidder 1	Cat 545C - operator 1	North Canterbury – New Zealand
Skidder 2	Cat 545C - operator 2	North Canterbury – New Zealand
Skidder 3	Cat 518B	North Canterbury – New Zealand
Skidder 4	Tigercat 630D	Milton – New Zealand
Skidder 5	Timberjack 460D	North Canterbury – New Zealand
Skidder 6	Tigercat 620C	Milton – New Zealand
Skidder 7	Cat 535 B	Mosgiel – New Zealand
Skidder 8	Cat 535 C	Mosgiel – New Zealand
Skidder 9	Cat 535 B	Mid Canterbury – New Zealand
Harvester 1	Komatsu 901TX	Lower Austria – Austria
Harvester 2	Komatsu 911.4 Snake	Carinthia – Austria
Forwarder 1	Komatsu 890.1	Lillehammer – Norway
Harvester 3	Komatsu 941	Lillehammer – Norway

4.2. Machine slope

By combining a measure of machine slope and GPS, spatially explicit real-time machine slope was determined for the forest machines. In order to determine the slope that the working machine was achieving a method of continually measuring and logging the machine slope was needed. This was done with the use of a HOBO® Pendant™ G accelerometer (Onset Inc). This device allowed for three axes of data collection of slope gradients at a preset sampling rate. The sampling rate used was 2 Hz. This was selected to provide a large enough sample size from the machine with the limited storage of the device while still sampling at a high enough frequency to capture short events experienced by the machine. The software supplied with the unit made for easy data removal using the USB docking device provided, with outputs for both acceleration (ms^{-2} to a maximum of 29 ms^{-2}) and slope (degrees). The device allowed for an accurate measure of the slope the machines encountered during operation, as well as the velocity of the slope change. The machine vibration allowed for the identification of periods of time the machine was not working. The equipment was mounted at various locations depending on the type and layout of the machine. As it was the slope of the operating vehicle that was being collected, it was important to ensure that the data collected was that being experienced by the machine and not the machine operator. This was due to the slope experienced by the machine operator being different to that experienced by machine body, particularly for the machines with self-levelling cabs, primarily encountered in Europe. As a result of this the inclinometer was mounted on a non-levelling piece of the machine while collecting data from these self levelling machines. On non-levelling machines the device was generally mounted on the back of the cab unit. This was done to try and minimise the likelihood of it being knocked off and lost during operation. Prior to mounting it was ensured that the cab was mounted in a rigid fashion and not resting/mounted on rubber grommets etc. Due to the way that the data was analysed, the measure of slope was not affected by the orientation of the machine and as such was not impacted by the slewing of the excavator housing.

The slope of the machine (machine slope) was calculated using the Pendant values of tilt captured from each machine. The Pendant accelerometer used to determine machine slope calculated this as the slope of each axis (x, y and z) individually. The slope of the plane was then calculated using the pitch and roll of the vehicle for that moment in time.

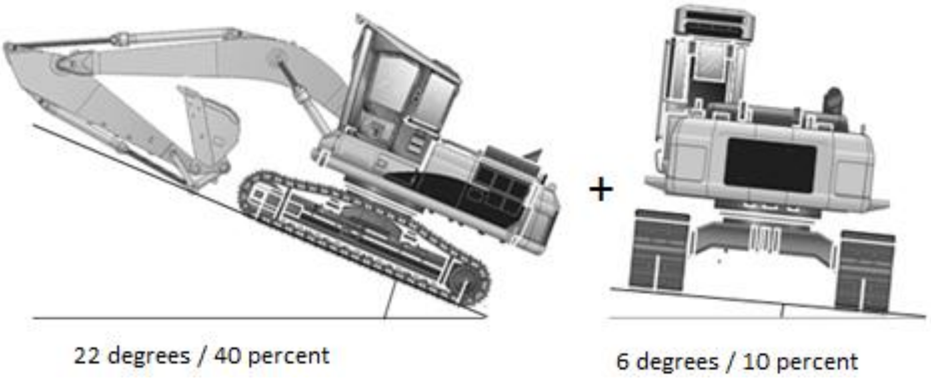

Figure 17 Showing an example of the slope of the two axes of a plane, the pitch (left) and the roll (right)

The pitch of the machine in Figure 17 is simply the machine gradient in the direction of travel, 22 degrees in this case. However, the slope of the plane of the two axes in Figure 17 is actually greater at 22.8 degrees, using the equation$= \cos^{-1}((\cos x) * (\cos y))$, due to the inclusion of roll in the calculation of the slope of the plane. Due to Microsoft Excel using radians and the Pendant providing data in degrees, the exact formula used was $= [\cos^{-1}((\cos(x * (\frac{\pi}{180})) * (\cos(y * (\frac{\pi}{180}))]*\left(\left(\frac{180}{\pi}\right)\right)$. The formula converts the degrees to radians for the calculation then converts the final answer back into degrees. Calculating the slope of the plane was important so as to match the data extracted from computer software when analysing the terrain slopes. The values of tilt used in the calculation were dependant on the orientation of the accelerometer when mounted on the vehicle. The use of slope of a plane removed the need to measure vehicle orientation or direction of travel, due to the ability of excavator to pivot about the Y axis.

4.3. Machine location

To be able to accurately plot the machines location for comparison with terrain slope a method of logging the machines location was needed. GPS devices were chosen for this task, GPS tracking of forestry machines is a common practice and has been proven to be an accurate measure of machine movement (Taylor et al., 2001; Veal et al., 2000). The GPS devices used were Garmin 60CSx and Garmin 62cs handhelds (Garmin Inc) with the use of a GPS12XL external antenna. The GPS unit employed an external antenna mounted on the roof of the machine to ensure a good GPS signal. This was particularly important in Europe where the use of thinning and selective harvesting methods meant that vegetation might impair GPS signal strength. This proved to not be the case with generally strong signal while operating (±3m accuracy). The GPS was set to log the location every second. In addition to the GPS location of the machine, this system also enabled the determination of altitude, speed and distance travelled. The GPS points were imported into in ArcMap using the add XY data from the tool menu, the created file was then saved as a shape file.

4.4. Terrain Slope

To answer the research question it was necessary to contrast the actual real-time machine slope with the estimated slopes faced by the machines. Estimated slopes were taken from contour maps. There were three different resolutions of contour data used; 5 metre contour data was used for all machines from Europe, with 10 and 20 metre contour data used in New Zealand. The 5m contour data in Europe was sourced from Skog og Landskap in Norway and BEV (Bundesamt für Eich und Vermessungswesen) in Austria. All 20m contour data in New Zealand was LINZ data, sourced with the use of koordinates.com. The 10m contour data was sourced from forest owners or manages. Not all of the machines measured had 10m contour data available for analysis but 20m contour data was available for all machines.

Two different methods were used to try and determine the slope of the terrain. Both methods used ArcMap (ESRI Ltd), version 9.3.1 build 3000, with the 3D analysis and spatial analysis tool extensions for ArcMap. Method one used a contour map that was converted to a TIN (triangular irregular network) file. A TIN file is a digital means to represent a surface, TINs are a form of vector based data and are constructed by triangulating a set of points. The points are connected with a series of edges to form a network of triangles. The non overlapping triangles represent the terrain surface, with the edges representing a change in the terrain surface. The TIN was created using the ‘create TIN from features’ in 3D analysis and a contour file as the input. The height source was set to the elevation of the contour file and triangulated as a hard line. The TIN file was then used to calculate the surface slope using 3D analysis ‘surface analysis’ to create a raster file of the slope. The raster file of the slope had the output measurement set to degrees and the Z factor and cell size (metres) both set to one. The second method of creating a raster of the slope converted the contour file into a raster file using the ‘Topo to Raster’ function rather than creating a TIN file. The Topo to Raster tool used the contour file as its ‘input feature data’ with the ‘Field’ selected as the contour files elevation and the ‘Type’ set to contour. The output cell size used was 5.8 metres for all machines and contour resolutions and all other variables were left as the default settings. The resulting raster was used to calculate the raster of slope using the same steps as method one.

A slope values from the rasters was assigned to each machine GPS location point using the ‘extract values to points’ feature, which is part of the spatial analysis extension in ArcMap. The ‘input point features’ were the machine GPS locations for that area, the ‘input raster’ was the slope raster created. The interpolate values at the point location was selected. This feature calculates the value from the cell as well as the cells adjacent using bilinear interpolation. The slope values corresponded to the value of the plane that each GPS point intercepted when the GPS points were overlaid over each raster of terrain slope. The data from the resulting file was then exported as a tab delimited text file and imported into the Excel workbook with the output of slope in degrees.

4.4.1. Slope measurement control test

In order to confirm that the accelerometer and the corresponding slope calculation were working as intended, lab testing was conducted. The test consisted of measuring the slope of a known plane with the accelerometer and then checking the output to confirm that the accelerometer and the calculation used to calculate the slope were both working correctly. The process consisted of mounting the accelerometer on a piece of wood (50mm x 100mm x 100mm) and placing the piece of wood with the accelerometer mounted on it on a larger board of which the slope was known. The smaller piece of wood was then moved around on the larger piece so as to generate some vibration or noise while measuring the slope. This was repeated, increasing the slope of the larger board at 10^{o} increments from zero through to 60^{o}. The movement was logged for 30 seconds per increment with a 2 Hz measuring frequency. The data showed that the accelerometer and the slope calculation were working correctly, although there was a small amount of ‘noise’ associated with it ($\pm 1.1^{o}$ average).

4.4.2. In field data collection

The tracking data from the GPS was stored on the micro SD card to allow for more storage space and reduce the risk of data loss. The time from the accelerometer was synchronised with the GPS to allow for the data to be easily merged at the completion of each machine study. Additional data collected onsite included the make and model of the vehicle being studied, the task being performed and machine location.

4.5. Data compiling

The initial data was collected from the machines with the use of the described Pendant accelerometer and GPS data. The data from these was then downloaded to a computer using the Hoboware© computer program for the Pendant data and a combination of DNR Garmin

(Version 5.04, Minnesota Department of Natural Resources) and MapSource (Version 6.15.7, Garmin Inc) computer programs for the GPS. All programs allowed for the data to be saved as a tab delimited text file which was then opened in Microsoft Excel. All the data was then compiled into a single Excel work book, with one workbook used per machine. The spread sheet included information from the GPS; x and y coordinates, altitude, date, time, leg length (distance between a point and the point preceding it), and leg speed (speed between a point and the point preceding it). Information from the Pendant software gave the three axes of acceleration (ms^{-2}) required to calculate slope, which were given as a ‘Tilt’ of X, Y and Z. All information from the Pendant was input into the spreadsheet which included time, acceleration of the X, Y and Z axis and their corresponding tilt values. The calculation of real-time slope was then done using the two appropriate values of ‘tilt’, depending on the orientation of the pendant when mounted on the machine. The terrain slope was one column for each DTM used, which was dependent on the number of data resolutions available.

4.5.1. Data post-processing

Due to the noise established in lab testing it was appropriate to average the measure of slope over a number of points so as to get a more realistic measure of machine slope. This was done by using a moving average whereby the slope output was averaged over 10 data points (5 seconds). This proved effective at removing the noise in the lab testing and as such was applied to the data collected from the machines.

Due to the high frequency of the Pendants data collection and the means of the slope collection (accelerometer) there was occasionally a slope artefact in the data sets of the machines. This was resolved by forcing the slope calculation for each measurement to ignore any value that was above a predetermined limit, limiting the calculation to include only values deemed as feasible for a machine to reach on that axis without rolling. The spreadsheet was written to give an output on the total number of errors and the percentage of errors relative to the total number of measurements. The artifact percentage was typically below 0.2% of the total data collected.

Due to the nature of the study it was important to exclude data collected while the machine was idle. An idling machine would have serious impacts on the averages and distribution of slope if included in the data analysis. To resolve this machine slope data was analysed after the idle time was removed. This was achieved by writing into the slope equation a requirement for the machine to have a varying degree of slope over a set interval for the data to be included. This was done prior to the averaging of the machine slope. This method assumed that there was a degree of noise with regards to the vibration of the working machine. This method proved adequate in removing idle time, which was cross checked with the GPS data to ensure the machine was indeed stationary.

4.6. Statistical analysis

The collated data was explored in Excel to determine if there were any basic relationships between the slope of the DTM and the machine slope. The machine slope was analysed with respect to the DTM slope to determine the residual of the two measures of slope. The use of Excel also allowed for easy graphical representation of the slope experienced during each machines working period. Excel proved to be inadequate for in-depth analysis due to the large nature of the data sheets.

More in-depth data analysis was done using the software package R (version 2.13.2) as it was better suited to doing statistical analysis with large data sheets. Statistical analyses were performed in order to answer the null hypothesis that there is no difference between the machine slope and the terrain slope as it is determined from the DTM. Linear regression was used to model the relationship where lm: $\text{slope}_{\text{machine}} \sim \text{slope}_{\text{terrain}}$. A summary of the linear regression provided by R gave values for the residuals, coefficients and the stand error. Differences were considered statistically significant at a level of $p\text{-value}<0.05$.

5. Results

5.1. Evaluation of Terrain Slope

Deriving a continuous slope surface in ArcMap from contour data can be achieved in two ways, from either a TIN or a raster. Both of these data models were used to give a measure of terrain slope. These two models were contrasted to determine which was more appropriate for comparison with measured machine slope. Method one, which used a TIN file to calculate slope, resulted in a large proportion of zero values due to the manner in which the slope value was calculated, combined with the way in which the TIN file was created. The flat areas of a TIN file result from a triangle that is formed from three points at the same elevation value (Figure 18).

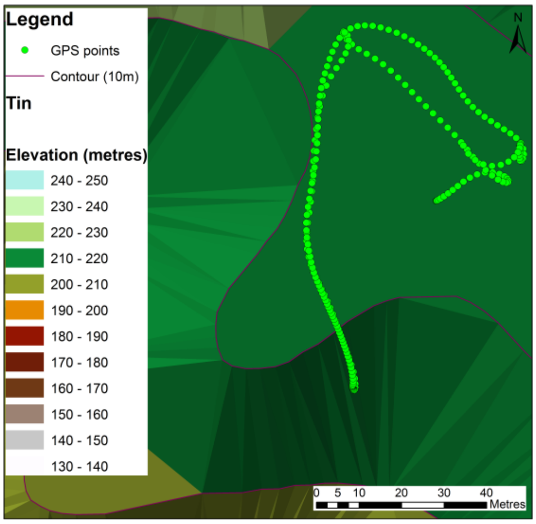

Figure 18: Showing a TIN made using 10 metre contours, note the large amount of flat areas. The skidder GPS points illistrate where the machine was located during a single drag during the period of the study. While a visiual interpritation suggests the skidder is working on a ridge the majority of the individual GPS points are located on the flat areas of the TIN

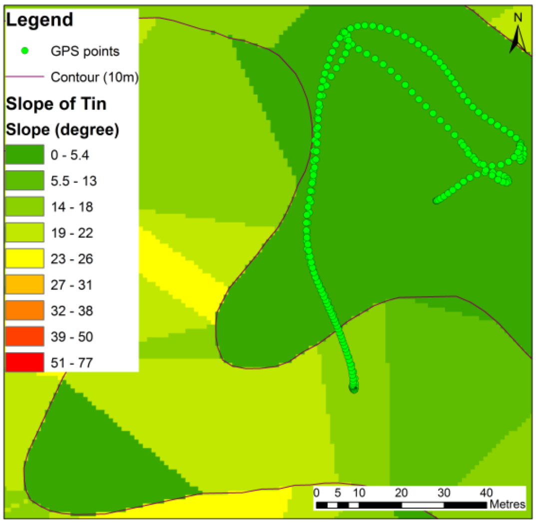

Figure 19: Showing the resulting slope raster created from the TIN pictured in Figure 18. Note how the areas of slope closely reflect that of the TIN.

Note how in Figure 19 the slopes closely resemble the structure of the TIN file used to create it (Figure 18). There is also rapid change in the slope at the edges of the each triangular surface. The alternative raster method (method 2) showed an advantage over using a TIN as it didn’t create large amounts of flat land (slope = 0 degrees) with all values of elevation being determined from the contour independently (Figure 20).

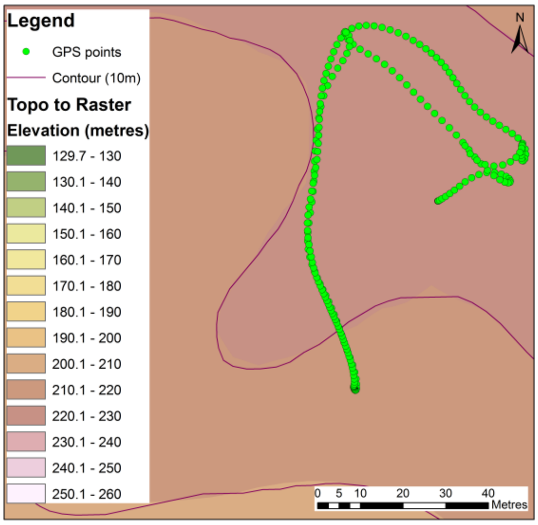

Figure 20: Showing the Topo to Raster file made with a 10 metre contour. GPS points illistrate where the machine was located during a single drag during the period of the study.

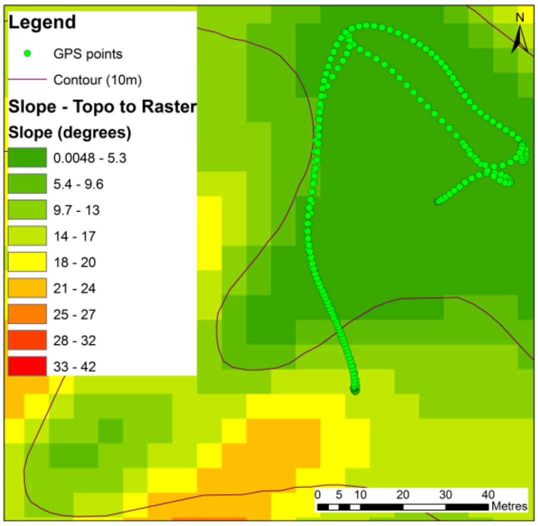

Figure 21: Showing the resulting slope raster created from the Topo to Raster file pictured in Figure 20. Note how slope areas don't as closely resemble that of the contour file with much slower transitions in slope.

The disadvantage with the Topo to Raster method was its limitation due to cell size. The cell size was restricted when constructing large raster files due to the maximum file size that the computer was able to create. The cell size could be reduced by clipping the contour file to just cover the working area, resulting in a useable cell size.

The variability between the two resolutions, 20m and 10m, of contour data illustrates the disadvantage of using the TIN method to calculate terrain slope. Using the TIN to determine slope (method one) resulted in a large amount of zero values being calculated. Figure 22 (felling), Figure 24 (shovelling) and Figure 26 (skidder) show the disparity that occurred between 20 and 10 metre DTMs using method one for the three types of machines studied in New Zealand. These figures are to illustrate the difference in slope distribution between the two methods and between the two resolutions of contour data. Due to the lesser availability of the higher resolution 10m contour data some machines slope data is not represented at this level. It is clear from all three figures that method one shows a poor slope distribution and over represents the frequency of zero slope (flat) area that the machine encountered. Method 2, comparatively, showed a much better distribution of slope (Figure 23 [felling], Figure 25 [shovelling] and Figure 27 [skidder]) with a much more realistic frequency of zero values. Due to this all individual machines were analysed using method 2 only, however all analysis of machines by machine type was done using both methods.

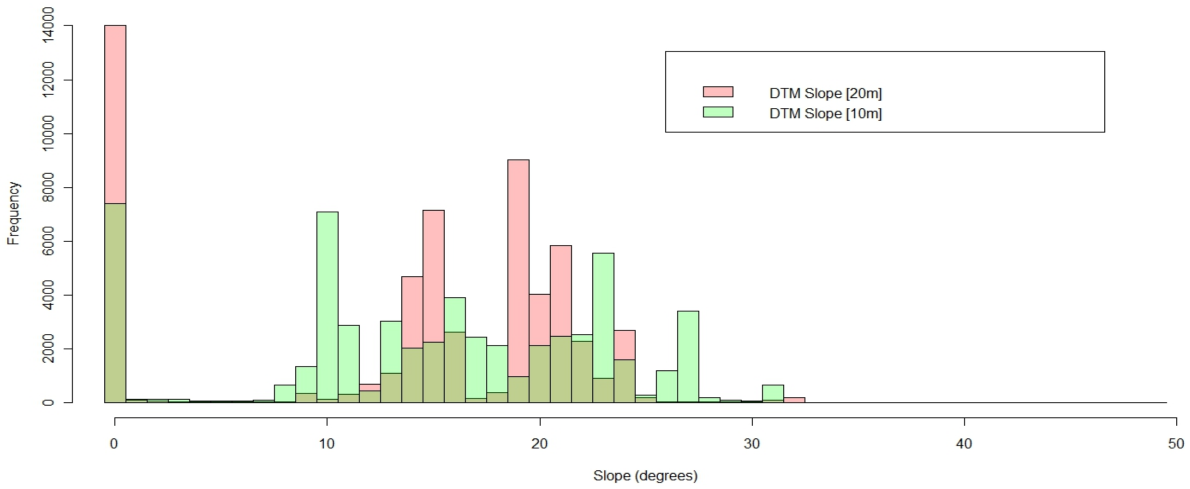

Figure 22: The frequency of slopes experienced by all felling machines based on the two levels of DTM data, 20 metre and 10 metre contours for method 1. Note the darker green colour shows where the two bars overlap.

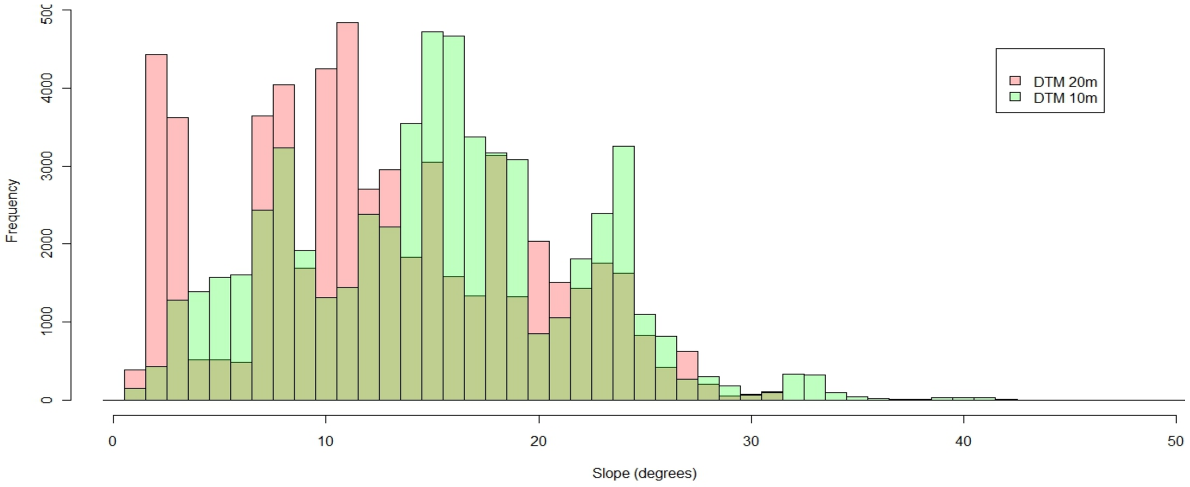

Figure 23: The frequency of slopes experienced by all felling machines based on the two levels of DTM data, 20 metre and 10 metre contours for method 2.

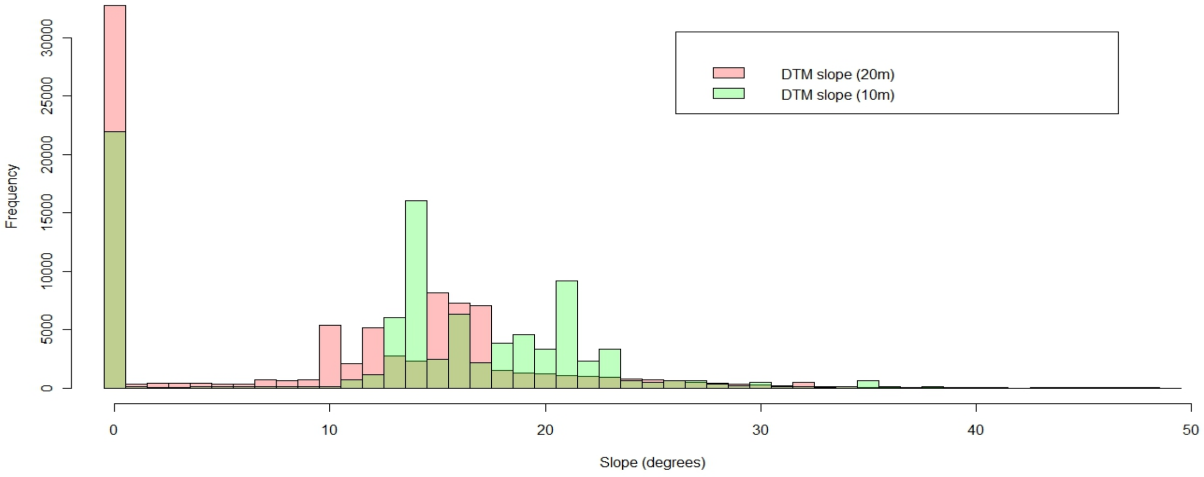

Figure 24: The frequency of slopes experienced by shovelling machines based on the two levels of DTM data, 20 metre and 10 metre contours for method 1.

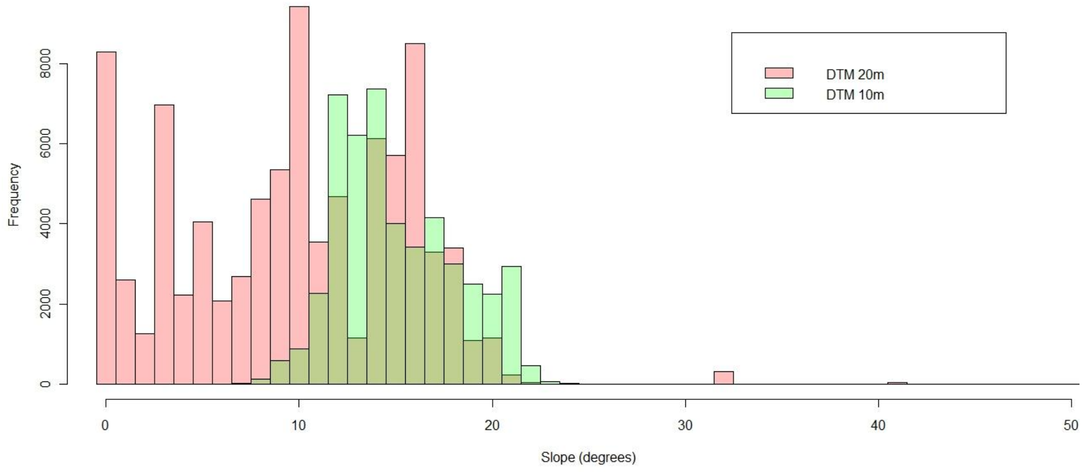

Figure 25: The frequency of slopes experienced by shovelling machines based on the two levels of DTM data, 20 metre and 10 metre contours for method 2.

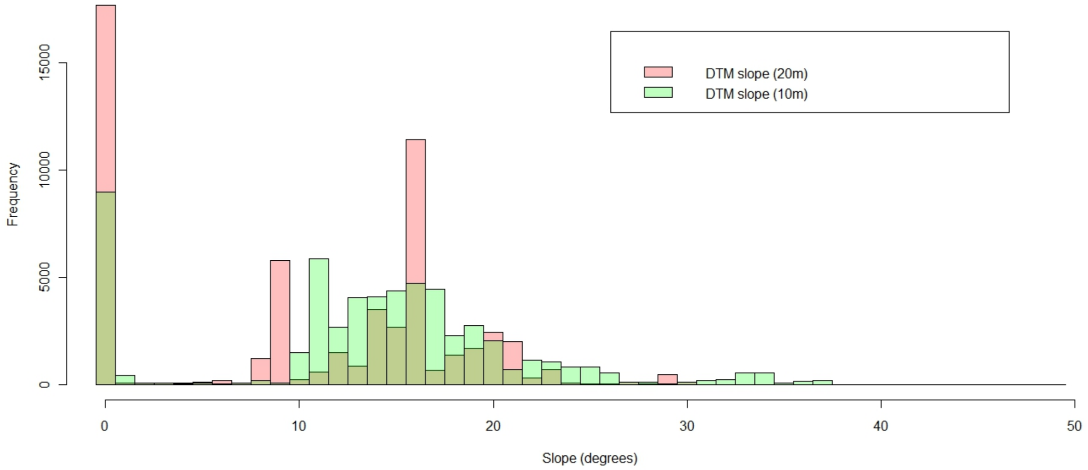

Figure 26: The frequency of slopes experienced by skidders based on the two levels of DTM data, 20 metre and 10 metre contours for method 1.

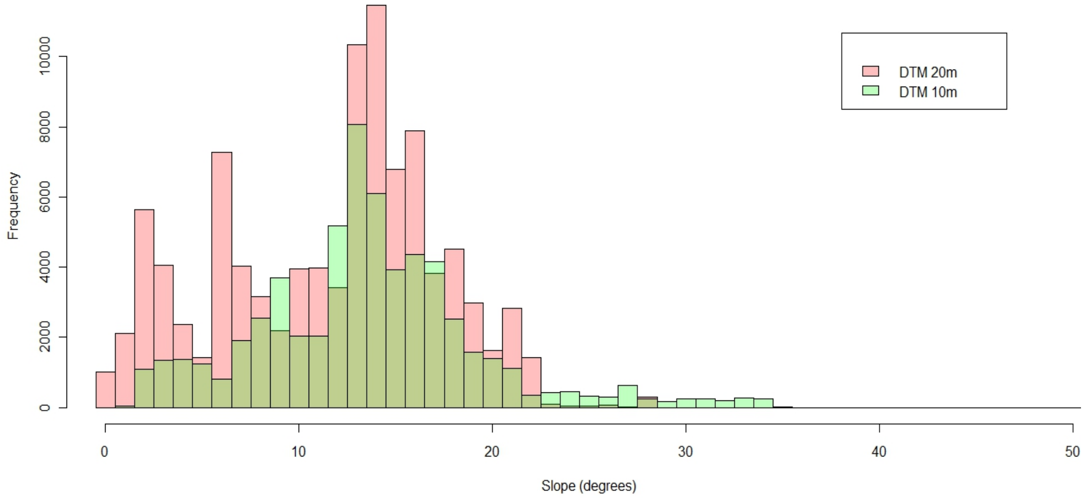

Figure 27: The frequency of slopes experienced by skidders based on the two levels of DTM data, 20 metre and 10 metre contours for method 2.

Analysis of the data was done to determine if there was statistical difference between the two different methods as well as between the two resolutions used for all 3 machine types (Table 4).

Table 4: Showing the P values for a Wilcoxon signed rank test for the two methods of slope at both elevation levels. This was done to determine if there was a statistical difference between the two methods as well as between the two different data resolutions.

	Method and resolution analysed	p-value
Feller	Method 1 - 20m ~ Method 2 - 20m	<0.001
	Method 1 - 10m ~ Method 2 - 10m	<0.001
	Method 1 - 20m ~ Method 1 - 10m	<0.001
	Method 2 - 20m ~ Method 2 - 10m	<0.001
Shoveller	Method 1 - 20m ~ Method 2 - 20m	<0.001
	Method 1 - 10m ~ Method 2 - 10m	<0.001
	Method 1 - 20m ~ Method 1 - 10m	<0.001
	Method 2 - 20m ~ Method 2 - 10m	<0.001
Skidder	Method 1 - 20m ~ Method 2 - 20m	<0.001
	Method 1 - 10m ~ Method 2 - 10m	0.01685
	Method 1 - 20m ~ Method 1 - 10m	<0.001
	Method 2 - 20m ~ Method 2 - 10m	<0.001

All variables tested proved to be statistically different at the 0.05 significance level. Thus we reject the null hypothesis and conclude that the elevation values derived from 10m contours differ from the elevation values derived from 20m contours. Furthermore, we conclude that the elevation values derived from the TIN method differ from the elevation values derived from the raster method.

5.2. Summary of Machine and DTM slopes

A summary of the individual machine slopes is given in Table 5. The table includes each individual machine's averages, 95th and 5th percentiles for machine and DTM slopes using method one as well as overall averages for the four machine types. The difference between the machine slope measured and the terrain slope calculated from the DTM was also determined.

Table 5: Individual machine and DTM slopes (method 1) with 5th and 95th percentiles and the machine slope minus the respective DTM slope (* used 20m DTM data, ** used 5m DTM data)

	Average Machine Slope (5th, 95th percentile)	Average DTM slope - method 1 (5th, 95th percentile)	Machine slope minus DTM slope method 1
Feller 1	22.9 (12.4, 31.9)	21.0 (11.8, 27.1)	1.9(0.6,4.8)
Feller 2	14.1 (7.4, 22.0)	15.6 (0.0, 28.6)	-1.5(7.4,-6.6)
Feller 3	22.4 (10.7, 36.4)	16.1 (0.0, 23.3)	6.3(10.7,13.1)
Feller 4	15.2 (7.5, 26.3)	12.3 (0.0, 17.9)	2.9(7.5,8.4)
Feller Average	**18.6 (9.5, 29.1)**	**16.2 (2.9, 24.2)**	**2.4(6.6,4.9)**
Shovel 1	23.5 (15.0, 33.0)	15.6 (12.9, 20.6)	7.9(2.1,12.4)
Shovel 2	14.4 (6.4, 25.6)	22.5 (20.3, 30.2)	-8.1(-13.9,-4.6)
Shovel 3*	14.2 (6.0, 24.1)	8.2 (0.0, 15.9)	6.0(6.0,8.2)
Shovel 4*	16.3 (8.9, 24.5)	15.1 (13.2, 18.4)	1.2(-4.3,6.1)
Shovel 5	21.1 (10.7, 33.1)	17.8 (0.0, 31.5)	3.3(10.7,1.6)
Shovel Average	**17.9 (9.4, 28.1)**	**15.9 (9.3, 23.3)**	**2.0(0.09,4.8)**
Skidder 1	17.1 (9.2, 29.1)	17.6 (10.8, 34.4)	-0.5(-1.6,-5.3)
Skidder 2	17.2 (8.9, 26.3)	17.9 (10.8, 33.9)	-0.7(-1.9,-7.6)
Skidder 3	6.4 (4.2, 9.5)	11.6 (0.0, 26.0)	-5.2(0.2,-16.5)
Skidder 4	17.9 (6.3, 29.9)	8.7 (0.0, 19.2)	9.2(6.3,10.7)
Skidder 5	14.3 (8.2, 23.1)	18.7 (14.9, 24.1)	-4.4(-6.7,-1)
Skidder 6	14.4 (5.3, 22.2)	12.4 (0.0, 20.4)	2(5.3,1.8)
Skidder 7*	11.6 (3.1, 19.2)	15.1 (12.7, 19.0)	-3.5(-9.6,0.2)
Skidder 8*	13.1 (4.5, 21.1)	14.5 (1.9, 19.1)	-1.4(2.6,2)
Skidder 9	16.1 (5.9, 23.9)	13.0 (7.9, 16.9)	3.1(-2,7.0)
Skidder Average	**14.3 (6.2, 22.7)**	**14.4 (6.6, 23.7)**	**-0.01(-0.4,-1)**
Harvester 1**	22.2(6.8, 36.5)	19.5 (16.4, 20.4)	2.7(-9.6,16.1)
Harvester 2**	20.7 (6.8, 35.6)	20.2 (12.1, 28.9)	0.5(-5.3,6.7)
Forwarder 1**	13.8 (5.5, 24.9)	21.4 (12.9, 33.3)	-7.6(-7.4,-8.4)
Harvester 3**	11.1 (5.8, 16.8)	16.8 (11.6, 24.3)	-5.7(-5.8,-7.5)
European Average	**17.0 (7.0, 28.5)**	**19.5 (13.2, 26.7)**	**-2.5(-6.2,1.8)**

Of the four machine types measured the felling machines appeared to be operating on the steepest slopes with regards to real-time machine slope. The felling machines operated on an average slope of 18.6 degrees with excavator based shovelling machines on similar terrain slopes at 17.9 degrees. It was expected that shovelling and felling machines would see similar results as, although the machines were performing different tasks, they were still operating on similar terrain and handling similar payloads (whole tree lengths). European machines operated on the next steepest slopes at 17.0 degrees followed by skidders at 14.9 degrees. There was statistical difference (p-value= <0.001), at the 0.05 significance level, between all four of the machine types with respect to slope. However this is a reflection of the slopes that the machines are operated on not a measure of whether the machine was operated on a slope steeper than would have been expected based on machine operation or design. As such the difference between the machine slope and the DTM slope was calculated to determine if there was a statistical difference between machine types. The null hypothesis of the statistical analysis was that there would be no difference between the machine slope minus the terrain slope for the four machine types. Analysis using a Kruskal-Wallis rank sum test showed that there was a significant difference (p-value= <0.001), at the 0.05 significance level, between the four populations. As such the null hypothesis was rejected and it was concluded that the 4 machine types experienced different machine slopes with respect to their terrain slope.

Table 6 shows a summary of the individual machine slopes is using method 2. The table includes each individual machine's averages, 95th and 5th percentiles for machine and DTM slopes as well as overall averages for the four machine types. The difference between the machine slope measured and the terrain slope calculated from the DTM was also determined.

Table 6: Individual machine and DTM slopes (method 2) with 5th and 95th percentiles and the machine slope minus the respective DTM slope (* used 20m DTM data, ** used 5m DTM data)

	Average Machine Slope (5th, 95th percentile)	**Average DTM slope - method 2 (5th, 95th percentile)**	**Machine slope minus DTM slope method 2**
Feller 1	22.9 (12.4, 31.9)	25.0(17.1,33.6)	-2.1(-19.7,11.7)
Feller 2	14.1 (7.4, 22)	15.7(10.1,19)	-1.7(-8.2,7.6)
Feller 3	22.4 (10.7, 36.4)	16.6(4.3,24.8)	5.8(-10.8,22.6)
Feller 4	15.2 (7.5, 26.3)	10.2(2.9,16.4)	5.0(-3.8,13.1)
Feller Average	**18.6 (9.5, 29.1)**	**16.9(8.6,23.4)**	**1.8(10.6,13.8)**
Shovel 1	23.5 (15.0, 33.0)	13.7(10.6,20.8)	9.8(-0.5,19.7)
Shovel 2	14.4 (6.4, 25.6)	15.5(12.8,18)	-1.2(-10.7,11.1)
Shovel 3*	14.2 (6.0, 24.1)	6.8(4,9.8)	7.5(-1.8,18.1)
Shovel 4*	16.3 (8.9, 24.5)	15.4(11.3,18.3)	0.9(-6.9,9.7)
Shovel 5	21.1 (10.7, 33.1)	16.8(10.2,21.4)	4.3(-7.3,17.4)
Shovel Average	**17.9 (9.4, 28.1)**	**13.6(9.8,17.7)**	**4.3(-5.4,15.2)**
Skidder 1	17.1 (9.2, 29.1)	17.6(9.5,33)	-0.6(-20.1,17.4)
Skidder 2	17.2 (8.9, 26.3)	17.5(8.4,33)	0.1(-20.3,16.8)
Skidder 3	6.4 (4.2, 9.5)	13.4(2.1,26.6)	-6.9(-21.4,4.7)
Skidder 4	17.9 (6.3, 29.9)	9.9(3.4,18.4)	8.0(-4.0,19.7)
Skidder 5	14.3 (8.2, 23.1)	17.9(13.5,21.4)	-3.5(-11.7,8.7)
Skidder 6	14.4 (5.3, 22.2)	12(4.2,18.5)	2.3(-5.3,10.5)
Skidder 7*	11.6 (3.1, 19.2)	16.2(10.7,21.8)	-4.6(-15.1,5.5)
Skidder 8*	13.1 (4.5, 21.1)	16(10.4,21.8)	-2.8(-13.2,7.3)
Skidder 9	16.1 (5.9, 23.9)	13.6(11.7,16.3)	2.5(-7.4,10.7)
Skidder Average	**14.3 (6.2, 22.7)**	**14.9(8.2,23.4)**	**-0.5(-13.2,11.3)**
Harvester 1**	22.2(6.8, 36.5)	19.5(17.7,21)	2.7(-12.5,15.9)
Harvester 2**	20.7 (6.8, 35.6)	19.7(10.9,30.1)	-0.8(-18.8,15.9)
Forwarder 1**	13.8 (5.5, 24.9)	21.7(13.5,33.3)	-7.6(-24.2,-9.2)
Harvester 3**	11.1 (5.8, 16.8)	16(11.3,23)	-5.7(-15.4,-5.7)
European Average	**17.0 (7.0, 28.5)**	**19.2(13.3,26.8)**	**-2.9(-17.7,4.3)**

Analysis using a Kruskal-Wallis rank sum test was also done for the difference between machine slope and terrain slope calculated using method 2. The analysis again showed that there was a significant difference (p-value= <0.001), at the 0.05 significance level, between the four populations. As such the null hypothesis was rejected and it was concluded that the 4 machine types experienced different machine slopes with respect to their terrain slope for method 2.

5.3. Individual Machine Evaluation

One machine was analysed to determine the limitations of analysing the machines on an individual basis. One of the major limitations with individual machine analysis was that one machine might have stark differences in slope due to an unknown variable and result in an unrealistic depiction of what the machine was doing. An example of this is shown in Figure 28 and Figure 29, which show that the machine was either being driven in such a fashion that it was experiencing much steeper grades than would be expected, or that the two methods of slope calculation both underestimate the slope of the terrain. Another example of a different skidder is shown in Figure 30 using method 2 to illustrate the vast difference between individual machines.

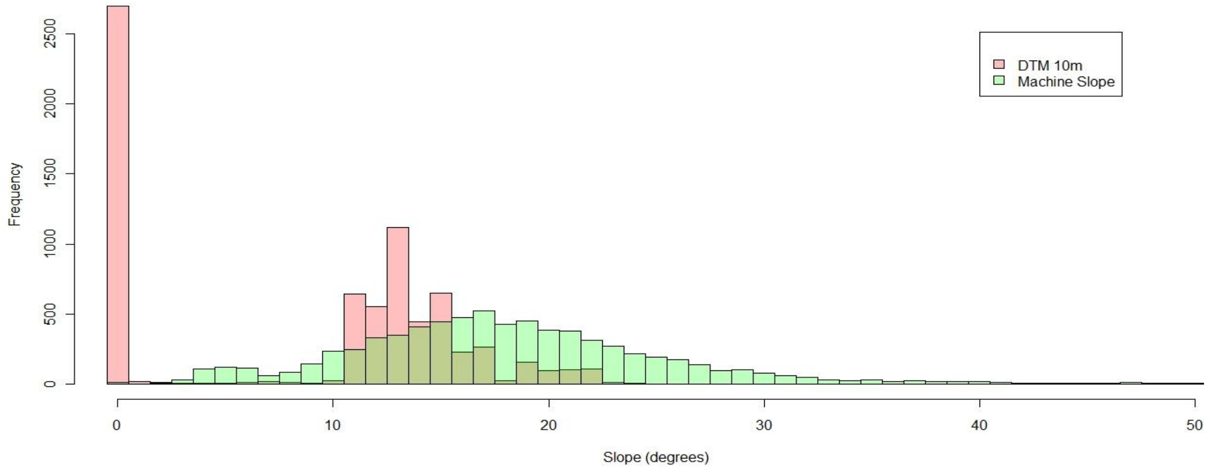

Figure 28: The frequency of slopes experienced by skidder 4 (Machine slope and 10m DTM slope [method 1]).

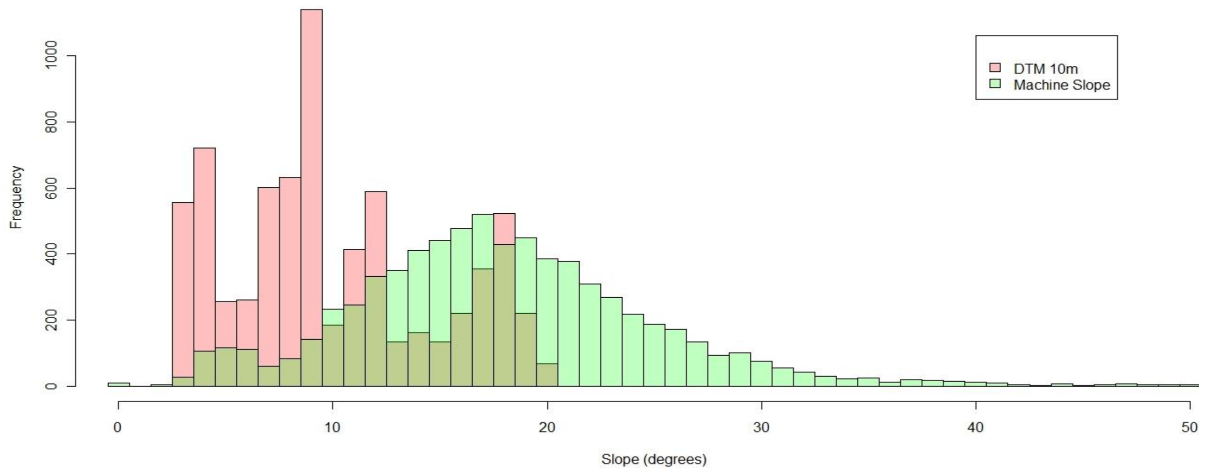

Figure 29: The frequency of slopes experienced by skidder 4 (Machine slope and 10m DTM slope [method 2]).

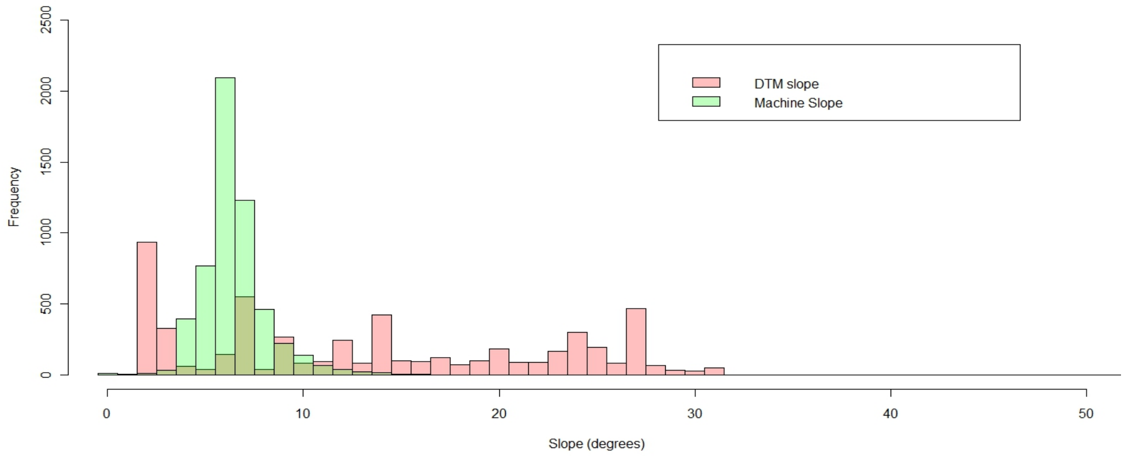

Figure 30: The frequency of slopes experienced by skidder 3

The two graphs (Figure 29 and Figure 30) show very different relationships between terrain and machine slope as well a very different distribution of terrain slope (see Appendix for all individual machine figures). For these reasons it was deemed necessary to group the data based on machine type.

5.4. Evaluation of Machine Categories

For this analysis data from machines of the same type (felling machines, shovelling machines, skidders or European based machines) was combined to try and establish if there was a correlation between machine slope by type and DTM slope. The combining of the machines by type was done to try and build a more robust data set for the regression analysis. The combining was also done to try and reduce the impact individual operators or machines had on the total regression analysis, with one of the aims of the research attempting to see if it was possible to predict machine slope based on DTM slope alone.

5.4.1. Shovelling

Shovelling machines operated on average at 17.8 degrees machine slope and a 95th percentile of 30 degrees. Figure 31 and Figure 32 show the distribution of the slopes experienced by shovelling machines, as well as that calculated using the two methods of slope based on the terrain covered by the machine.

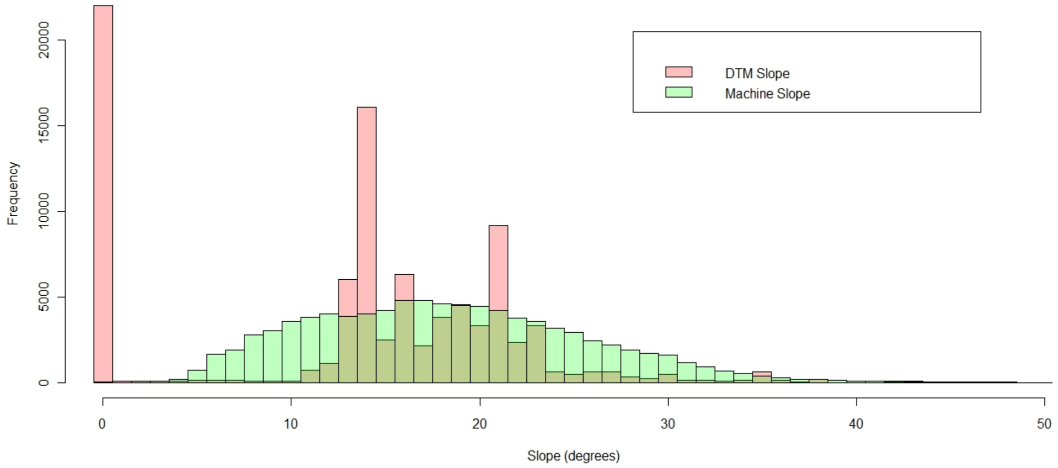

Figure 31: The frequency of slopes experienced by all shovelling machines monitored (Machine slope and 10m DTM slope [method 1]).

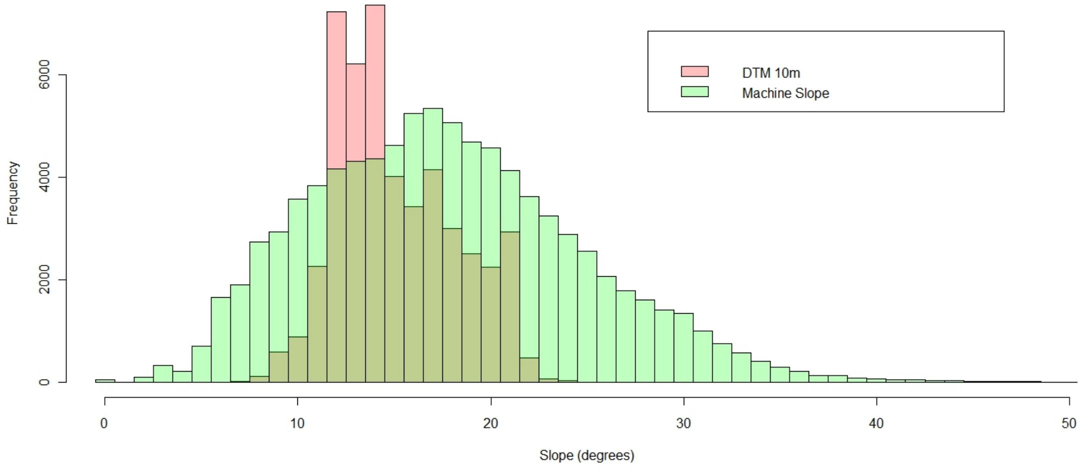

Figure 32: The frequency of slopes experienced by all shovelling machines monitored (Machine slope and 10m DTM slope [method 2]).

The slopes experienced by the shovelling machines are vastly different to those given by the DTM slope, using method one, for the same terrain, with a large proportion of the slopes given as zero slopes. Method two showed a much better distribution of slopes and did not seem to over represent the proportion of flat areas. A box and whisker graph (Figure 33) was used to show the variation between the machine slope and DTM slope calculated using method one.

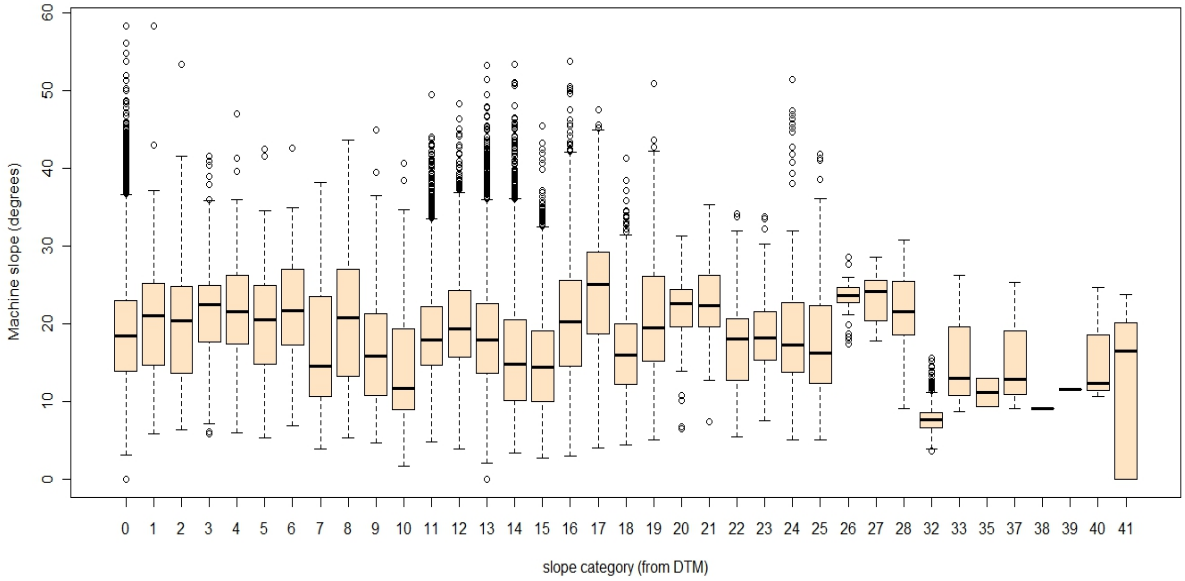

Figure 33: Box and whisker showing the disparity between machine slope and 20m DTM slope [method 1] for shovelling machines

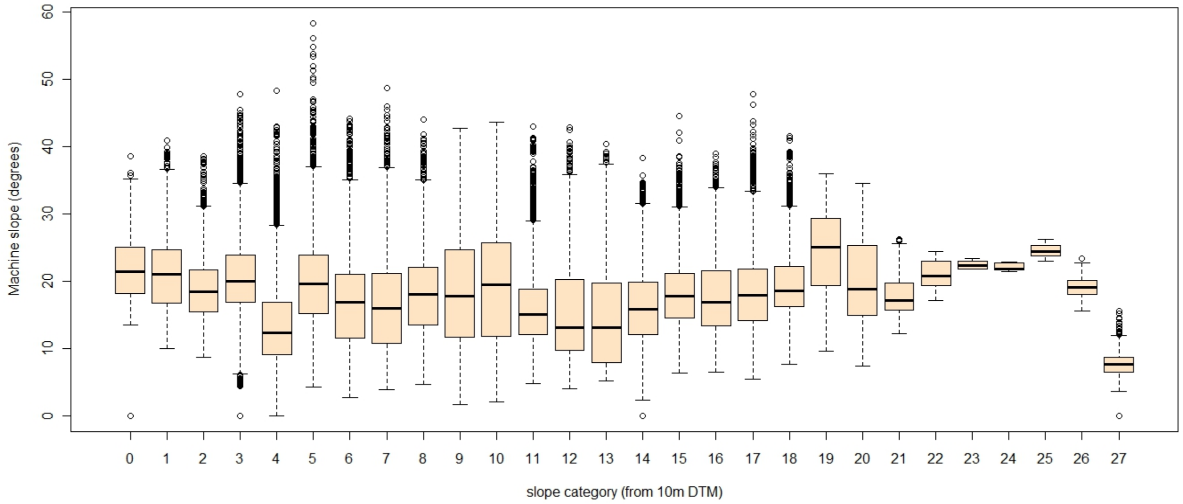

Figure 34: Box and whisker showing the disparity between machine slope and 20m DTM slope [method 2] for shovelling machines.

It is clear that the large number of values of zero from the DTM distorts the data, with machines experiencing slopes from zero to greater than 58 degrees on areas that the DTM gives as zero. Similarly, this occurred with other slopes of the DTM that were over represented, such as the 14 and 21 degree categories. Method two (Figure 34) showed a similar pattern, with a larger number of outliers. The box and whisker graphs often showed errors at the extreme ends of the DTMs data slope range. Figure 35 shows a box and whisker graph overlaid over with the corresponding histogram of the same DTM.

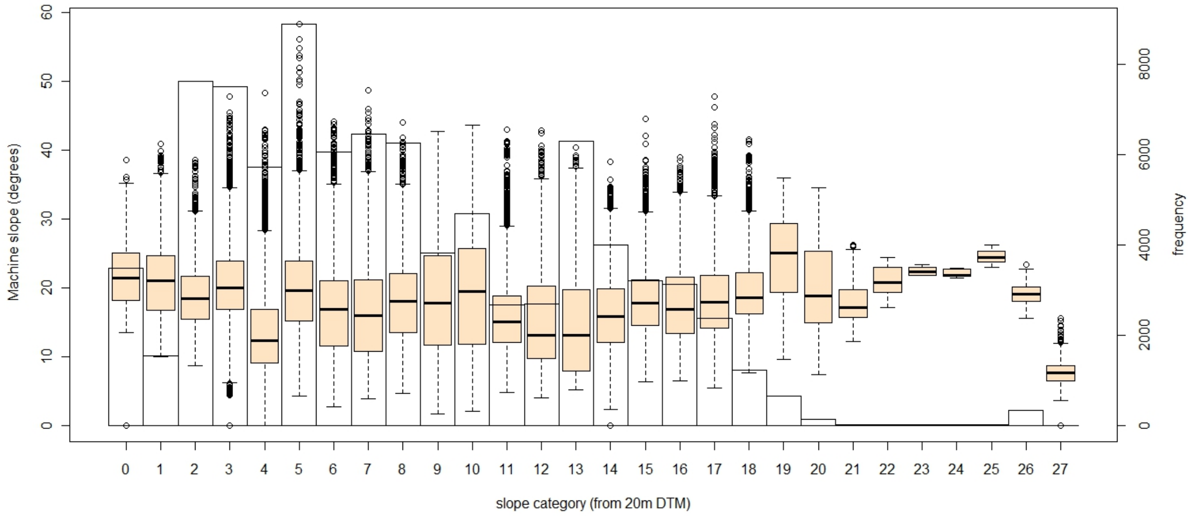

Figure 35: Box and whisker showing the disparity between machine slope and 20m DTM slope [method 2] with the distribution of the 20m DTM slope [method 2]

Figure 35 shows that the distribution of the machine slope shows less variation at the high slope ranges, in this case greater than 19 degrees. This is in fact a result of the machine having limited interaction with that particular DTM slope. This is due to the machine only crossing the raster cell with said slope value on a limited number of occasions. As such the box and whisker should be used with caution outside the range of slopes with relatively high frequencies.

5.4.2. Felling

Felling machines operated on slopes up to 31.1 degrees at the 95th percentile with the average slope being 19.1 degrees. Figure 36 and Figure 37 show the distribution of the slopes experienced by the felling machines monitored as well as that given by the two methods of DTM based on the terrain the machine covered.

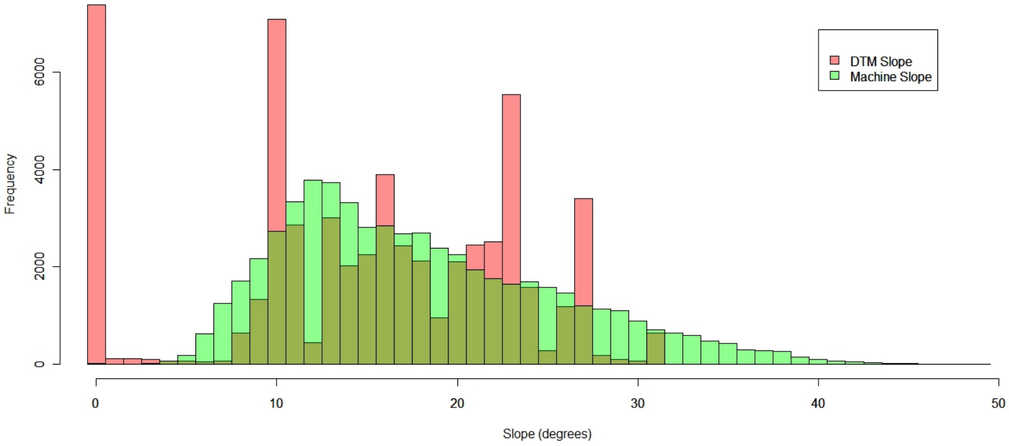

Figure 36: The frequency of slopes experienced by all felling machines monitored (Machine slope and 10m DTM slope [method 1]).

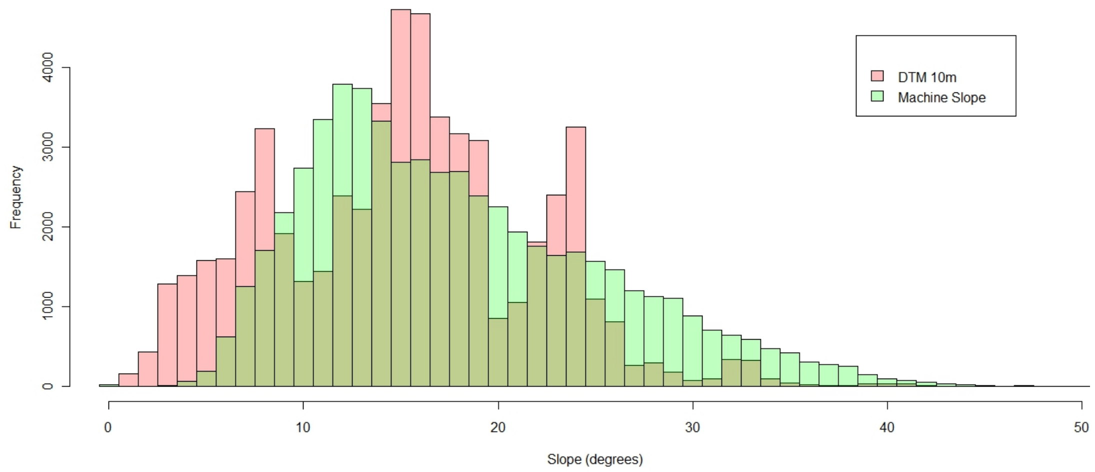

Figure 37: The frequency of slopes experienced by all felling machines monitored (Machine slope and 10m DTM slope [method 2]).

The slopes experienced by the felling machines are again, as with shovelling machines, different to those given by the DTM slope, using method one, with a large proportion of the slopes given as zero slopes. Method two again showed a better distribution of slopes and did not over represent the proportion of flat areas.

The box and whisker graphs (Figure 38 and Figure 39) show the difference between what the DTMs assumed the slope to be compared to the slope actually experienced by the machine.

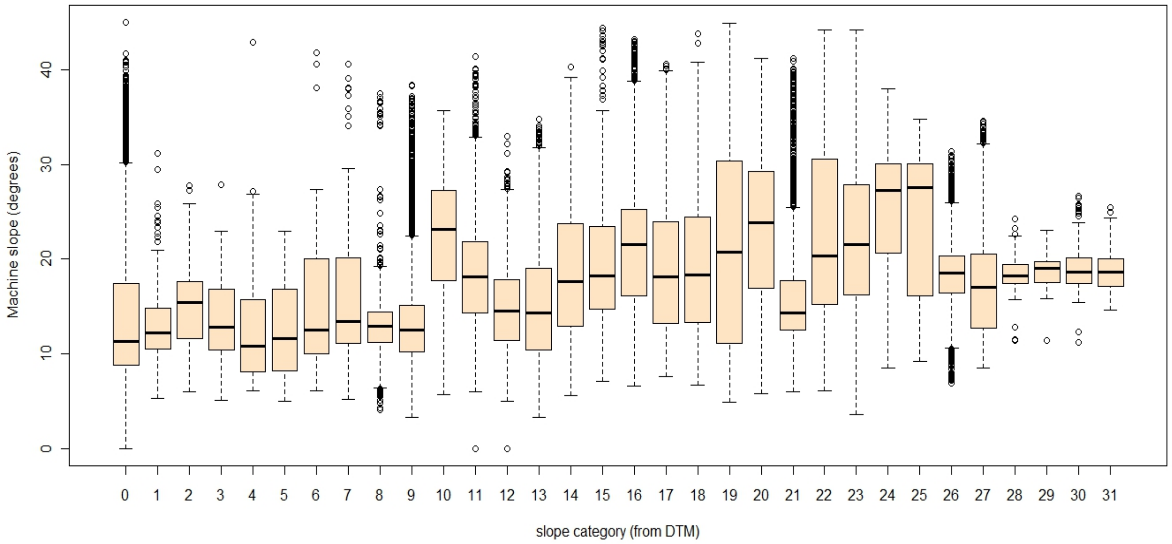

Figure 38: Box and whisker showing the disparity between machine slope and 10m DTM slope for felling machines [method 1].

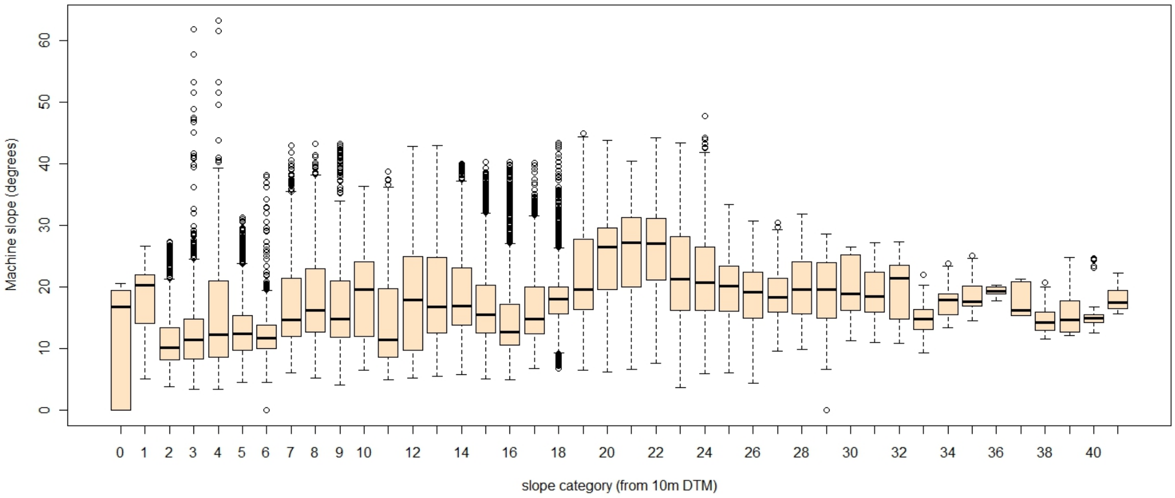

Figure 39: Box and whisker showing the disparity between machine slope and 10m DTM slope for felling machines [method 2].

As with the shovel data it is clear that the large number of values of zero from the DTM distorts the data as well as other slopes the DTM that were overrepresented, such as the 9 and 21 degree categories. Method two (Figure 39) showed a similar pattern, with a larger number of outliers on slope categories that appeared to be overrepresented.

5.4.3. Skidders

In general the skidders studied operated on lower slopes, on average, than those of any of the other machines, with respect to both machine slope (12.9 degrees) and DTM (14.3 degrees). As with the other New Zealand based machine types, the skidder’s DTM data again showed a very high proportion of zero values being calculated when using method 1, as well as a large frequency of a few numbers rather than a more normal distribution, such as that of the machine slope (Figure 40).

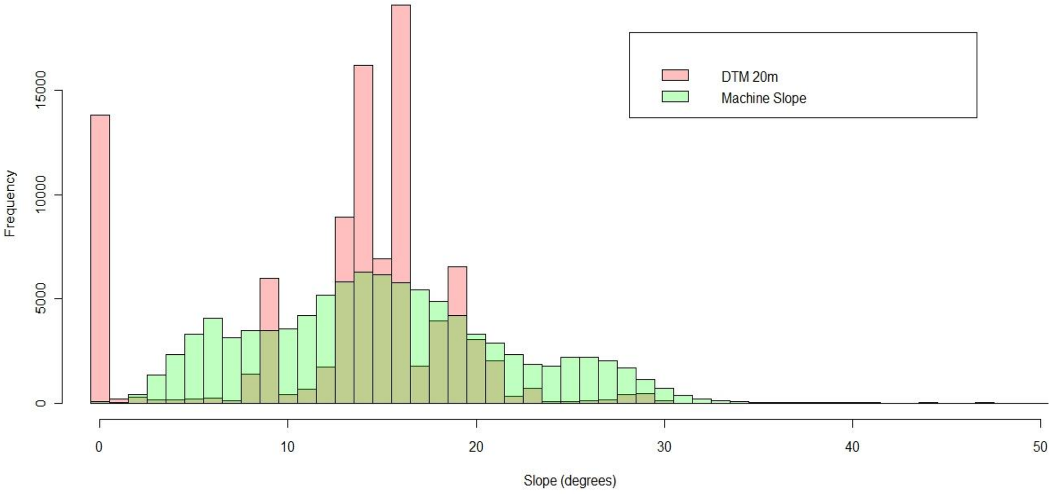

Figure 40: The frequency of slopes experienced by all skidders monitored (Machine slope and 20m DTM slope [method 1]).

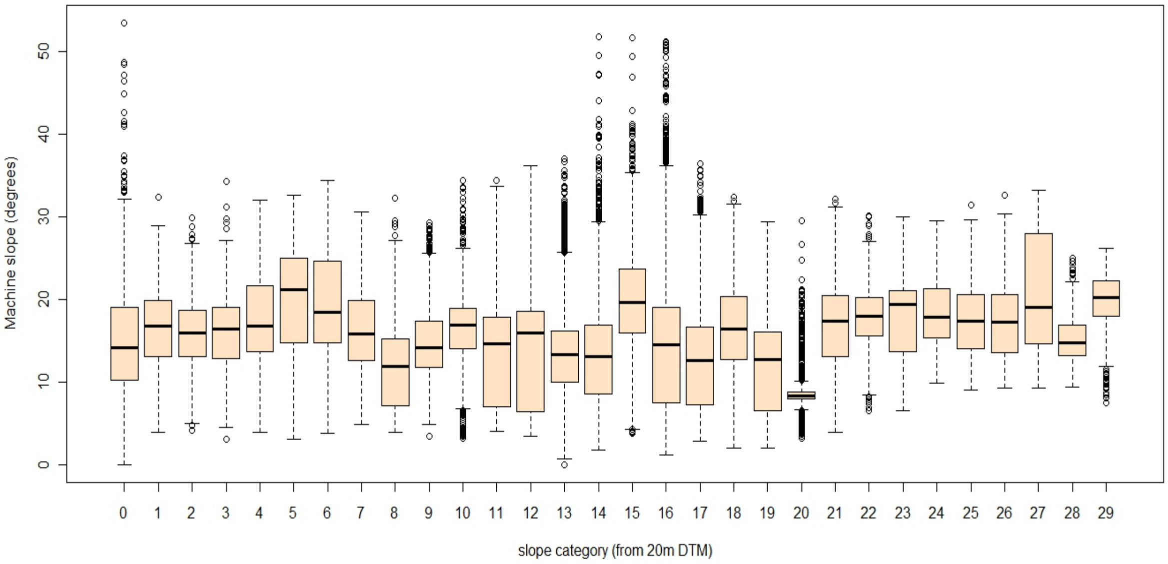

Figure 41: Box and whisker showing the disparity between machine slope and 20m DTM slope for skidders [method 1].

The box plot (Figure 41) again reflects this distribution with a large number of outliers for the values that had a high frequency calculated from the DTM. Method two again showed a more normal distribution with respect to slope than method one (Figure 42 and Figure 43), although again it showed a large frequency of a few numbers. The box plot again showed a large number of outliers.

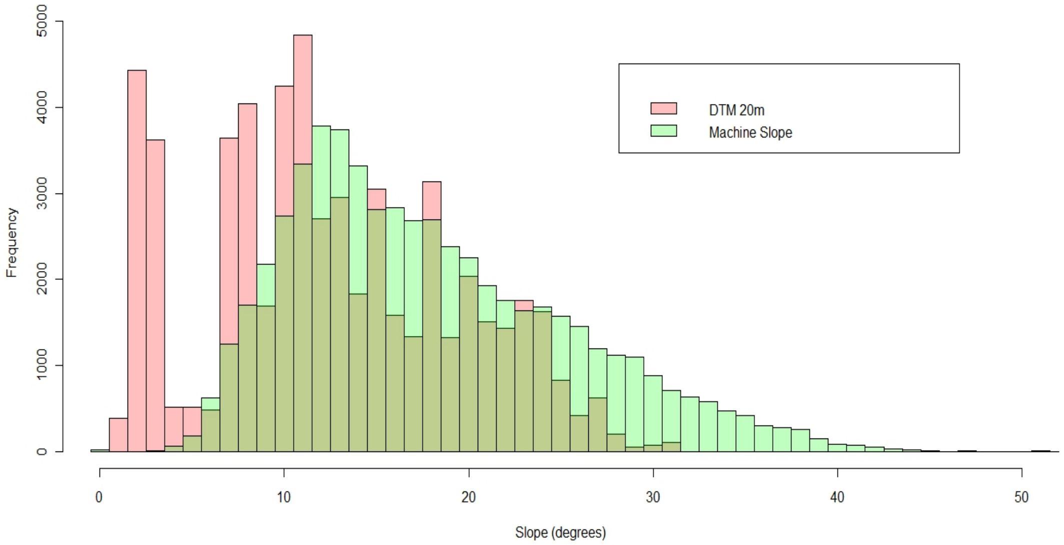

Figure 42: The frequency of slopes experienced by all skidders monitored (Machine slope and 20m DTM slope [method 2]).

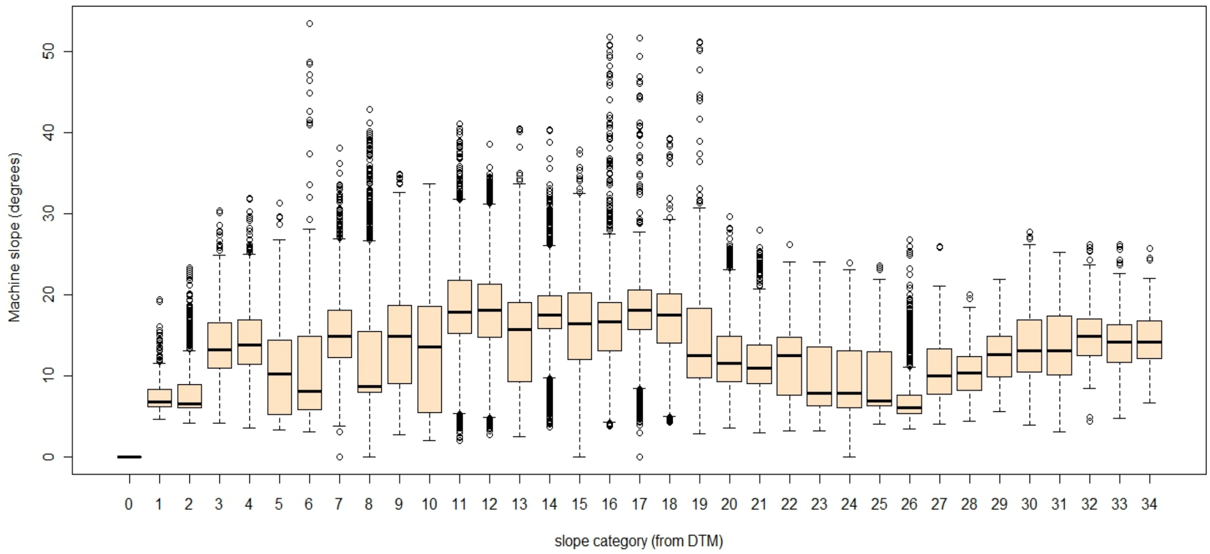

Figure 43: Box and whisker showing the disparity between machine slope and 10m DTM slope for skidders [method 2].

5.4.4. European

The European machines consisted of both harvesters and forwarders. On average, these machines operated on a slope of 17.0 degrees and a 95th percentile of 28.5 degrees. The contour data available in Europe was of a higher resolution, with 5m contour intervals for all four sites resulting in a seemingly better spread of DTM slopes when calculated in R. This better spread also allowed a higher level of detail and meant that there were no large frequency values for zero seen (Figure 44), resulting in a slightly distorted box plot for the lower machine angles below 10 degrees (Figure 46 and Figure 47). The higher resolution DTM data seems to have resulted in the difference in the DTM slope calculation between the two methods being comparatively minimal.

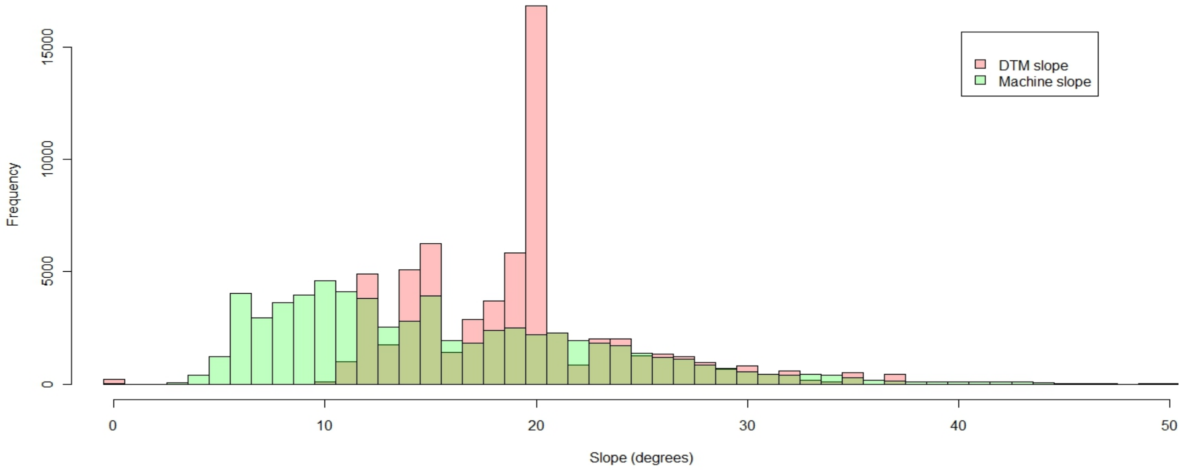

Figure 44: The frequency of slopes experienced by all European based machines monitored (machine slope and 10m DTM slope [method 1]).

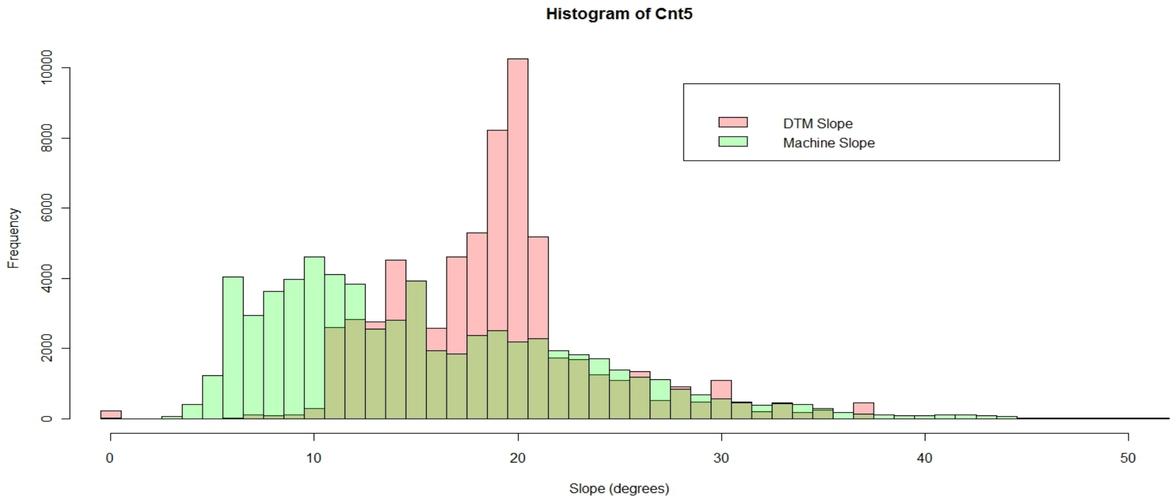

Figure 45: The frequency of slopes experienced by all European based machines monitored (machine slope and 10m DTM slope [method 2]).

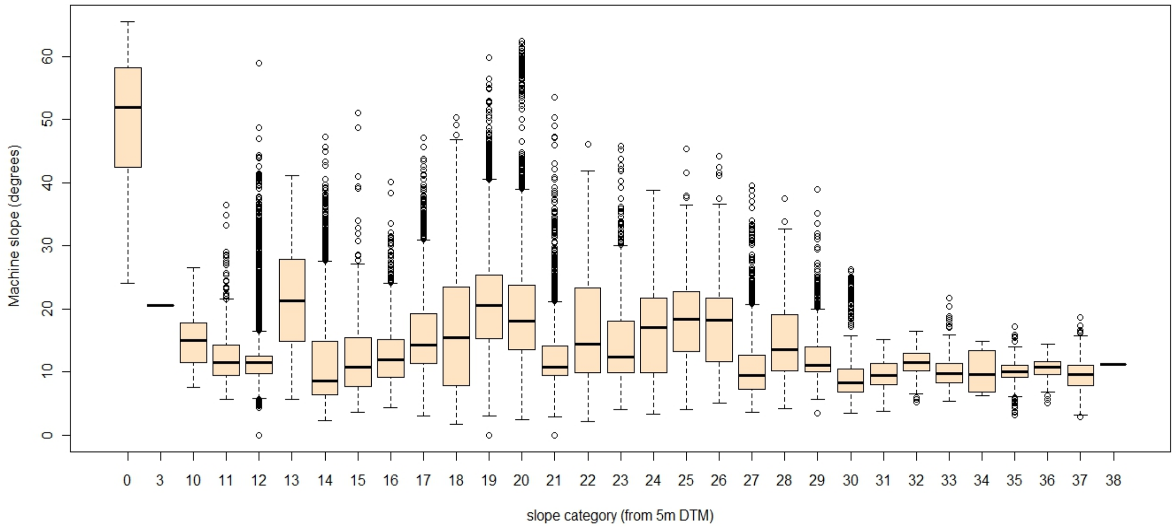

Figure 46: Box and whisker showing the disparity between machine slope and 10m DTM slope [method 1] for European based machines.

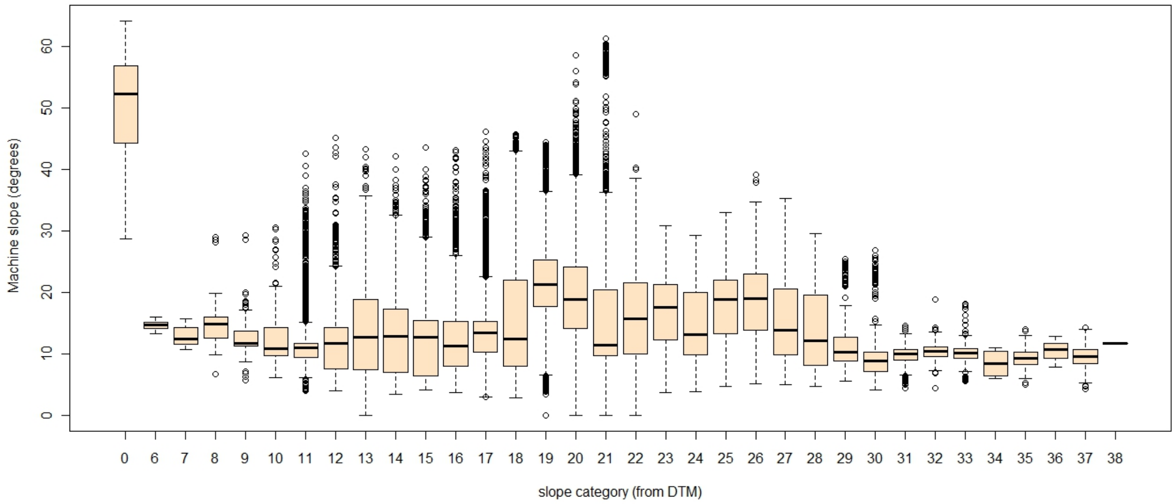

Figure 47: Box and whisker showing the disparity between machine slope and 10m DTM slope [method 2] for European based machines

Despite the seemingly better distribution of slopes with the higher resolution of data there were still a few numbers that appeared to be over represented. However upon further investigation it was shown that this large proportion of slopes was real. It was the result of two of the Austrian machines working on terrain that was very similar in slope combined with the machines limited movements over new terrain due to the nature of the machines operation in a continuous cover system. The European machines on average were 3.1 degrees lower than that of the DTM. This is compared to the New Zealand based machines which were over their respective DTM slopes for fellers and shovelling machines, 1.8 and 4.3 respectively. Skidder's machine slopes was less than the DTM slope by 0.5 degrees.

5.5. Linear Regression

Simple linear regression was conducted on the four machine types to determine if DTM slope was a statistically significant factor with regards to machine slope. Table 7 shows the results of the analysis using the two levels of DTMs for each machine type using both methods of slope calculation.

Table 7: Showing the value for linear regression results for all four machine types. (*= significance level >99.9%, **= significance level of 90%.)

	Factor	t value	Pr(>|t|)	Adjusted R-squared
Feller	Contour - 20m (method 1)	6.06	<0.001*	<0.001
	Contour – 10m (method 1)	27.72	<0.001*	0.013
	Contour - 20m (method 2)	108.80	<0.001*	0.172
	Contour – 10m (method 2)	71.79	<0.001*	0.083
Shovel	Contour - 20m (method 1)	-31.21	<0.001*	0.011
	Contour – 10m (method 1)	235.74	<0.001*	0.054
	Contour - 20m (method 2)	-21.06	<0.001*	0.009
	Contour – 10m (method 2)	-23.78	<0.001*	0.006
Skidder	Contour - 20m (method 1)	31.67	<0.001*	0.010
	Contour – 10m (method 1)	24.05	<0.001*	0.010
	Contour - 20m (method 2)	16.23	<0.001*	0.004
	Contour – 10m (method 2)	14.62	<0.001*	0.002
European	Contour – 5m (method 1)	-1.78	0.0756 **	<0.001
	Contour - 5m (method 2)	5.16	<0.001*	<0.001

All factors measured proved to be significant at a level of p-value<0.05 with the exception of the European machines using method 1. The adjusted R squared for all factors were minimal with the highest value being for feller – contour 20m (method 2) with an adjusted R squared still only explaining 17.2% of the machine slope variation. This suggested that while there was a relationship between the machine and DTM slopes it was a very poor relationship, with DTM slope predicting only a small amount of the variation in machine slope.

5.6. Machine Slope Relative to ACOP Limits

The New Zealand department of labour approved code of practice for safety and health in forestry operations (ACOP guidelines - 1999) states that forestry machines on slopes should not exceed 22 degrees (40 percent) for tracked machines and 17 degrees (30 percent) for wheeled machines when manufacture's limits are not given. An analysis was carried out to determine the percentage of the time each machine spent exceeding their limits based on the ACOP guidelines applicable to the respective machine (Table 8). This was done under the assumption that none of the machines in the study had manufactures specifications regarding their maximum slope. The percentages are based on the number of recordings when the machine was in excess of the limits, relative to the total time the machine type was working.

Table 8: Showing the percentage of machines spend in excess of the ACOP guidelines for the machine slope and the two methods of DTM based slope calculation

	Machine slope	Contour method 1	Contour method 2
Feller 1	59%	53%	70%
Feller 2	6%	38%	0%
Feller 3	46%	32%	38%
Feller 4	18%	0%	0%
Feller Average	32%	31%	27%
Shovel 1	58%	0%	0%
Shovel 2	11%	29%	0%
Shovel 3	11%	2%	2%
Shovel 4	12%	2%	0%
Shovel 5	41%	30%	2%
Shovel Average	27%	13%	1%
Skidder 1	43%	34%	34%
Skidder 2	51%	32%	32%
Skidder 3	0%	45%	36%
Skidder 4	51%	8%	14%
Skidder 5	29%	68%	61%
Skidder 6	33%	23%	20%
Skidder 7	46%	2%	0%
Skidder 8	14%	21%	40%
Skidder 9	21%	21%	37%
Skidder Average	32%	28%	29%
Harvester 1	82%	95%	96%
Harvester 2	38%	47%	46
Forwarder 1	31%	79%	82%
Harvester 3	4%	35%	33%
European Average	39%	64%	64%

The major causes of the disparity between the percentage of time spent in excess of the limit for the machine slope and the DTM is a result of differing machine operators/operator techniques and the DTM poorly predicting machine slope as shown by the linear regression.

6. Discussion

6.1. Terrain slopes

Terrain slope proved to be very variable between the two methods. As shown in the results this is a result of the large number of zero values that occur due to the manner in which the TIN file used in method 1 is constructed. Method two was still limited in its output as the slope of the raster was still calculated from the low resolution contour data. Despite method 2 being the most suitable method in determining terrain slope both methods suffered from a flaw resulting from the original contour files. The flaw lies in the fact that the terrain between two adjacent contour lines at different altitudes is assumed to be flat when calculated in ArcMap. An example of a cross-section of a slope calculation is given in Figure 48 of four evenly spaced 20m contours at 20 percent slope. The figure shows a theoretical cross-section of a slope with all three lines being the same possible cross-section of a 20m contour file.

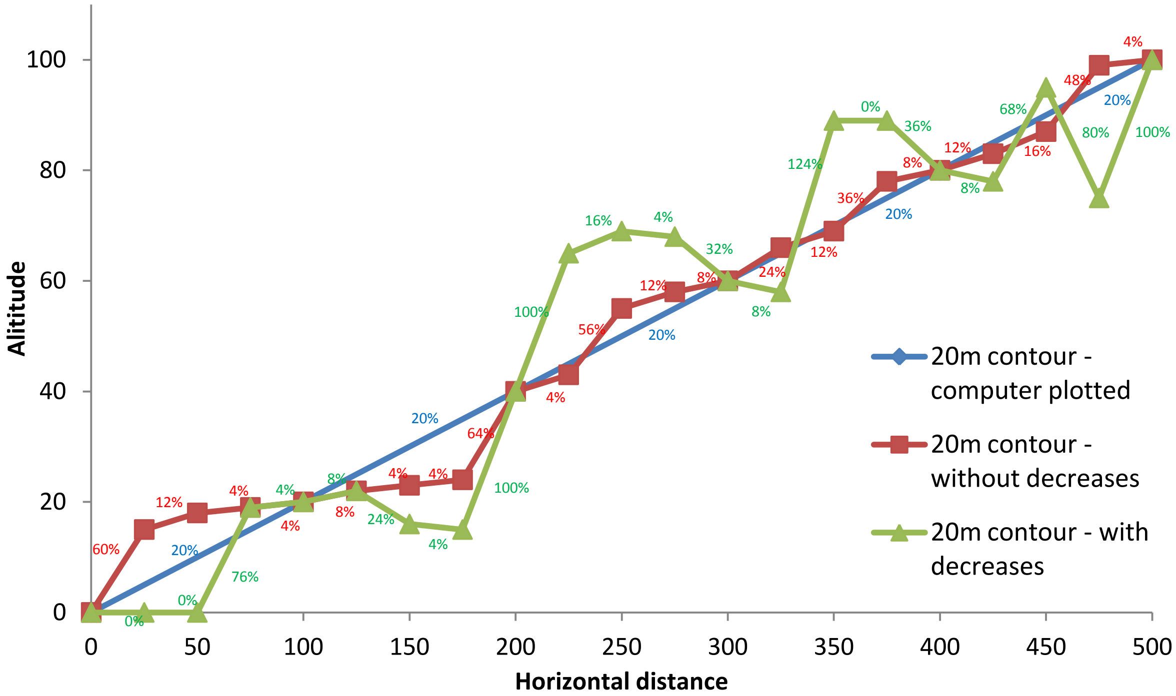

Figure 48: Showing the theoretical differences in actual slope calculated from a contour file.

The straight line (blue) is an example of how the computer/GIS would interpret a 20m contour. The second line, the line with square markers, shows a line with varying slopes however the line never decreases in altitude as the horizontal distance increases. The final line, with triangular markers, shows a line that allows decreases in altitude as the horizontal distance increases.

The straight line and the line with square markers have the exact same slope if averaged out over the whole distance at 20 percent. The final line, triangular markers, is significantly greater at 38 percent if averaged out using the absolute values of slope. The percentage values for the individual lines between each two known points illustrates the major differences in terrain slope that are possible but not seen in a computer plotted 20m contour file. The triangular marked line shows slopes greater than 100% that would not be “seen” when mapped in ArcMap. This significant limitation of low resolution DTM data illustrates its inability to accurately determine the true terrain form as a machine would experience it.

6.2. Machine slopes

While the overall averages for each machine type were within the ACOP guidelines for slope, individual machines were exceeding these limits for various periods of time during operation. This was true for all but one machine measured. There were also a large number of extreme events involving very steep machine slopes, up to 45 degrees (100 percent). In addition to this there were machines that spent a large percentage of their total operating time in excess of the limits. Four New Zealand machines spent more than 50% in excess of the respective ACOP limits and a further five machines spent more than 30% in excess of the ACOP limits. One major concern, with respect to time spent in excess of the associated machine limit, is the disparity between the time the machine spent in excess and the time the DTM predicted the machine would be in excess. The average contour slope and DTM predicted machine slope excess gives an indication as to what terrain each machine was likely to have encountered during operation. All three types of New Zealand forestry machines had, on average, exceeded the ACOP limits more for the machine slope than for the DTM based slope. This suggests that the machines were experiencing more slope than would have been expected from the influence of terrain slope alone. This meant that either the machine operation or machine design was resulting in a greater number of occurrences. A higher resolution DTM would be needed to determine the individual machines terrain ‘experience’ accurately and, due to the low resolution of the DTM used, only the overall averages can be used with confidence.

The European machines showed the opposite trend to this and, given the higher resolution of the DTM, some inferences about the individual machines can be made. All of the four machines showed a much higher DTM occurrence for ‘over limit’ values than for machine slope. The two Norwegian based machines showed a very large difference, with over 30% more for DTM than for machine slope ‘over limits’ for both machines. The Austrian machines showed a lesser disparity between ‘over limits’ with approximately 10% more for the DTM than the machine slope. The key difference between the two European countries, with the machines being almost identical, was the use of skid trails being permitted in Norway and not in Austria. This meant that while all machines were operating on similar terrain, 17 to 21 degrees on average, the use of skid trails by the Norwegian machines allowed them to mitigate the effects of the terrain slope on the machine better. This was also apparent when comparing the overall machine averages with the Norwegian forwarder and harvester. Their average machine slopes were 13.8 degrees and 11.1 degrees respectively, despite the terrain slope (based on DTM data) being 21.4/21.7 degrees (method 1/method 2) and 16.8/21.17 (method 1/method 2) degrees on average. The prevalence of slope mitigation was less for the Austrian machines, with average machine slopes of 22.2 degrees for the harvester and 20.7 degrees for the Snake harvester, and terrain slopes of 19.5/19.5 degrees (method 1/method 2) and 20.2/19.7 degrees (method 1/method 2) respectively. The Snake harvester had a much lower occurrence of ‘over limit’ values due to the machine being tracked not wheeled, which resulted in the machine limit being deemed to be 22 degrees rather than the 17 degree limit used for the other wheeled machines.

6.2.1. Machine design

New Zealand has by and large adopted a very American style to its forest harvesting with regards to its machine types and methods. This has resulted in a very different approach to forest harvesting, particularly with machine operation, compared to Europe. New Zealand’s forest harvest and shovelling machines are typically based around modified excavators. These machines are generally designed for heavy construction and demolition work and, as such, aren’t developed with steep slopes in mind. There are specific steep slope machines for construction/demolition as well as forestry specific machines, but their adoption into the New Zealand forestry sector has been minimal. Excavators are by design not particularly stable; they have a high centre of gravity, the ability to swing a large mass around a point, resulting in large changes in load distribution, and are completely rigid across the whole track base. This track rigidity causes the machine to experience a large amount of vehicle sway as a result of travelling over uneven terrain. Although the velocity of slope change or the effect of dynamic changes in load were not included in this research they are also considered key factors that affect machine stability (Eger and Kiencke, 2003).

A major difference between the New Zealand machines and the European machines, particularly with respect to harvesting, lies in machine design. New Zealand’s harvest machines all employ a rigid track base, whereas the European machines utilise a front bogie wheel in the case of the six wheeled harvesting machines, and rear bogie wheels on the six wheeled forwarders. The Snake harvester uses four trapezoidal rigid tracks mounted in the same way as the bogie wheels (passive bogies). This allows the four tracks to remain in contact with the ground surface individually while the machine remains stable (Figure 49).

Figure 49: Komatsu 911 Snake harvester showing the advantage of passive bogie quad tracks. Note how the front visible track is on a different plane to the two rear tracks however all tracks are in full contact with the ground.

The use of the passive bogie wheels allows for the machine to manoeuvre over obstacles, without the whole machine swaying (Figure 50). When a rigid track moves over an obstacle the whole machine is forced to experience it resulting in very rapid changes in machine slope (Figure 51).

Figure 50: Showing the advantage of a passive bogie wheel as the vehicle negotiates over a boulder. (Hellström et al., 2008)

Figure 51: Showing a rigid track machine experiencing excessive slope due to an obstacle.

A good demonstration of the disadvantages of a rigid track base is to place a square flat piece of wood on a flat surface with an object placed under one corner. The piece of wood will rock on an axis in line with the object and the opposing corner of the piece wood. This is effectively what a rigid track based machine does when it encounters an obstacle, resulting in a large portion of the track base that is out of contact with the terrain surface (Figure 52).

Figure 52: Photo series of a rigid track bulldozer reversing over a stump, note the rapid change in the machine slope over a relatively short distance.

The key driver for tracked machines in New Zealand over wheeled machines is the perception that tracks provide better stability than wheels, as they have more tractive efficiency. Tracked machines do have better tractive efficiency than wheeled machines, particularly in soft even surfaces where the entire track is in contact with the terrain surface. However, due to the uneven nature of forests and the rigid track systems employed by excavators, this is not always the case. The focus of the modifications to New Zealand tracked forest machines has largely revolved around improving the tractive performance of the machine and its ability to negotiate obstacles, rather than trying to improve stability. This includes increases in undercarriage width and height to increase stability and clear stumps and by adding larger cleats to the tracks to increase traction. The increase in the machine width has minimal advantage in the machine stability as the machine is also raised in height raising its centre of gravity. There has been some development with regards to tethered machines in New Zealand but they are in early stages of development.

Excavators that don't have the ability to level the machine housing also have issues resulting from the weight of the machine being distributed to the down slope point of the tracks when on steep terrain. The advantage of the self levelling machine is that it can redistribute the housing weight to try and maintain an even weight distribution across the whole track base. Bogie wheels provide a mix of the advantages of both wheels and tracks. They also provide a degree of suspension and improve traction and stability, as they are able to move over an obstacle independently of the base machine (Bailey and Burt, 1981). Bogie wheels are also not as limited by wheel size when trying to move over large obstacles as a single wheel, effectively reducing the impact of the obstacle (Hellström et al., 2008). Wheels inherently have trouble with obstacles if the radius of the wheel is less than the height of the obstacle it is trying to negotiate (Hardarson, 1998).

6.2.2. Machine operation

Another major difference between New Zealand and European machines lies in the machine operation, due in part to the harvest system and in part to machine design. New Zealand's forest excavators tend to zigzag up and down a slope, felling trees to one side as the machine moves slowly across the slope. This is in part due to the clear felling nature of New Zealand forestry, as well as the minimal advantage the rigid track system provides to stability when orientated down slope. In contrast, the European machines operate up and down the slope (almost exclusively down slope in the case of forwarders). This is due to the longer, more slender, machine (relatively) being much more stable when operated down slope than cross slope. As such the machines are capable of very steep slopes, although forwarders do need a means of getting back up the slope via a gentler path if more than half loaded. Model based research on static stability of six wheeled forwarders in England showed that an empty forwarder travelling uphill was stable up to approximately 38 degrees. However, due to articulation the machine was much less stable when turning on slopes, with stability dropping to 28 degrees unloaded (Hunter, 1993).

Figure 53: An eight wheeled forwarder in Austria working on steep terrain operating down slope as it loads its bunk and then reversing back uphill when empty.

In Norway, where the use of skid trails was permitted, machines were able to utilize the skid trails to move up the slope and then drive off the trail directly down slope for either felling or forwarding purposes. The other option employed by European machines, particularly in Austria where skid trials are not permitted, was to use areas of lower slope to move up hill and then work on the steeper areas as the machine descended Figure 53. European harvesters were less limited with respect to up or down slope travel, but kept cross slope travel to the minimum on steep terrain.

6.3. Machine slope predication

Through the use of DTM slopes, which are readily available to a forestry company, it was hoped that a model could be developed to determine the relationship between machine slope and terrain slope as calculated from the DTM. This model would aid harvest planners in being able to better allocate machines based on their suitability and to locate and mitigate areas of higher risk. The information gathered from the machines in New Zealand and in Europe clearly shows that while the terrain slope is a highly significant factor in determining machine slope, it typically explains only a very small percentage of the variation of machine slope. There are also a large number of other possible influences, including machine type, machine configuration (e.g. feller head or processing head), machine operator, whether skid trails are used, terrain roughness, soil type and degree of loose material, depth of soil and underlying materials, amount of slash being encountered, tree size/weight, when felling or shovelling, and stump height.

A machine operator plays an important role in the slopes that a machine experiences. This is due to the ability of a skilled operator to mitigate the effect of most of the other possible factors involved. It is expected that a machine operator will use his or her knowledge and skill in areas of steep terrain and take appropriate measures to ensure that the machine remains within the safe operating limits. An example of this difference was observed in Mosgiel, Otago where two operators were using near identical skidding machines, skidding from the same locations, with very similar 'over limit' frequencies for the terrain slope (using both methods), but experienced very different frequencies of 'over limit' percentages for machine slope. This was a result of the machine operator making different manoeuvres in slightly different ways. For example the machine operating further in excess of the limits tended to spend more time travelling forward before making a U turn on much steeper slopes than the one operating more within the limits. These continuous operational differences resulted in different amounts of over limit percentages between the two machines.

Some of the times the machines exceeded these limits were, in some cases, a result of something that the operator deemed safe and, as such, were carried out repeatedly, but caused the machine to exceed the slope limits. Such cases included an operator using his boom to work his machine down a steep skid trail batter, resulting in a very steep machine slope recording. Another case consisted of a skidder turning directly up a skid trail batter to initiate a 3-point turn. These, and many other occurrences, can account for some of the machine operators slopes some of the time, but there are many more that machine operators either didn't deem 'unsafe' or had no other option if they were to 'get the job done'. It is important to note that all operators actively managed their machines slopes and, for the most part, took care to ensure that their machine was in a position of safety. This active management of the machine slopes contributed in part to the limited amount of variation explained by the regression model of terrain slope.

7. Conclusion

Managing machines on steep terrain is a continuing concern worldwide and will become of greater concern in New Zealand as the annual harvested volume increases over the next 15 years. The current approach to steep terrain harvesting in New Zealand, outside the use of cable yarders, has been based around the use of excavators with minor modifications in an attempt to better negotiate steep slopes safely.

With respect to the actual slope of the machine the use of a terrain map from a DTM proved to be inadequate for mapping machine slope, with only a very small percentage of the machines slope variation being explained by the terrain slope.

All but two of the New Zealand machines worked on terrain slopes in excess of the ACOP slope guidelines as calculated in ArcMap from contour data. All but 1 of the 18 New Zealand based machines would have exceeded the limits at some time if the slope referred to machine slope. There were some machines that operated in excess of the limits for a large percentage of the time they were studied for, with four machines exceeding the limit for more than half of the study time.

There appears to be a major advantage in the ‘European’ undercarriage that was in use by all four machines studied in Europe. Independent axles with bogie wheels or tracks aid in machine stability enabling it to operate on very steep terrain while keeping the actual machine slope within a safe level. This was in contrast to New Zealand machines that were operated at steeper slopes than would have been expected based on the terrain slope.

This research project has established empirical data for a range of machines operating under a range of conditions. It has provided an insight into the lack of a formal relationship between terrain and machine slope. It showed that many of the machines exceeded the ACOP guidelines on a regular basis and did so while actively managing their machines slope when possible.

8. References

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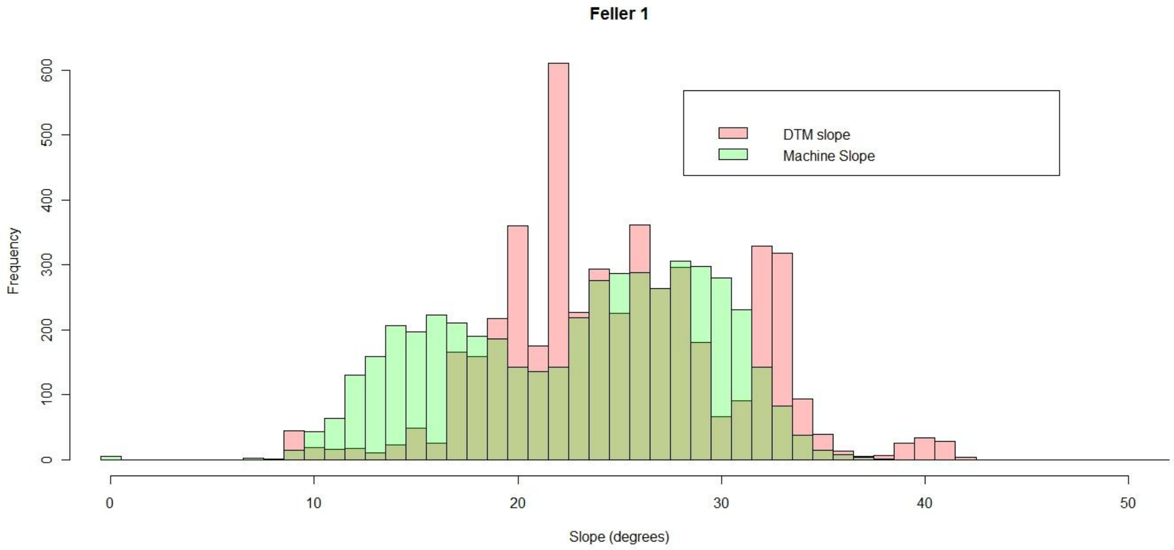
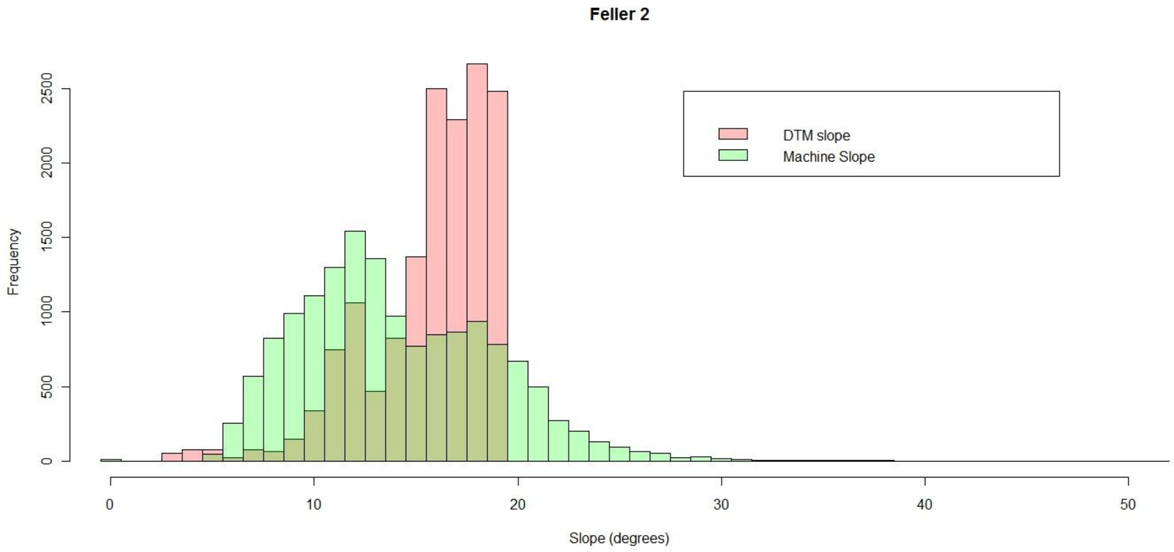
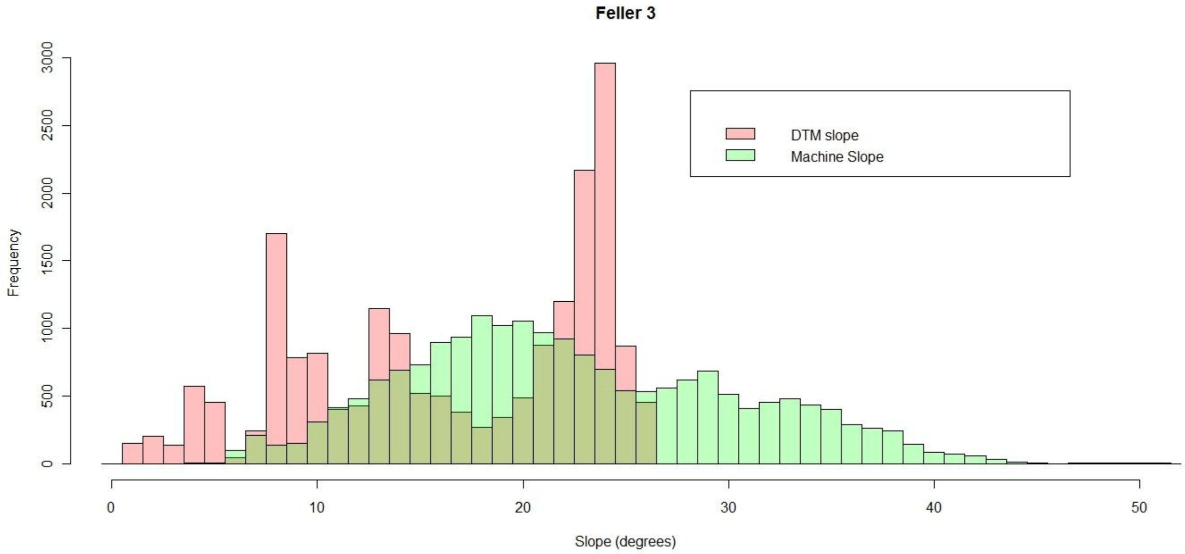
9. Appendices

Charts for each individual machine in the study showing the frequency distribution of both machine and terrain slope.

Felling machines



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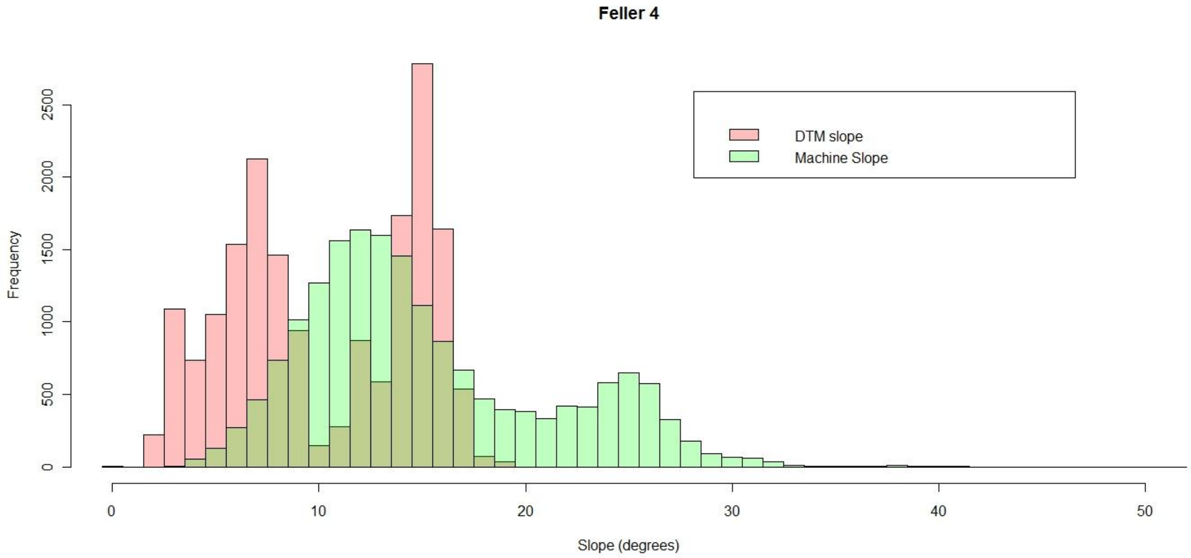
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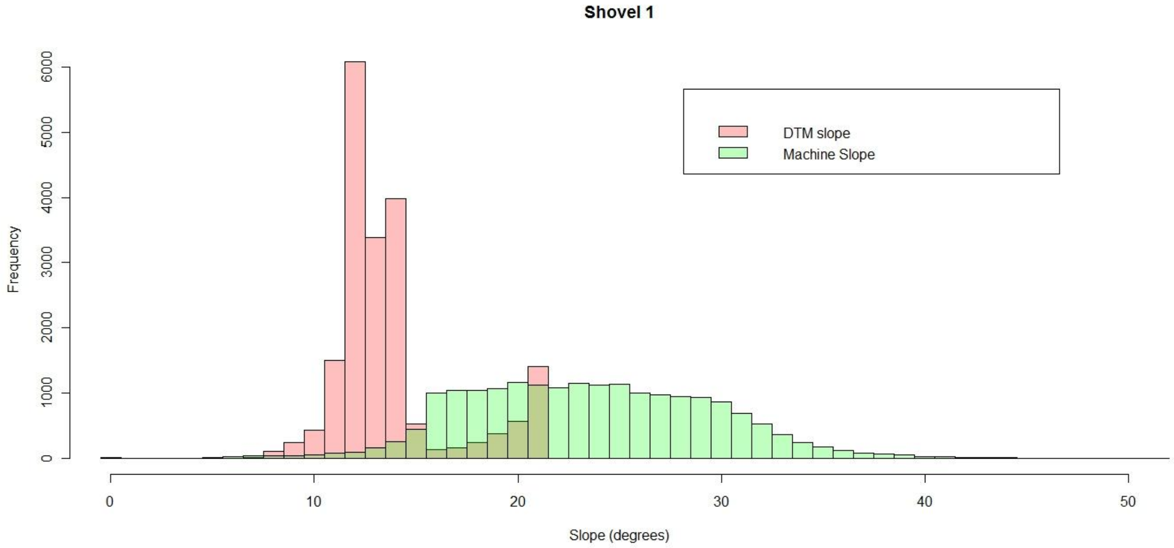
Shovelling machines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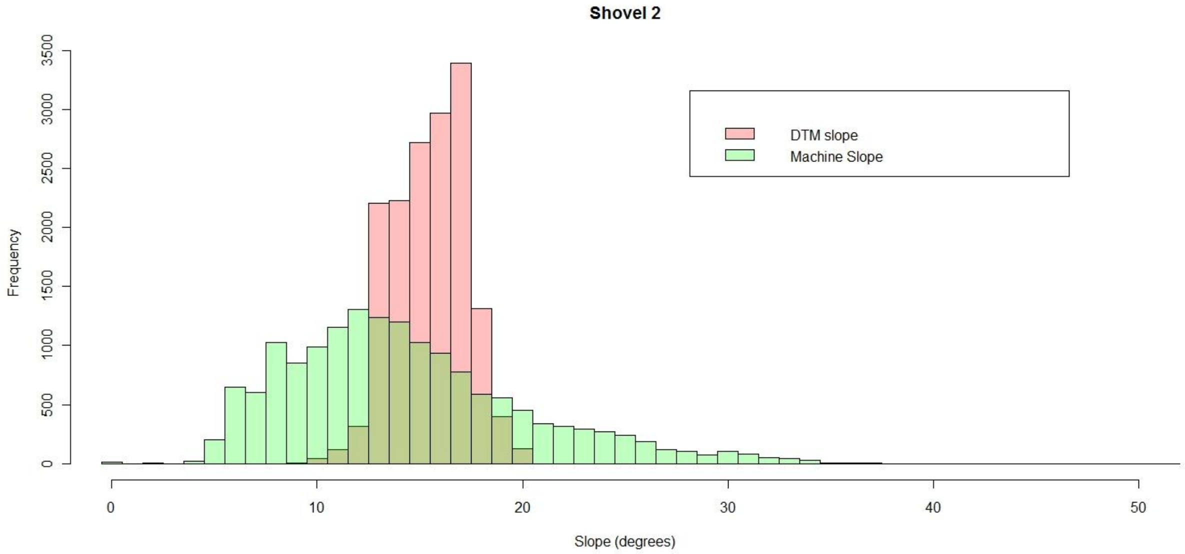
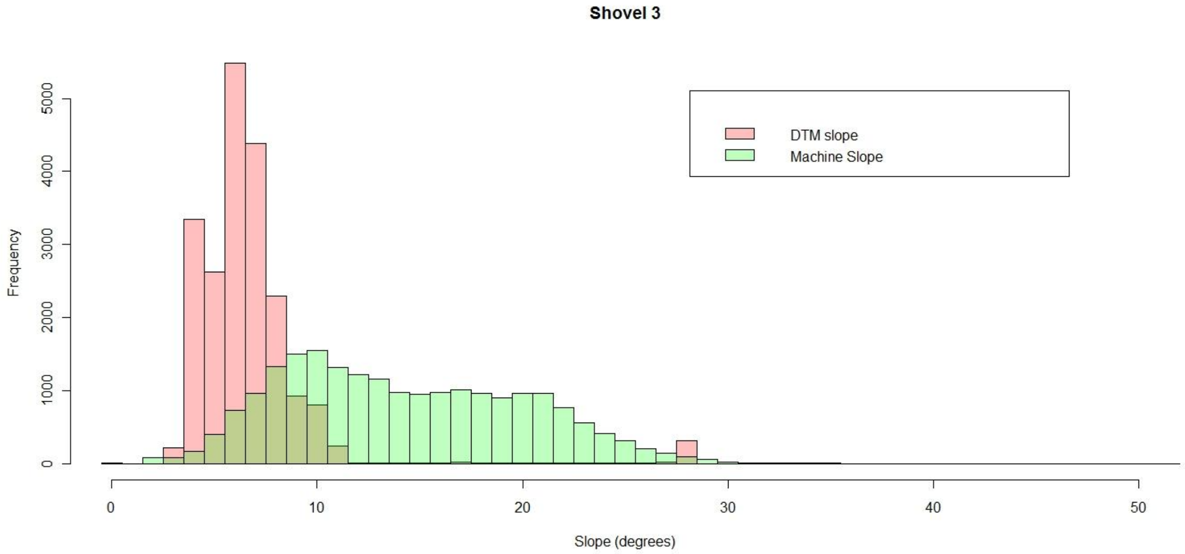

Shovel 2
Frequency
0
500
1000
1500
2000
2500
3000
3500
DTM slope
Machine Slope
0
10
20
30
40
50
Slope (degrees)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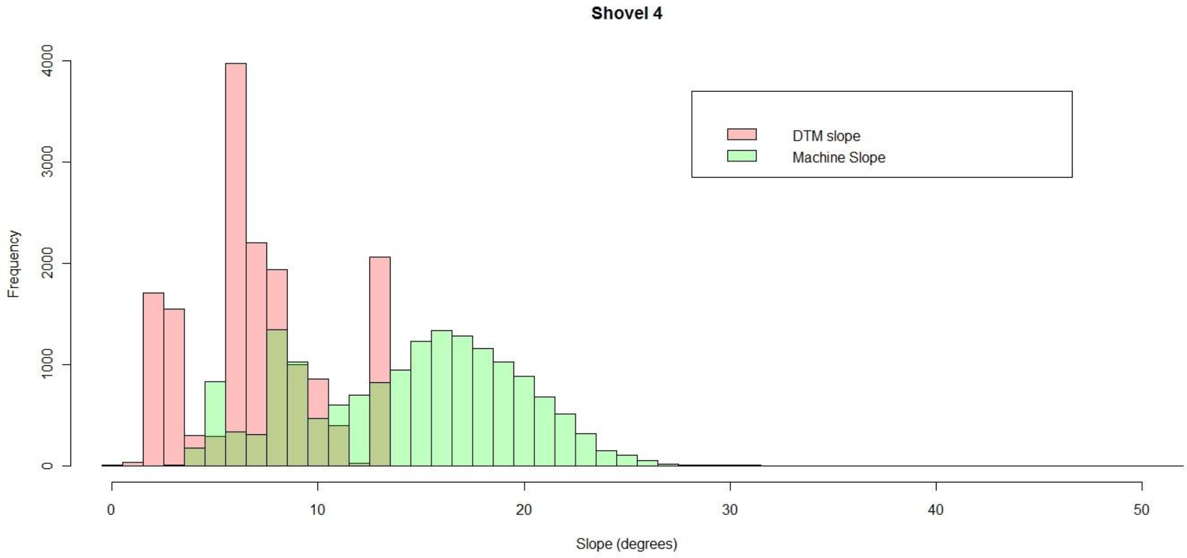
2000
3000
4000
5000
DTM slope
Machine Slope
0
10
20
30
40
50
Slope (degrees)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Frequency
0
1000
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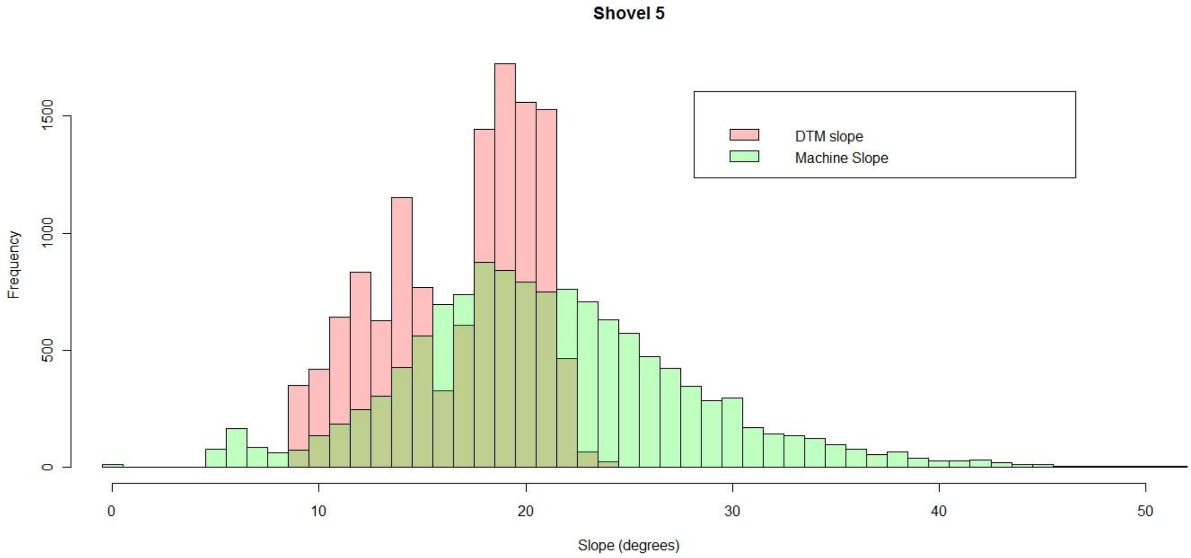
4000
DTM slope
Machine Slope
0
10
20
30
40
50
Slope (degrees)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Machine Slope
Frequency
0
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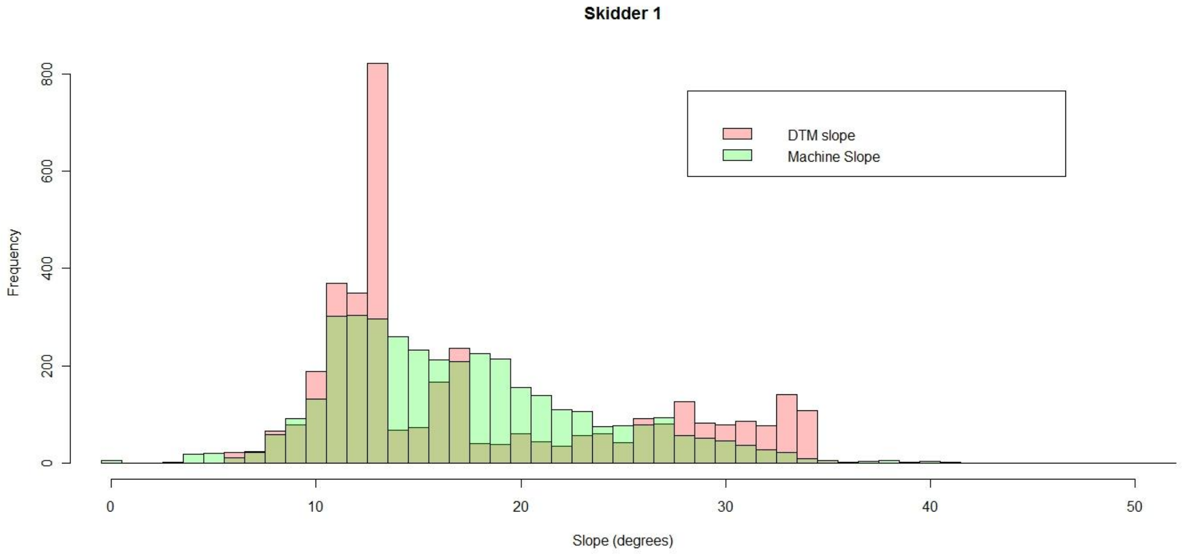
1000
1500
0
10
20
30
40
50
Slope (degrees)

Skidders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DTM slope
Machine Slope
Frequency
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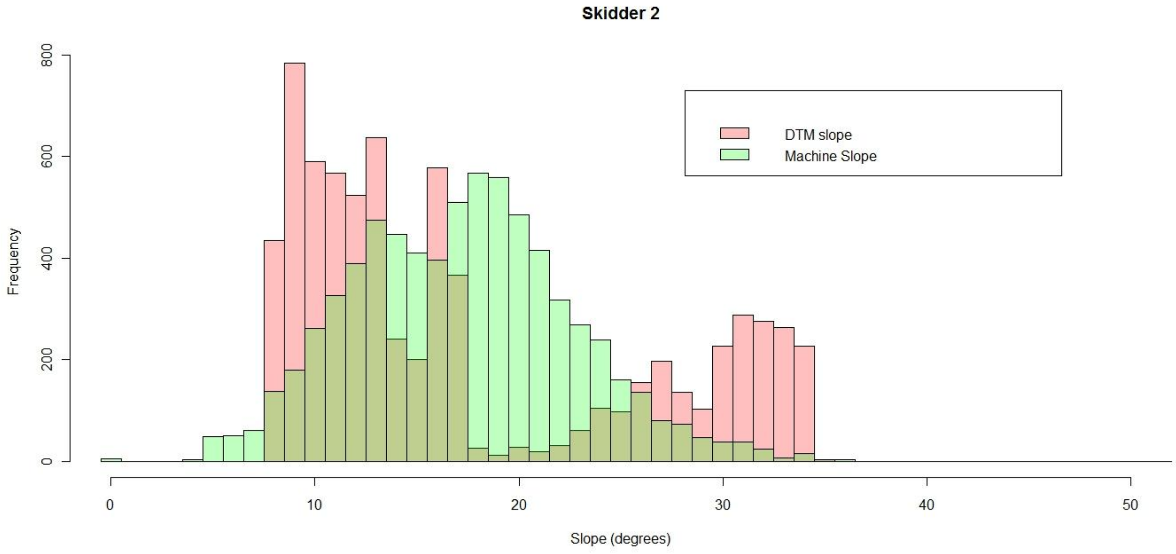
400
600
800
0
10
20
30
40
50
Slope (degrees)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Machine Slope
Frequency
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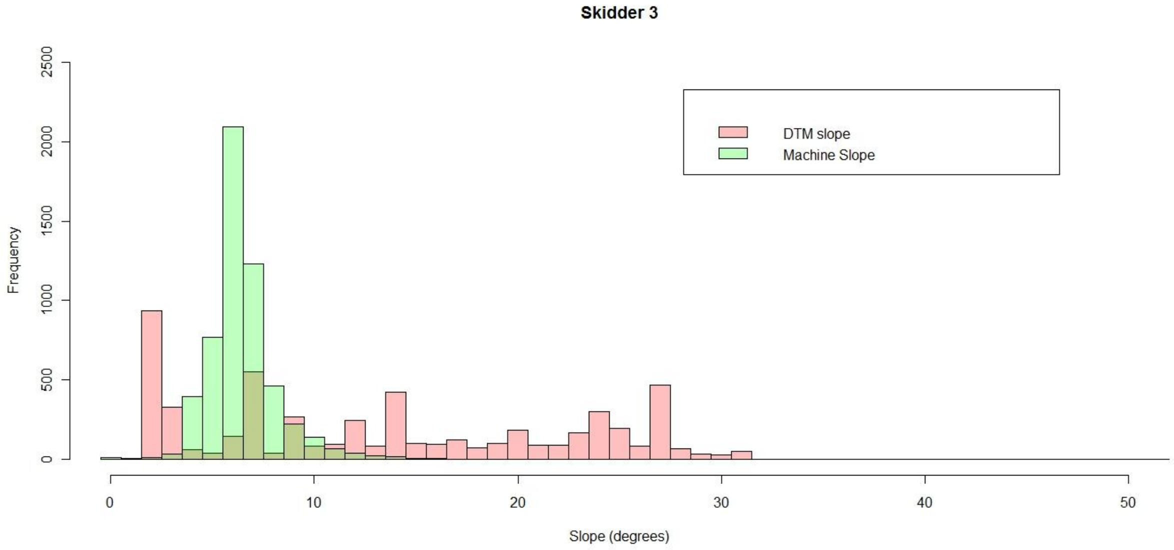
400
600
800
0
10
20
30
40
50
Slope (degrees)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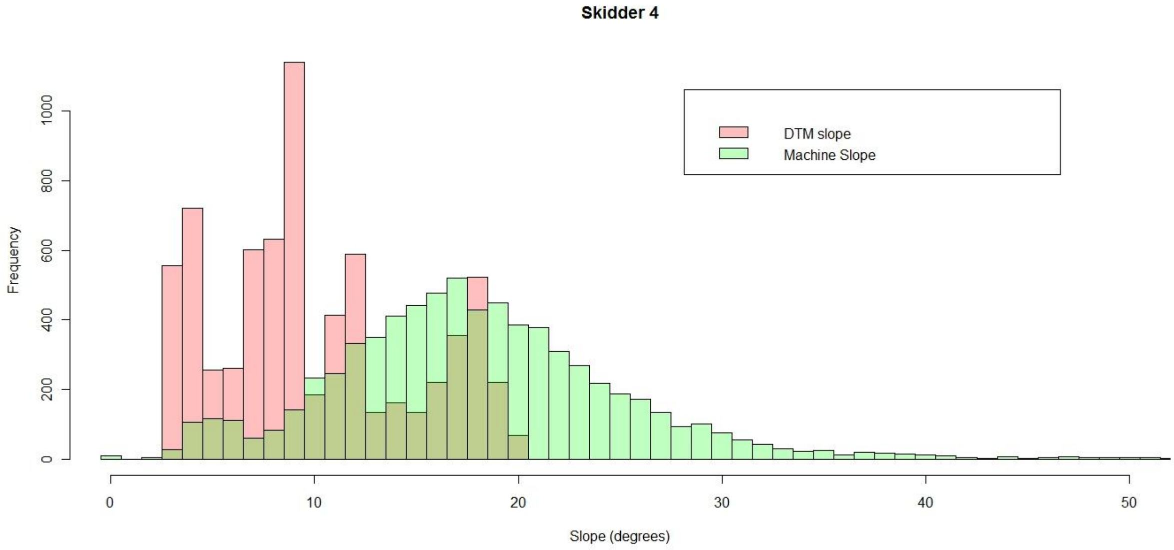
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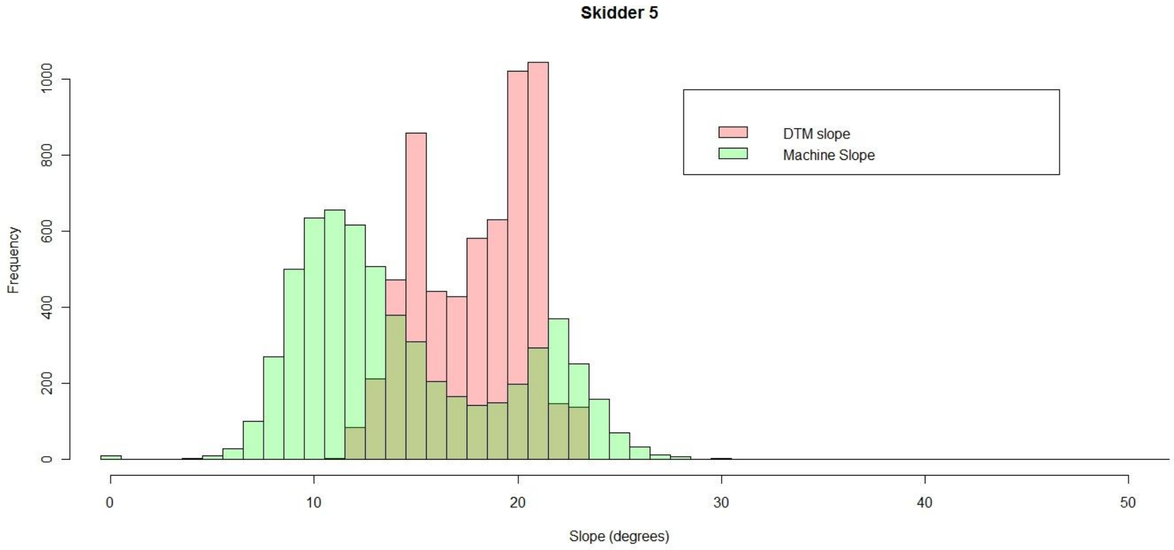
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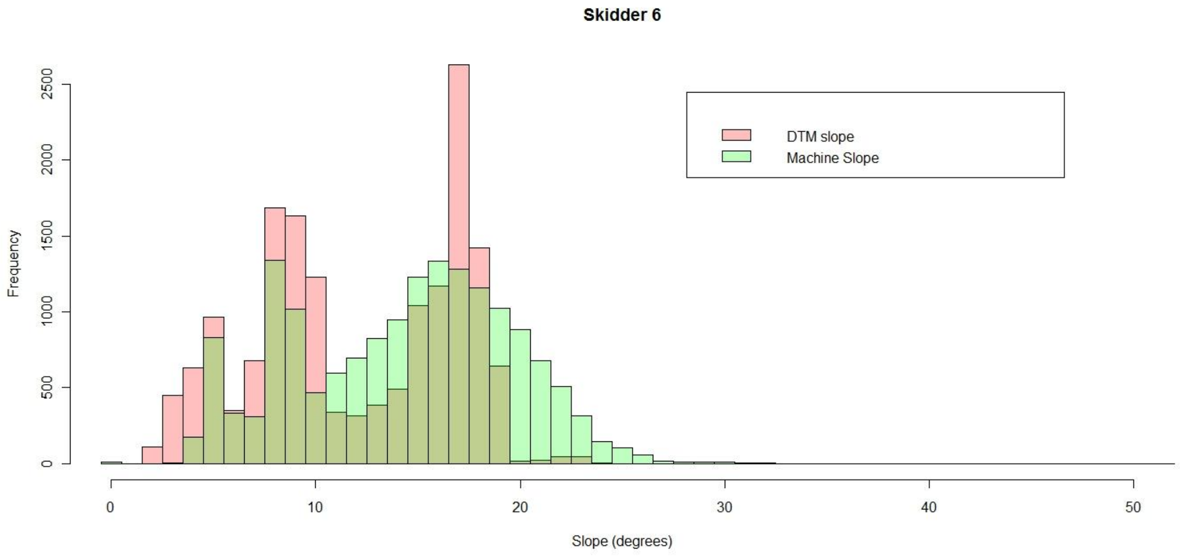
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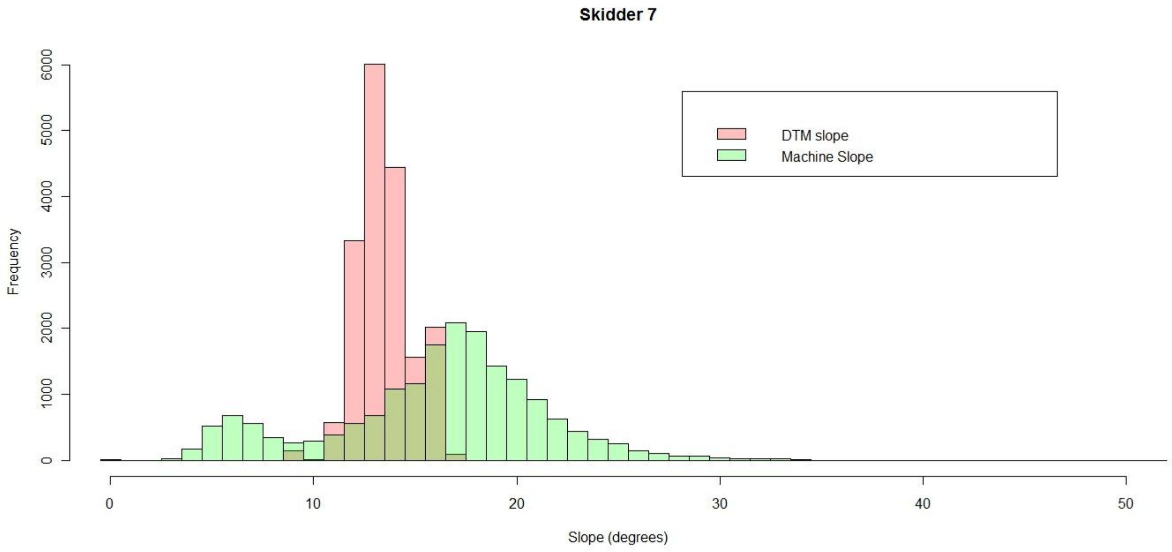
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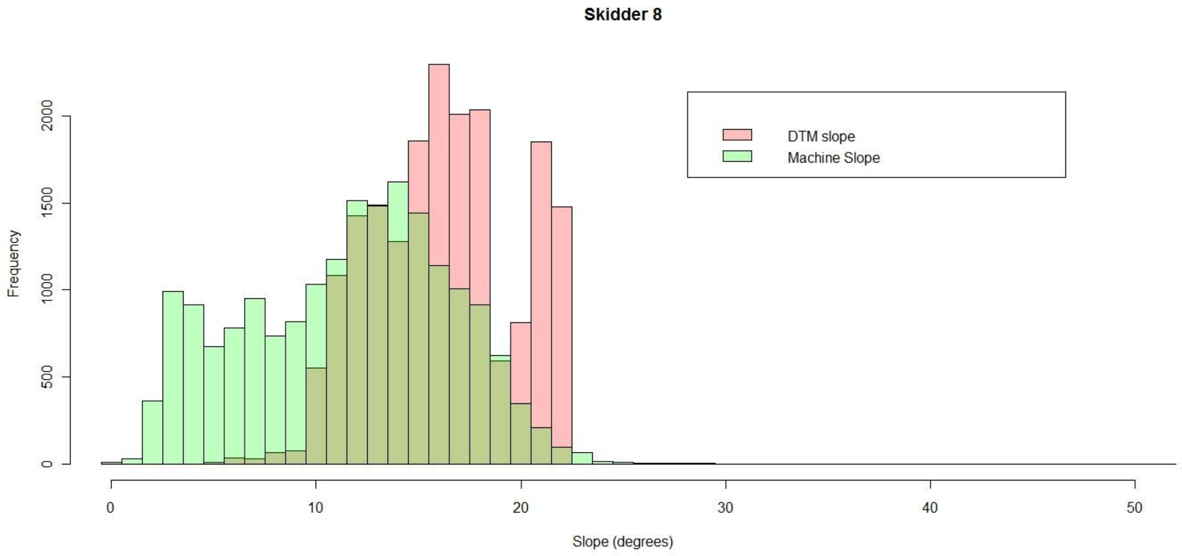
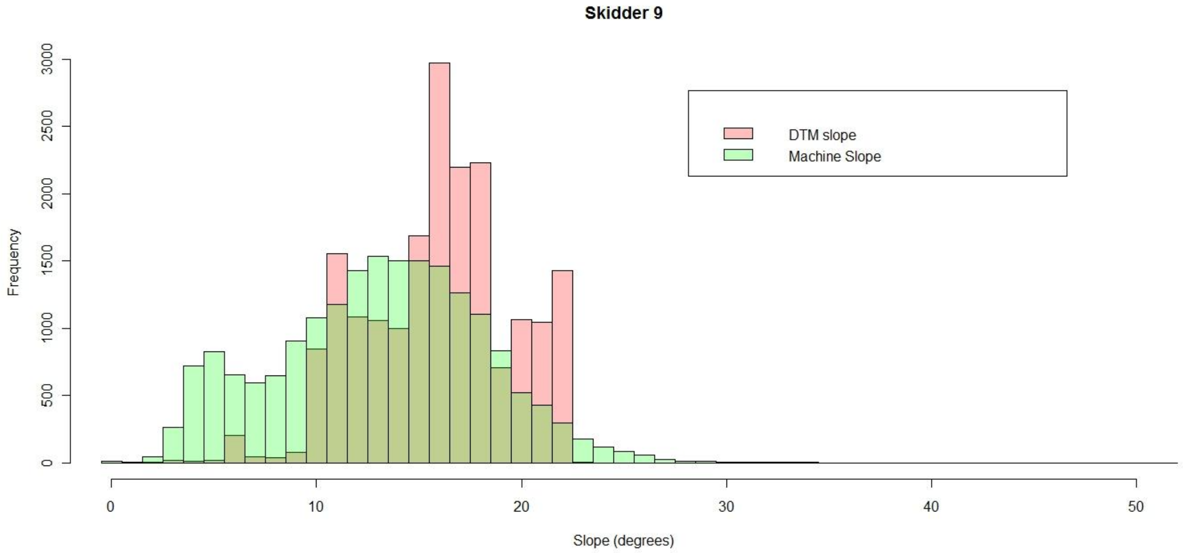
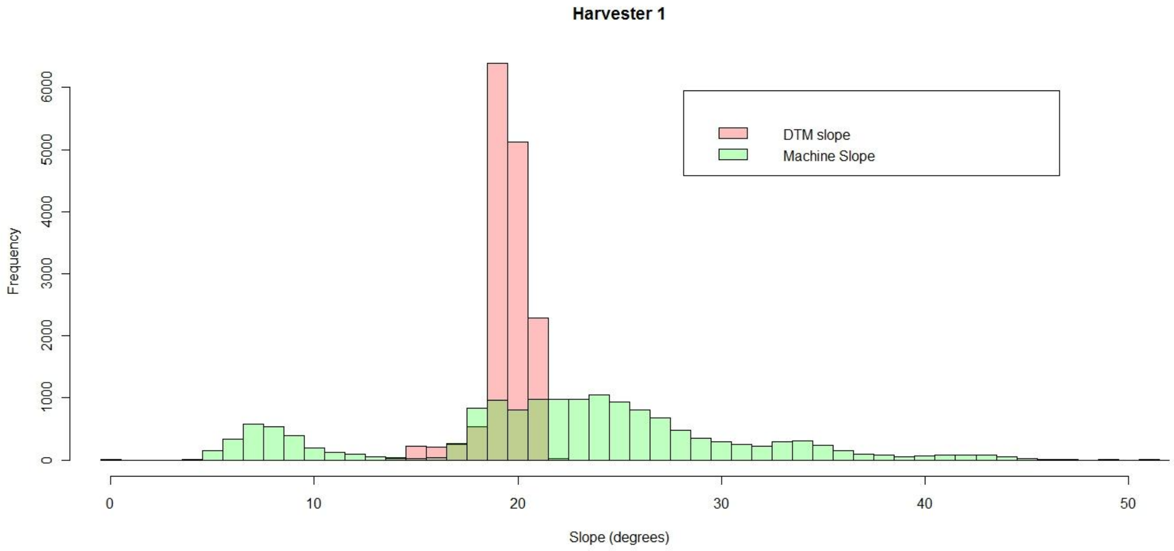
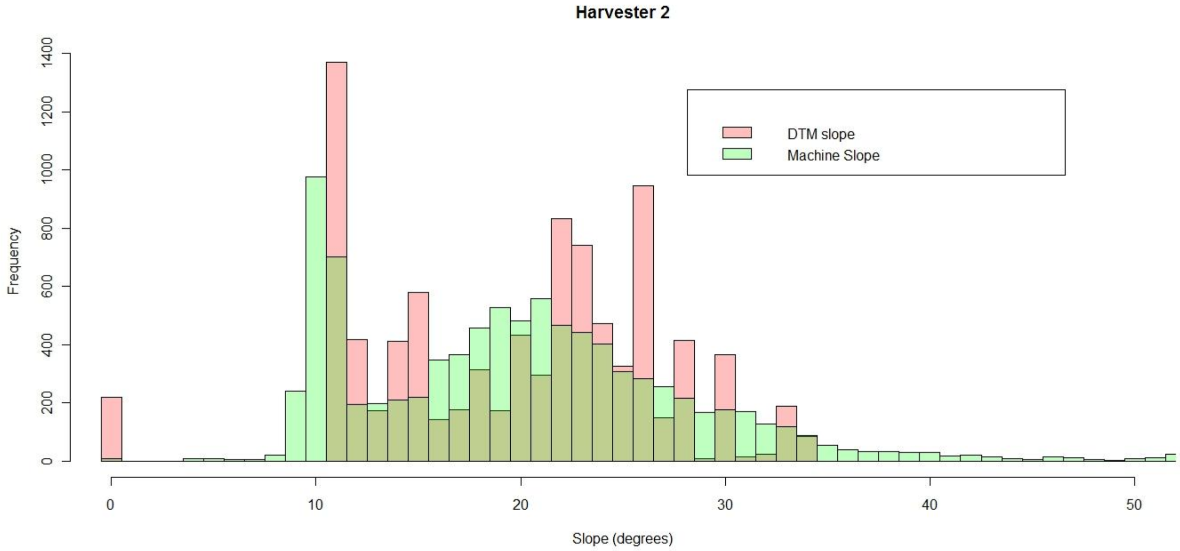
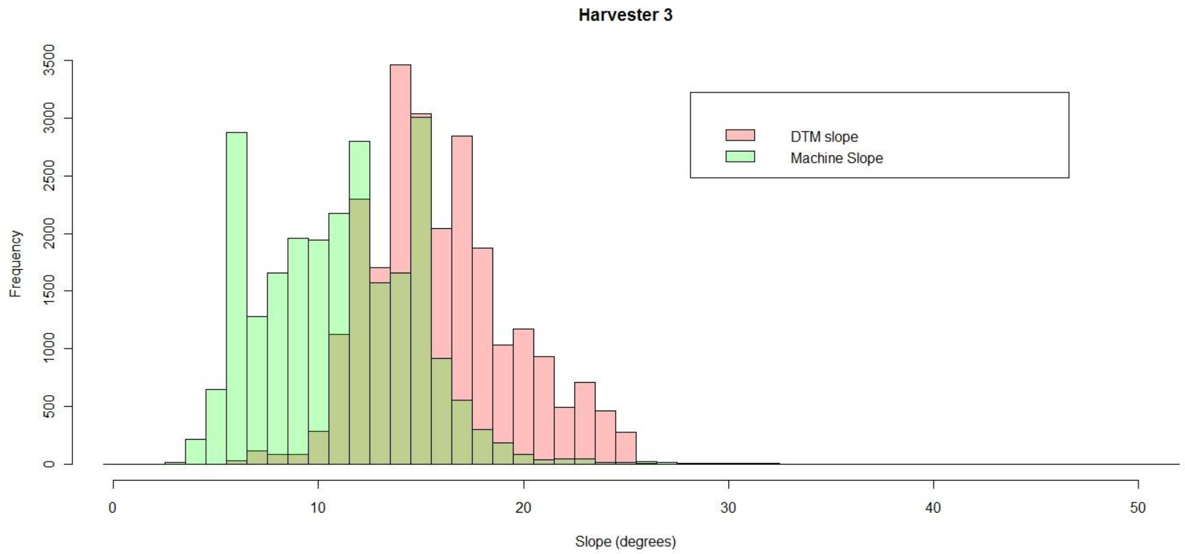

Skidder 8

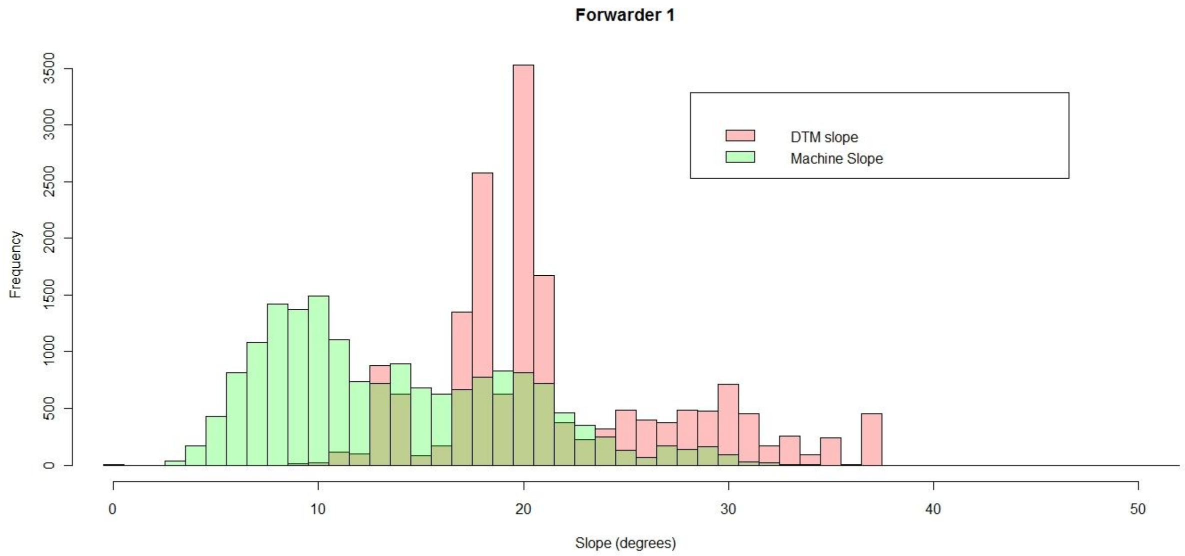


European machines






Harvester 3
DTM slope
Machine Slope
Frequency
0
500
1000
1500
2000
2500
3000
3500
0
10
20
30
40
50
Slope (degrees)


Forwarder 1
DTM slope
Machine Slope
Frequency
0
500
1000
1500
2000
2500
3000
3500
0
10
20
30
40
50
Slope (degrees)