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Assessing Stabilisation from Soil Disturbance Caused by Steep Slope Harvesting Operations

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EXECUTIVE SUMMARY

In New Zealand, mechanised harvesting of plantation forests on steep slopes has become commonplace to both improve safety and system productivity. Mechanised harvesting can increase the level of soil disturbance when compared to motor-manual alternatives. This can lead to increased erosion risk on steep slopes. This study investigates soil disturbance and post-harvest vegetation recovery in steep-slope plantation forests following mechanised harvesting operations in New Zealand.

Soil disturbance and vegetation recovery was assessed in fourteen mechanically harvested steep land plantation forests across New Zealand during 2024. For this study, the harvested sites were characterised by the use of steep slope winch-assisted mechanised harvesting. Sites were assessed immediately after harvest, as well as at one-, two- and three-years' post-harvest. At each site the chosen harvest areas were in close proximity to minimise variability in terrain, harvest methods, soil, and weather conditions. A line transect method was used to documenting disturbance types such as soil mixing, topsoil removal, rutting, and changes in slash and vegetation cover. A total of 52,541 geo-located observations were collected. These data were correlated with terrain features through GIS mapping to analyse temporal and spatial patterns of disturbance and recovery.

Regression analysis showed that all disturbance types, except for erosion features, were significantly influenced by the time since harvest. As time progressed, soil disturbance and slash decreased, while vegetation cover increased. Stand age was the largest determinant of site differences, with more recently harvested stands showing more significant disturbance and less vegetation recovery. Slash cover declined over the three years post-harvest, while vegetation cover increased, meaning there was a slow increase in ground cover overall. By the third year, exposed soil was reduced by 50%, with vegetation cover averaging 65%, a nine-fold increase. Terrain characteristics also played a critical role in disturbance patterns. Steeper slopes had greater soil disturbance, with less slash and vegetation cover compared to more gentle slopes. Vegetation and slash were more prevalent in valley bottoms, whereas rutting, soil mixing and scraping was more prevalent on spurs. Aspect further influenced erosion, soil mixing, and vegetation recovery. At higher elevations on the sites, disturbances and slash were more pronounced, possibly due to their proximity to landings. Relatively lower elevations showed more vegetation recovery.

This report summarises the Master of Forestry Science work of James Powers, completed in may 2025. For the full report click the following link: https://doi.org/10.26021/16017

INTRODUCTION

NZ forest industry and operating conditions

The forest industry contributes $6.6 billion to the New Zealand GDP, and employs between 35,000 and 40,000 people (MPI, 2024). Logs are the fourth largest export by value in New Zealand, behind horticulture (OEC, 2022). Though New Zealand only contributes 1.3% to the global trade of forest products (MPI, 2024), it is the largest exporter of softwood logs worldwide (UNFAO, 2023). An estimated 34.4 million cubic metres of timber was harvested in 2021 (NZFOA, 2023). 1.76 million ha of plantation forest are planted in New Zealand, 6.6% of the land area. 90% of this is planted in radiata pine (NZFOA, 2023).

NZ conditions

New Zealand's conditions are characterised by steep terrain and young, highly erodible geology (Visser, 2014). The logging operations in these areas typically involve large tree sizes, with trees exceeding three cubic metres being common, and an average piece size of 2.4 cubic metres (NZFOA, 2023; Visser, 2014). Located on an active plate boundary in a zone of strong westerly winds, New Zealand experiences frequent intense rainstorms and high rainfall, creating a high-energy geomorphic environment conducive to erosion (Basher et al., 2011; Basher, 2013). Erosion rates surged during European colonisation due to widespread deforestation, introduction of grazing animals, and intensive land use practices (Glade, 2003; Mosley, 1978; Page et al., 2000). Rainfall-triggered shallow landslides stand out as the primary erosion type in the steep plantation forests, although other mass movements, gully erosion, and surface and streambank erosion also contribute significantly (Basher, 2013). The establishment of the State Forest Service in 1921 marked a shift towards afforestation to meet timber demands, particularly with radiata pine on erosion-prone land (Marden & Rowan, 1993; Roche, 1990). Significant erosion protection plantings started in the 1960s, with large areas of the Gisborne region being reforested (Marden et al., 2005), while areas of the country were also aerially seeded (Faulkner et al., 1972). While forests have been utilised effectively to control erosion and mitigate natural hazards, reducing erosion by 70-90% during large storms, the subsequent harvesting of these forests has led to increased soil issues (Basher, 2013; O'loughlin, 2004; O'Loughlin, 2005; Phillips et al., 2012; Poole, 1960).

Steep slope harvesting

The New Zealand forest industry increasingly operates on steep terrain—around 50% of harvesting occurred there in 2015, with over 60% expected by 2025 (FGR, 2010; Harrill *et al.,* 2019). Harvesting on steep slopes using cable yarders is typically 31% more costly than ground-based systems (Lyons *et al.,* 2023). Mechanisation has expanded rapidly, especially in cable yarding, where 90% of personnel now operate machines. This shift reduces dependence on skilled labour (Bayne & Parker, 2012; Kirk et al., 1997) and increases productivity by 25–40% through improved timber presentation (Acuna et al., 2011; Amishev & Evanson, 2010; Visser, 2015; Visser & Stampfer, 1998).

Historically, steep-slope harvesting relied on motor-manual felling and cable yarding with chokers. Following ten fatalities in 2013 (NZFFA, 2016; WorkSafe, 2023), a government–industry inquiry led to widespread mechanisation for safety. Future Forest Research introduced the principle “no worker on the slope, no hand on the chainsaw” to keep operators in machine cabs (FGR, 2015).

By 2017, 57% of operations used mechanised felling—up from 23% in 2009—and serious injuries fell sixfold between 2010 and 2016 (Raymond, 2017).

Harvesting system types

Machines are classified by the extraction system they use, typically Cut-to-Length (CTL) or Whole-Tree (WT). CTL employs a harvester to fell and process trees into logs, and a forwarder to transport them to the roadside. WT uses a felling machine to bring down and bunch trees, a skidder to haul them to a landing, and a processor to cut stems into logs there (Visser, 2015).

Machinery may run on wheels, wheels with belts, or tracks (Figure 1), each differing in manoeuvrability, size, cost, and ground impact. Tracked machines are larger and more powerful, common in high-production regions like New Zealand and North America, while advanced wheeled machines dominate in Europe (Visser & Stampfer, 2015).



Figure 1: Wheeled harvesting machine, with band tracks on the front bogey (left) and a tracked harvesting machine (right).

Winch assist

Winch-assisted harvesting ("winch assist") was developed to address the challenges of operating machinery on steep terrain. It enhances machine manoeuvrability by transferring tractive force through a winch cable anchored uphill of the machine on the slope (Amishev, 2016; Hunter, 1993; Visser & Stampfer, 2015). This adoption not only reduces costs but also improves safety. Winch assist systems were then integrated into forest machinery starting from the late 1970s, primarily to enhance forwarders' capabilities to match harvesting machines (Hartsough et al., 1988; McKenzie & Richardson, 1978). New Zealand adapted this technology for excavator-based machines used in steep terrain in the 2010s (Amishev & Evanson, 2010).

The use of winch assist has expanded machine operation in ideal conditions with purpose-built machinery, to slopes of up to 100% (Amishev & Evanson, 2010; Visser & Stampfer, 2015). However, manufacturers typically limit operations to around 50% (Holzfeind *et al.,* 2020). It's noteworthy that machines often exceed safety guidelines for slope operations (Berkett, 2012). Currently, 78% of cable yarder crews fell trees mechanically, a significant increase from just 1% in 2010 (Raymond, 2017; Visser, 2023), with 85% incorporating winch assist into their operations (Visser, 2023).

Site disturbance

Site disturbance in forestry encompasses a range of activities that alter the chemical, biological, or physical attributes of a site, including soil compaction, puddling, smearing, mixing, and displacement of soil and litter (McMahon, 1995c). These disturbances are primarily caused by earthworks, machine operations such as travel, tree removal during road construction, thinning, logging, and preparation for planting. The consequences of such disturbances extend beyond the immediate site, with impacts observed both on-site and off-site, the latter often manifesting at a considerable distance from the forest area. These impacts include increased erosion and sedimentation, alterations in soil nutrients, crop productivity, soil quality, and the social license to operate.

Studies conducted in New Zealand forests have revealed varying degrees of deep disturbance, ranging from 5% to 15% of the total area, influenced by factors such as terrain, soil characteristics, and logging practices (Marden et al., 2007). A comparison between the Tarawera and Raukūmara forests showed lower disturbance levels in Tarawera (5%) attributed to shorter slopes and better deflection, in contrast to Raukūmara (12%).

Landslides are the main source of sediment into a stream after a storm event (Basher, 2013). Despite this, harvesting increases sediment loads by five times, returning to pre-harvest levels within two to three years (Basher et al., 2011; Fahey & Marden, 2006; Marden & Rowan, 1997; Marden et al., 2007). Vegetation cover plays a crucial role in mitigating sedimentation, reducing sediment loads by 59% in shallow disturbance sites within two years post-harvest, while deep disturbance sites lack sufficient cover to achieve similar reductions (Marden et al., 2007).

The consequences of site disturbance extend to tree growth and economic viability, with removal of litter and compaction of topsoil leading to significant reductions in average tree volume (up to 42%) and economic potential (up to 60% loss in value) compared to control plots (Murphy et al., 2004).

Rutting

Rutting in forest harvesting machinery occurs when soil is displaced both vertically and horizontally. This displacement is primarily due to shearing stresses and soil compression, especially in moist or wet conditions (Horn et al., 2007; Williamson & Neilsen, 2000). Rutting serves as evidence that the soil's bearing capacity has been exceeded (Muro, 1982). The extent of rutting depends on various factors such as soil texture, bulk density, moisture content, organic matter, slope angle, vehicle type (gross vehicle mass), tire pressure, tire shape, and the number of trips made (Cambi et al., 2015). For example, the severity of rutting increases with slope steepness (Agherkakli et al., 2010), and there is a direct correlation between slope and the volume of displaced soil, although not necessarily with rut depth (Naghdi et al., 2009). Likewise, maximum rutting seems more closely related to overall vehicle mass (Eliasson, 2005).

WT and CTL extraction systems have been shown to cause similar levels of disturbance in the wheel track, however WT extraction also causes disturbance between the wheels due to stems dragging. Vegetation (slash mats) makes 1st pass rut depth small. After this, vegetation gets broken up, rut depth quickly increases thereafter (Liu et al., 2011). If no vegetation, 62% of compaction occurs in first pass (Williamson & Neilsen, 2000). 15-20kg of logging residue per metre squared can greatly reduce the level of rutting (Ilintsev et al., 2020).

Research has yielded mixed results regarding the performance of different forest harvesting machinery configurations. For instance, studies have shown that 1-metre wide wheels generated approximately 50% less rut depth compared to belts and 40% fewer than 710mm tyres (Haas et al., 2016). However, the addition of belts to wheel pairs has been found to potentially reduce rut depth by up to 40% (Bygdén et al., 2003). Wheels have been observed to create deeper ruts than tracks, (Jansson & Johansson, 1998; Johnson et al., 1991). Additionally, the comparison between wide tyres and tracks revealed similar rutting patterns (Murosky & Hassan, 1991). Conversely, tracked machines create deeper ruts when turning because their tracks compress soil inward during the turn and then push it outward. Wheeled machines experience less severe rutting while turning because their individual wheels follow different tracks, distributing pressure more evenly (Liu et al., 2011).

Compaction

Soil compaction occurs when applied pressure exceeds soil strength, reducing porosity and increasing density (Cambi et al., 2015). Porosity reductions of 50–60% can impair root growth and nutrient exchange (Ampoorter et al., 2007; Ares et al., 2005; Frey et al., 2009). The severity of deformation depends on factors such as initial bulk density, texture, organic matter, moisture, slope,

and harvesting practices (Ballard, 2000; Jamshidi et al., 2008; Williamson & Neilsen, 2000). Coarse soils tend to be less prone to compaction than fine soils (Steber et al., 2007).

Tires and tracks contribute similarly to compaction, though tracks distribute uneven pressure and cause more vibration (Jansson & Johansson, 1998; Muro, 1982; Sheridan, 2003). Near saturation, soils form ruts rather than compact, due to lateral displacement under pressure (Horn et al., 2004; Horn et al., 2007; Williamson & Neilsen, 2000). The compacted layer often reaches 40–50 cm depth, with compaction rising as moisture increases until rutting occurs (Ampoorter et al., 2012; Cambi et al., 2015; Han et al., 2006; Horn et al., 2007; Williamson & Neilsen, 2000).

Slope increases compaction risk (Agherkakli et al., 2010), and heavier machinery produces greater impacts (Jansson & Wästerlund, 1999). Extraction direction matters, with the most compaction during uphill skidding (Jourgholami et al., 2014; Picchio et al., 2012). Whole-tree vs. cut-to-length systems show little difference in effect (Han et al., 2006).

Compaction particularly reduces macroporosity (Ares et al., 2005; Seixas & McDonald, 1997), limiting infiltration and gas exchange (Ares et al., 2005; Arthur et al., 2013; Berli et al., 2004; Frey et al., 2009). Tree growth responses vary: several studies report no reduction (Ares et al., 2005; Ampoorter et al., 2007; Blouin et al., 2005), while some indicate minor declines due to increased resource competition (Smith, 2003). Regeneration within ruts can drop two- to seven-fold (Ilintsev et al., 2020). Sandy soils recover slowly, especially under repeated traffic (Ampoorter et al., 2007; Startsev & McNabb, 2000), and reduced voids may still restrict growth (Jansson & Wästerlund, 1999; Williamson & Neilsen, 2000).

Compaction also elevates runoff and waterlogging risks (Christopher & Visser, 2007; Startsev & McNabb, 2000). Bulk density (BD) and penetration resistance (PR) are primary indicators of physical change (Håkansson & Lipiec, 2000; Vaz et al., 2001). PR is especially sensitive to moisture variation (Vaz & Hopmans, 2001) and is often a more discriminating metric (Cambi et al., 2015; Cambi et al., 2016; Smith et al., 1997), with shear resistance additionally relevant in lowland forests (Cambi et al., 2016). Standardising PR measurements under uniform moisture is essential (Smith et al., 1997). Increases can reach 60–70% in coarse soils and up to 150% in fine textures, especially when wet (Ampoorter et al., 2010), including up to 115% in the top 10 cm (Abdi et al., 2017), with machinery intensity consistently driving PR increases regardless of soil type (Ampoorter et al., 2010; Cambi et al., 2016).

Best practice for minimising disturbance

National Environmental Standards for Plantation Forestry (NES-PF) aims to provide nationally consistent guidelines to manage the environmental effects of plantation forestry. For harvesting to be a permitted activity, it requires the following with respect to cutover disturbance (MPI, 2023).

- Sediment originating from harvesting must not:
    - Change the colour or clarity of receiving water bodies.
    - Render the water unconsumable by farm animals.
    - Have adverse effects on aquatic life.
- Butt suspension must be planned where possible.
- Disturbed soil must be stabilised or contained to minimise sediment entering the water.
- Slash must not move into a water body during a 5% annual exceedance probability event.
- No more than 15 m^3/ha of sound wood with large end diameter over 10 cm and length over 2 m may be left on the cutover.

The New Zealand Forest Owners Association (NZFOA) have a series of Forest Practice Guides (FPGs) which dictate good processes for minimising safety and environmental risk in forestry operations. They align with the Resource Management Act 1991 (RMA) and the NES-PF. The

following best practices, relevant to minimising cutover disturbance, are derived from the FPGs (NZFOA, 2020).

- Plan landing and backline locations to maximise deflection and pull as directly as possible across high-risk slopes.
- Consider where slash will be swept by dragging stems.
- Partially or fully suspended logs will generate much less disturbance when extracting.
- Leave areas of forest that create unacceptable risk.
- Spread the harvest out over a series of years in large, high-risk catchments.
- Reduce merchantable timber in the cutover.
- Use techniques that reduce felling breakage.
- Use slash, mulch, hydro-seeding or grassing to cover exposed, unconsolidated soil.
- Rehabilitate harvesting tracks by covering, installing water controls, and pulling back.

Site recovery

Site stabilisation

For a site to begin recovery, it must first stabilise (Whisenant, 2005). Stabilise is defined as maintaining a given or unfluctuating level or quantity (Dictionary.com, 2024). Increasing the cover of vegetation or litter, preferably both, is the most effective strategy for reducing erosion (Whisenant, 2005). Maintaining good ground cover is key to reducing rates of sheet, rill, and wind erosion (Basher, 2013). Plants protect the soil with their canopy, add litter to the soil surface, and stabilise the soil with their roots. Litter on the soil surface reduces erosion (Whisenant, 2005). Afforestation has been shown in many cases to stabilise soil, both in space-planted areas (Wilkinson, 1999) and in forested areas (Marden, 2012; Marden et al., 2014). Dense ground cover provides the best protection against surface erosion (grass), while woody vegetation offers the best protection against shallow landslides (Barker, 1995). Plant residues absorb rainfall energy and prevent soil detachment by rainfall splash. This study focuses on measuring stabilisation as opposed to recovery.

Soil recovery

Studies have shown that recovery from rutting on rolling terrain can take between 12 to 25 years under light and medium traffic loads, with more intense traffic prolonging the recovery period (Dickerson, 1976; Hatchell et al., 1970; Sohrabi et al., 2020), i.e., heavier machinery or higher traffic volumes result in longer recovery times (Sohrabi et al., 2020).

Soil types play a crucial role in recovery rates, with soils containing expandable phyllosilicates (sheet-like clay minerals that can soak up water and grow thicker (expand) because their layers spread apart) recovering faster due to wetting-drying cycles, compared to non-dynamic soils like sands (Greacen & Sands, 1980; Rab, 2004). Surface layers tend to recover faster than deeper soil layers (Mohieddinne et al., 2019). Additionally, the presence of biological activity in the soil contributes to faster recovery rates (Mohieddinne et al., 2019).

Factors that affect or that are affected by soil disturbance significantly decrease within two to six years after planting. These include sediment generation (four years), soil moisture (five years), throughfall (three years), landsliding (five to six years) (Marden et al., 2023).

Vegetation recovery

The causes of compaction in forestry operations are multifaceted and influenced by various factors. One significant aspect is the window of vulnerability observed after tree harvesting in steep plantation forests (Figure 2). This phase is characterised by increased soil moisture, rapid root decay, and

reduced root reinforcement, which collectively heighten the susceptibility to shallow landslides, posing a risk of slope failure during this period (Marden et al., 2023; O'Loughlin, 1985; Sidle & Ochiai, 2006; Sidle et al., 2005).

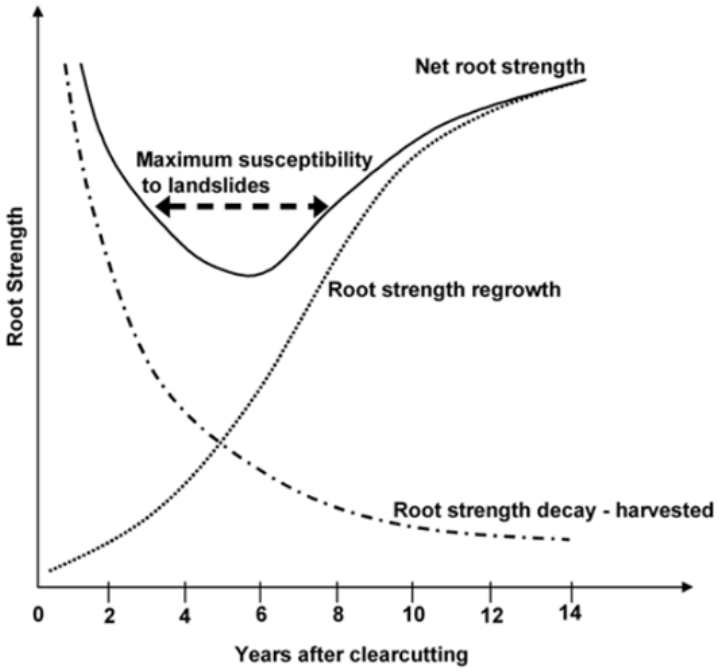


Figure 2: An example of typical changes in forest vegetation rooting strength after clear-cutting (Sidle et al., 2005).

Additionally, studies have shown that species richness in naturally regenerating forests is lower on skid trails, even after an extended period of 18 years (Pinard et al., 2000). This phenomenon was observed in rainforests, which typically have slower growth rates compared to New Zealand's radiata pine. In specific areas such as Tarawera in the Central North Island (CNI), vegetation cover initially occupied only about 1% of the ground after harvest. However, within seven months, this increased significantly to 33%, reaching 85% vegetation cover 21 months after harvest, albeit experiencing a drop due to pre-planting spraying activities. Similarly, in the Raukūmara Forest, 83% of the ground was covered in vegetation within two years (Marden & Rowan, 1997; Marden et al., 2007). Notably, the rate of initial recovery was observed to be faster in areas with less soil disturbance, highlighting the impact of soil disturbance levels on vegetation recovery post-harvest (Marden et al., 2007).

Fauna recovery

Studies have shown that harvesting operations lead to a decrease in the abundance of soil fauna, with an average reduction of 17% across different faunal groups. This reduction varies considerably among groups, ranging from a decrease of 56% in Oribatida to an increase of 67% in Araneae populations (Kudrin et al., 2023). The impact of harvesting on soil fauna recovery is also influenced by body size, with smaller groups exhibiting more pronounced negative effects compared to larger taxa (Kudrin et al., 2023). Despite these initial declines, most soil fauna groups show signs of recovery within a decade after harvesting (Kudrin et al., 2023).

Fungal and mycorrhizal biomass are reduced post-harvesting, which directly affects soil fauna that rely on these resources for nutrition and habitat (Bååth et al., 1995; Moore-Kucera & Dick, 2008). Clearcutting has been found to have a greater effect on soil fauna abundance and diversity compared to partial cutting practices (Chaudhary et al., 2016; Fedrowitz et al., 2014).

Measuring site disturbance

There are three main ground survey techniques for visually measuring site disturbance (McMahon, 1995a; Najafi & Solgi, 2010; Page-Dumroese et al., 2009) (Refer to Appendix 4 for remote sensing methods).

Point Transect (PT) Method

- Disturbance is classified at fixed, predetermined points along a transect.
- Transects are usually aligned parallel or perpendicular to site contours.
- Transects generally oriented perpendicular to extraction lines.
- Sampling points are located using a rod dropped at marked intervals.
- The percentage of each disturbance type is calculated from the number of points in each class divided by the total number of points.
- A random start point improves statistical reliability.

Line Transect (LT) Method

- Disturbance is recorded continuously along the transect line.
- Start and end points of each disturbance feature are measured.
- Total lengths of each disturbance class are summed and expressed as a percentage of the total surveyed area.
- Transects are evenly spaced and can follow site contours or be set at perpendicular angles.
- A modified version uses randomly oriented transects within fixed plots to capture more variation.

Grid Point Intercept (GPI) Method

- Sampling points are based on a square grid laid out systematically over the area.
- Grid size depends on the area being studied and desired sample size.
- The first transect is randomly oriented; others follow at 90°, 180°, and 270° angles.
- This ensures even spatial coverage and reduces sampling bias.

PT was found to be more accurate than the GPI method in studies using a 30 m spacing, when compared to GPI (McMahon, 1995a; Naghdi et al., 2016; Najafi & Solgi, 2010). Its success has been attributed to its simplicity, which makes it easy to apply and replicate in a range of contexts (McMahon, 1995c).

The PT methodology used in this study has been applied in various scientific studies. It has been incorporated into the harmonised European protocol for work studies in forestry (Magagnotti et al., 2011; Visser, 1997) and the USDA Forest Service monitoring protocol (Page-Dumroese et al., 2009). It is widely used to monitor soil disturbance from skidding and ground-based operations (Gondard et al., 2003; Naghdi et al., 2016; Pedofsky & Visser, 2020; Solgi & Najafi, 2014), and has also been used in cable logging operations (Laffan et al., 2001). In New Zealand it has been used to assess disturbance on 17 sites, including clear-cut and production-thinned areas where both high-lead cable yarders and ground-based systems were used (Murphy, 1982b).

PT is also commonly used to measure vegetation. LT and PT were found to be more accurate than plot-based measurements in this context, with PT requiring the least effort (Brady et al., 1995; Floyd & Anderson, 1987; Heady et al., 1959). Ocular estimates (where the proportion of vegetation types is estimated by eye) were found to detect more species, but GPI and PT were more accurate in estimating the proportion of each species (Godínez-Alvarez et al., 2009). Time required for LT and ocular methods was significantly lower than for GPI transects, and LT had the lowest coefficient of variation, followed by GPI and then ocular estimates (Godínez-Alvarez et al., 2009).

Classifying site disturbance

Quantifying the severity of soil damage through measurement of soil physical properties is time-consuming and requires skilled technicians (Murphy, 1982a). Visual assessments, though less precise, can be performed quickly by less experienced personnel and still provide useful results (McMahon, 1995c; Murphy, 1982a). Several classification systems exist. At the simpler end, a five-class system specifically addresses soil damage: (1) no machine traffic; (2) machines have travelled over the area without breaking the litter layer; (3) the litter layer is broken and the topsoil shows early signs of compaction; (4) most of the topsoil is puddled and the subsoil is compacting; (5) the subsoil is puddled and compacted (Murphy, 1982a).

This five-class system can be expanded into 15 sub-classes, with each class having 1 to 6 subdivisions. Each subclass can further be clarified with one of two modifiers, resulting in a total of 45 distinct disturbance classes (**Error! Reference source not found.**) (McMahon, 1995c). Variants of this system have been applied in New Zealand (Evanson et al., 2013; Visser & Spinelli, 2020, 2023) and internationally (Parker, 2007).

Table 1: Disturbance classifications this study adapted from (McMahon, 1995c).

DISTURBANCE CLASS	DISTURBANCE TYPE	CODE
Undisturbed		1
Shallow disturbance	litter in place litter removed, topsoil intact litter and topsoil mixed topsoil deposited on litter	2 3 4 5
Deep disturbance	topsoil removed, subsoil exposed erosion feature subsoil puddling 5-15cm deep rut 16-30cm deep rut >30cm deep rut subsoil/baserock deposit	6 7 8 9 10 11 12
Slash cover	10-30cm deep >30cm deep	13 14
Non-soil		15
CLARIFIER		**CODE**
Compacted Mineral/subsoil		C M

Another approach is used in the USDA Forest Soil Disturbance Monitoring Protocol, which employs fewer, broader categories. The USDA system defines four severity-based classes; for instance, ruts deeper than 10 cm, charring deeper than 5 cm, and compaction beyond 30 cm all fall under damage class 3 (Page-Dumroese et al., 2009).

Because these classification systems are subjective, strict and consistent criteria must be applied when assigning classes. When using soil indicators to determine disturbance class, each indicator may suggest a different class. Therefore, it is necessary to identify the overriding concern—such as soil texture, anticipated vegetative response, erosion, or site sensitivity—and base the classification of each monitoring point on that factor (Page-Dumroese et al., 2009).

METHODS

Study Sites



Figure 3: Location of sites studied.

This study was undertaken across numerous sites for data collection, spread from Northland to South Otago, as shown in Figure 3.

Sites from different forests have different weather (refer to Table 2), soil, terrain, harvesting crews and methods, infrastructure, and other factors. This means they cannot be directly compared.

In the analysis, sites within a forest were treated as the same site progressing over time. Therefore, they were chosen to be as similar as possible. The requirements for the 14 forests chosen to be used in the study are listed below.

- Homogenous geological and meteorological conditions across the forest.
- Steep enough for winch assist machinery to have been used.
- Large enough that harvesting has been occurring there for 3+ years.

As soil characteristics influence the extent and type of disturbance at each site, a substantial variation in soil properties was evident across different locations. Below is listed the soil type at each site (Manaaki Whenua - Landcare Research, 2019).

Table 2: Climate data for the nearest city to each forest (NIWA, 2020).

Forest	Location	Rainfall	Wet days	Sunshine	Mean temperature	Gale winds
		mm	>=1.0 mm	Hours	°C	Days
Whangarei	WHANGAREI	1490	132	1973	15.5	1
Wellsford						
Huntly	HAMILTON	1190	129	2009	13.7	2
Whangamatā	TAURANGA	1198	111	2260	14.5	5
Kawerau						
Ōpōtiki						
Raukūmara	GISBORNE	1051	110	2180	14.3	2
Waipaoa						
Mohaka	NAPIER	803	91	2188	14.5	3
Hunterville	PALMERSTON NORTH	967	121	1733	13.3	3
Maitai	NELSON	970	94	2405	12.6	2
Wakefield						
Warrington	DUNEDIN	812	124	1585	11	8
Lawrence						

Winch-assisted, mechanised harvesting was used at all sites. Motor-manual felling was also used in difficult areas at a lot of cases. This was generally at the contractor's discretion, so was not recorded. The main extraction method at all sites was a cable yarder. The only site preparation was desiccation spraying.

Point line transect method

The methodology employed in this study is based on an adapted version of the Logging Industry Research Organisation (LIRO) method for measuring soil disturbance, as outlined by McMahon in 1995. However, due to advancements since then, particularly in Geographic Information Systems (GIS) technology, certain aspects of the method have been updated and refined to ensure accuracy and relevance to current practices (McMahon, 1995c). Similar methods are explained in more detail in the USDA Forest soil disturbance monitoring protocol (Page-Dumroese et al., 2009). The process used to decide which classification a point falls into is outlined in Appendix 3.

1. Before arrival, the forest management located check sites, based on terrain, harvest system and proximity. They provided forest and harvest maps.
2. Four sites were chosen, one harvested in each of the four preceding years. Any variation from this is noted in the results section.
3. The boundaries of the harvest setting were identified by standing at a vantage point, such as a landing or road, and using the provided maps to assess the visible area.
4. The harvest area width was estimated from the maps. Any non-stocked areas or significantly atypical areas were excluded.
5. The number of transects was determined based on the desired absolute error in measurement and the number of data points required for accurate analysis (McMahon,

1995c). 3% absolute error was used for this study, achieved at 1111 data points per age class.

6. Transects were spaced evenly, according to elevation, across the setting. They were located to follow a contour. The LIRO method recommends orientating transects perpendicular to the dominant extraction direction (McMahon, 1995c). Transects following a contour generally achieves this.
7. Along each transect, classification points are located at 1-metre intervals. This spacing allows for the identification of small-scale features such as ruts, skid trails, and other disturbances (McMahon, 1995c).
8. At each classification point, the dominant disturbance class within a 30-centimetre radius was recorded. Each point can only be assigned one disturbance code. This classification system, adapted from McMahon's methodology, simplifies the assessment of soil disturbance into categories (Table 4).

Table 3: Number of sampling points required for a given error (McMahon, 1995c).

Absolute error (%)	Number of data points
1	10000
2	2500
3	1111
5	400

The number of transects was calculated according to the width of the site (Equation 1).

$$Number\ of\ transects = \frac{No.of\ data\ points}{Site\ width} \quad (1)$$

Table 4: Categorisation of soil disturbance.

Disturbance description	Code
Undisturbed	**0**
Dense vegetation	**1**
Topsoil mixing	**2**
Topsoil removed	**3**
Subsoil mixing	**4**
<15 cm deep rut	**5**
>15 cm deep rut	**6**
Erosion feature	**7**
Slash	**8**
Non-soil	**9**

Below are some examples of classifications (Figure 4). These were taken during method trials, and the number represents the classification the area would have received.

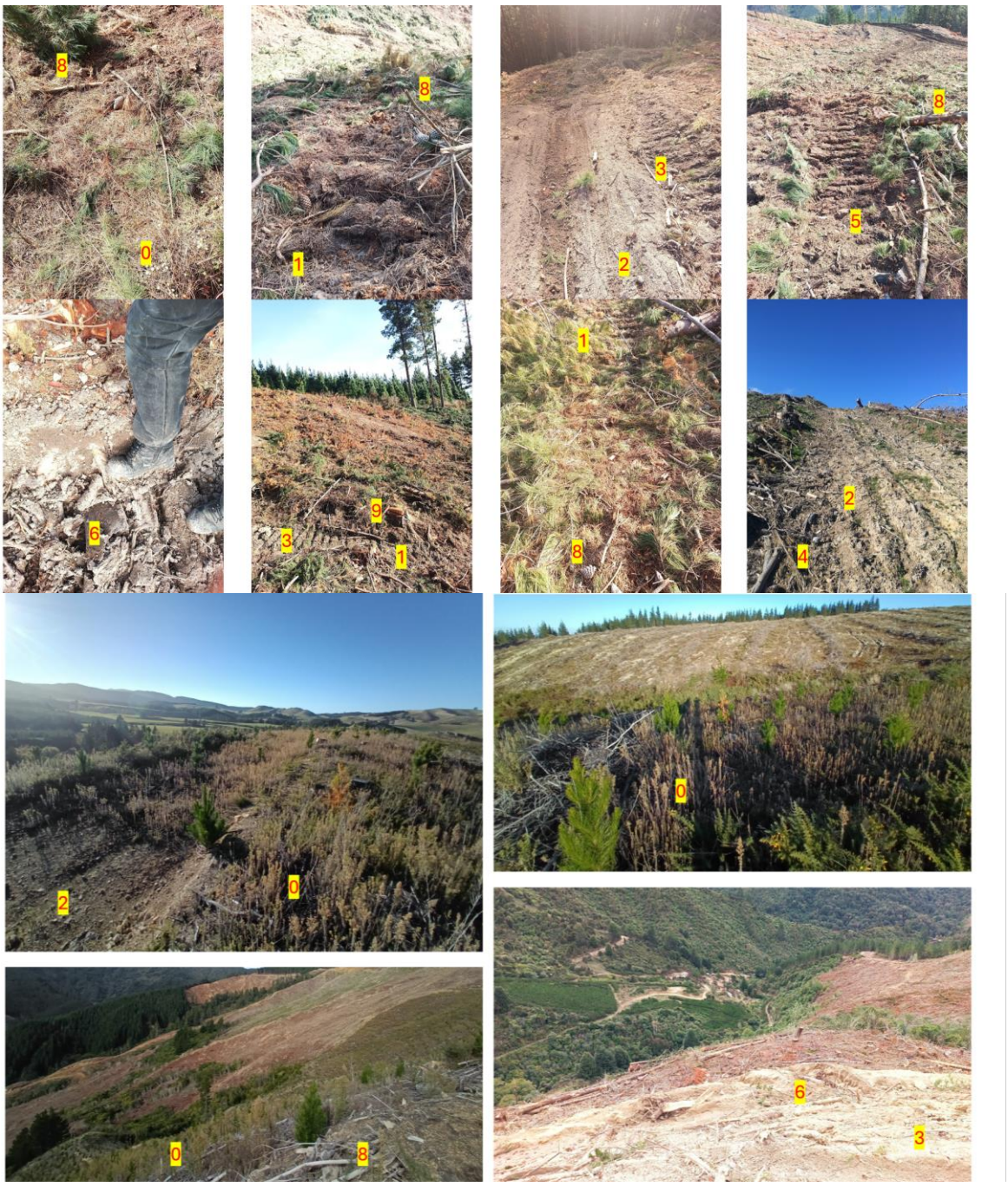


Figure 4: Example disturbance classifications according to Table 4.

Data processing

ArcGIS Pro, Microsoft Excel, and IBM SPSS (International Business Machines Statistical Package for the Social Sciences) Statistics were used for data processing. Public LiDAR data was utilised where available, while privately collected LiDAR data was obtained from the forest management company when public data was not accessible. ArcGIS Pro was employed to generate DEMs, aspect, slope, hillshade, contour, curvature, and flow accumulation maps for each forest. Additionally, GPS tracks recorded during data collection were processed to remove places where the track did not follow the transect. Figure 5 shows the original GPS track.

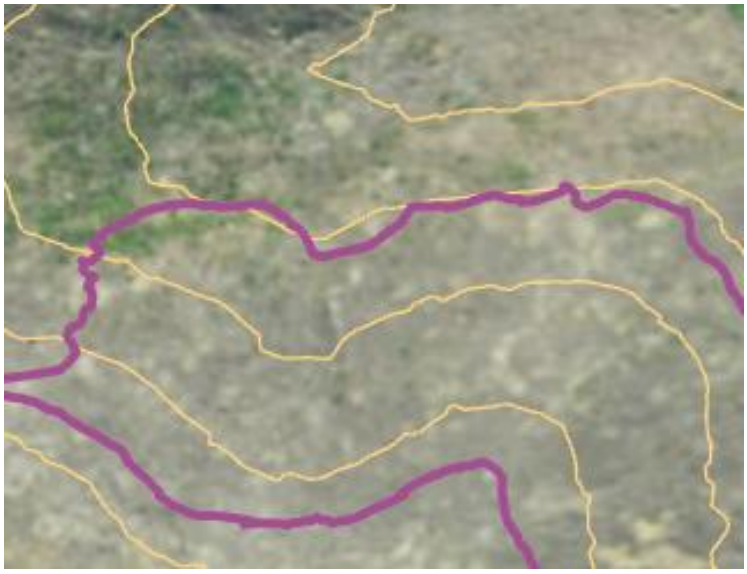


Figure 5: Original GPS track recorded during data collection (continuous line).

GPS tracks were refined using contour data to remove segments where obstacles required detours during data collection. Slow movement due to challenging terrain resulted in erratic GPS tracks. These sections were edited to ensure the points stayed in a uniform line when data points were later added at 1-metre intervals. Sections between transects were deleted. They were easily identifiable based on movement relative to the contours- while collecting data, transects followed contours, whereas travel between transects was perpendicular to them.

GPS points were recorded at 1-second intervals, resulting in uneven spacing due to variations in travel speed. To align these points with the actual data collection locations, the transect length was divided by the total number of recorded points in that transect. Additionally, field notes often referenced specific points and distances along the transect, allowing for further subdivision and improved positional accuracy. Figure 6 shows the GPS track after that process.



Figure 6: GPS track with sections removed, and converted to evenly spaced points.

Despite every effort to be accurate, it is estimated the positional accuracy of a data point is estimated at 20 m. This is due to the error of the GPS recording device (5 m in open terrain (Van Diggelen & Enge, 2015)), plus the recording error. This was the difference between the number of data points collected and the length of the transect according to the GPS. This averages around 15 m.

Data from processed LiDAR maps was assigned to each data point along the GPS tracks. Field-collected data was then integrated with the GPS track so that each point along the track had a disturbance code and terrain information assigned to it (Figure 7).

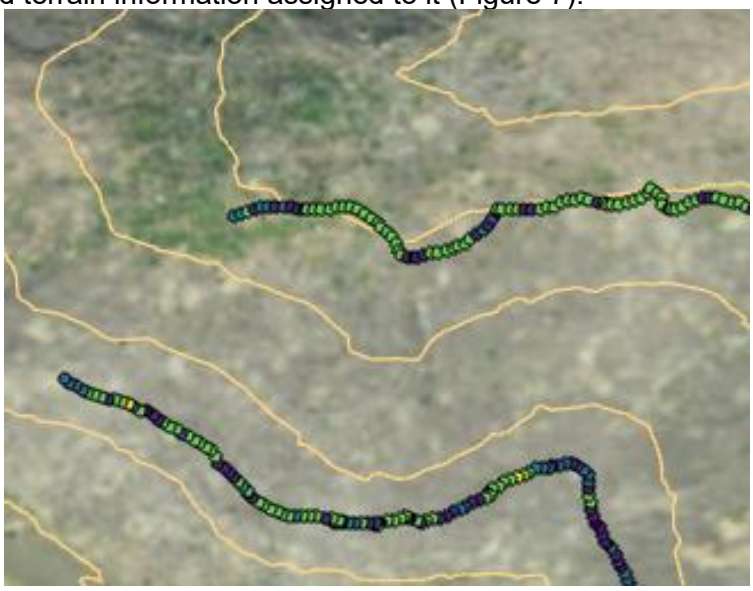


Figure 7: GPS track with all data added, with symbology set to display one of the layers.

Attribute tables were exported to CSV (Comma Separate Values) format and combined into a single file, with forest name and area added, resulting in a dataset containing 35 columns. Statistical tests, including linear regression and chi-square tests, were conducted on the processed data.

Industry Survey

The second part of this study was to survey harvesting contractors, harvest managers and harvest planners about the methods and policies they use to minimise soil disturbance during harvesting. The following questions were asked while conducting the soil surveys. The survey was conducted verbally (Results for the Industry Survey are in Appendix 4).

The following questions were asked of harvesting contractors.

1. What do you do to minimise soil disturbance during harvesting operations?
2. How does the equipment you use reduce your impact on the site? Was this a consideration when buying it?
3. What do you do to prevent erosion on the cutover during and after harvesting activities?
4. How has the way you've managed the soil disturbance changed over time? What do you think you will have to change in the future?

The following questions were asked of the harvest managers and harvest planners.

1. How do you assess soil and terrain characteristics before planning a harvest?
2. What techniques or equipment have you noticed reduce soil disturbance?
3. What details are provided to the contractor on allowable soil disturbance?
4. Does your company monitor the amount of disturbance after harvest?

RESULTS

Overall site cover

In total, 52,542 data points were collected across the 14 sites. Between two and four age classes were analysed at each site, according to what was available (Table).

Table 5: Ages measured and total number of data points at each site.

Site	Number of age classes	Ages measured	Total number of data points
Hunterville	4	0,1,2,3	4386
Whangarei	4	0,1,2,3	4373
Waipaoa	4	0,1,2,3	4368
Maitai	4	0,1,2,3	4365
Raukumara	4	0,1,2,3	4322
Huntly	4	0,1,2,3	4308
Wakefield	4	0,1,2,3	4277
Kawerau	4	0,1,2,3	4268
Whangamata	4	0,1,2,3	4130
Mohaka	4	0,1,2,3	4036
Wellsford	3	1,2,3	3237
Lawrence	2	0,1	2179
Warrington	2	0,1	2159
Opotiki	2	0,1	2133

Overall, slash and vegetation were clearly the two most common ground conditions, together making up 67% of points collected. Bare soil, therefore, covered 32% of sites overall, while non-soil made up the remaining 1% (Figure 8).

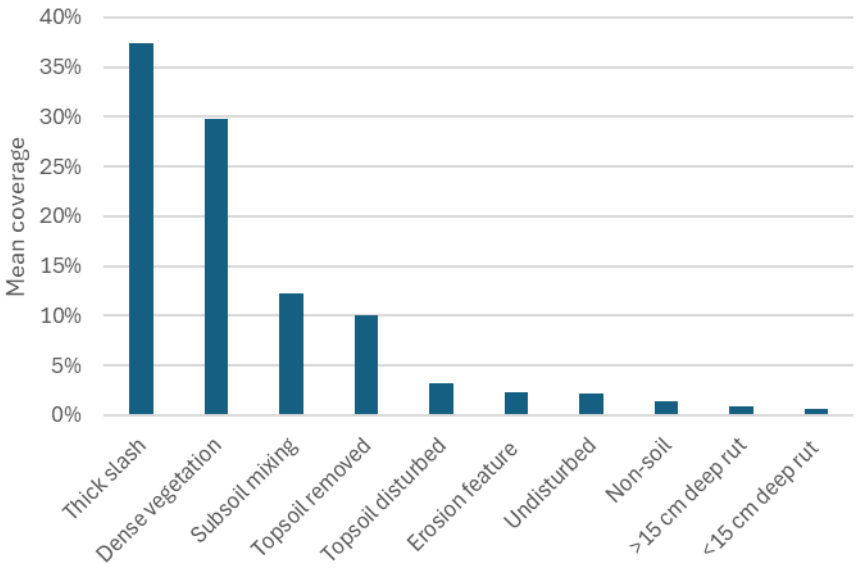


Figure 8: Proportion of each class over all age classes and all sites.

Slash and vegetation dominated ground cover across all measurements. Slash declined over time as it decomposed and became overgrown, while vegetation increased at a similar rate, resulting in only a slight overall rise in total cover. Vegetation expansion was limited during the first year due to release spraying, then increased rapidly afterward. This trend is more pronounced when viewing single-site data, since sites without release spraying lessen the contrast in the combined dataset.

Undisturbed forest floor was rarely recorded and quickly disappeared, as weeds readily grew through these patches. Figure 9 shows these three disturbance codes over the four age classes studied.

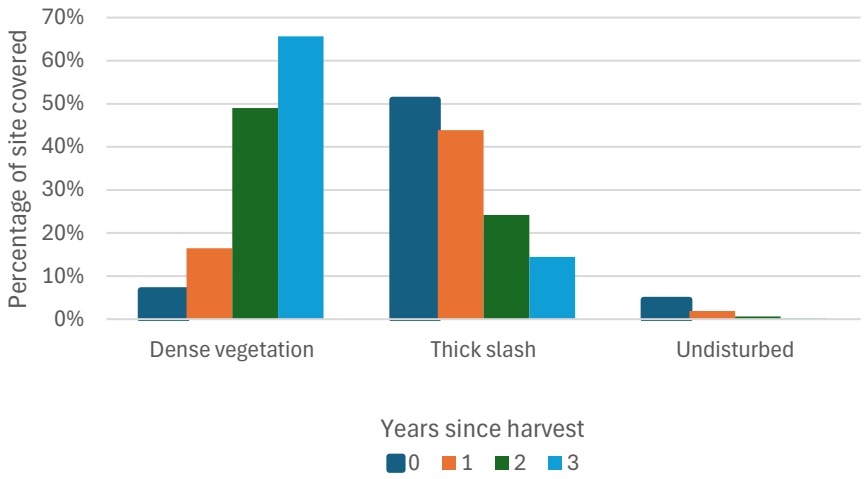


Figure 9: Vegetation, slash, and undisturbed over time at all sites.

Subsoil mixing declined steadily over time, faster than other exposed soil types. Weeds established well in these areas, although increasing compaction sometimes made it difficult to distinguish between “subsoil mixing” and “topsoil removed.” It never reached zero, likely due to continued disturbance from erosion or animal movement, and some mixing may have been obscured beneath slash and vegetation. This limitation is inherent to the survey method but consistent across the study.

Topsoil disturbance was generally low because steep slopes left little topsoil, and grouser depth often exceeded the topsoil layer, resulting in more subsoil exposure. Where topsoil was removed entirely, hard subsoil was left at the surface, slowing vegetation recovery. Some previously mixed subsoil may also have been reclassified as topsoil removed once it compacted. Figure 10 illustrates the trends in these three disturbance classes over time.

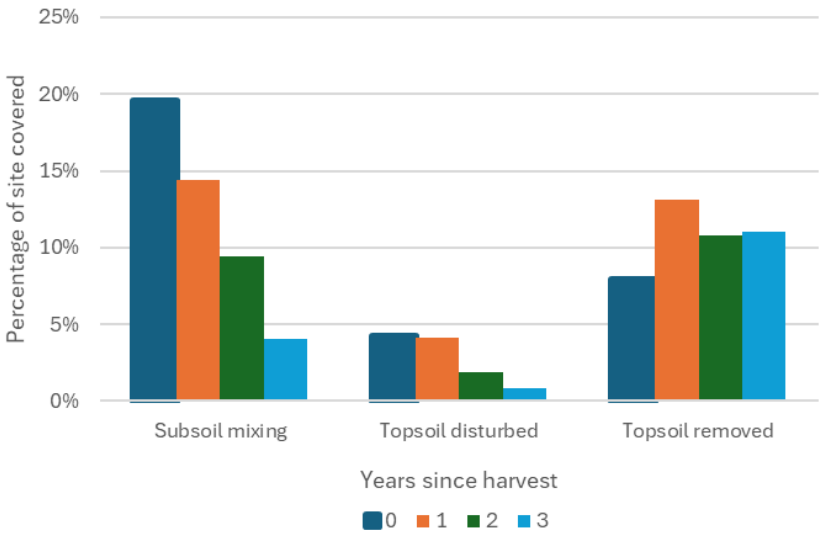


Figure 10: Subsoil mixing, topsoil disturbed, and topsoil removed over time at all sites.

Both depths of ruts displayed similar patterns, decreasing with time. This happened due to a few factors. First, ruts filled in, so were no longer visible. Second, vegetation grew in and over them, reducing fluvial erosion and making them invisible from above ground. Third, some ruts began eroding meaning they were reclassified as erosion features.

Erosion features are the only class that do not display a trend with time. The overall trends for these three classes can be seen in Figure 11.

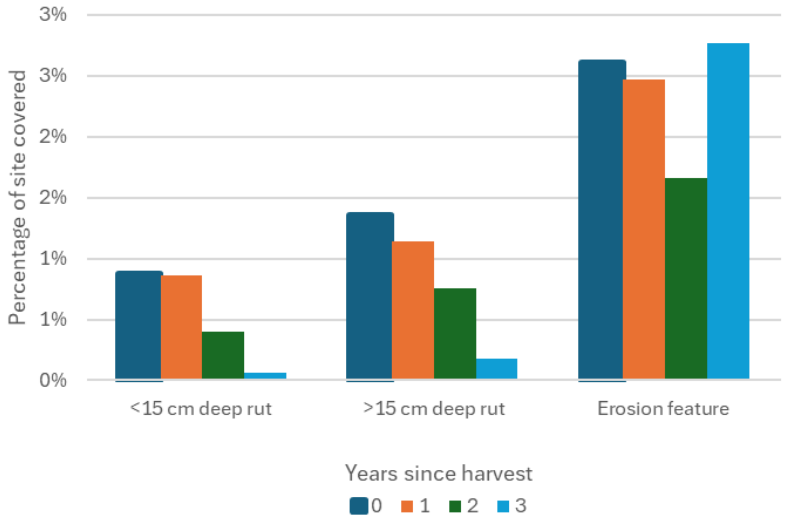


Figure 11: Shallow ruts, deep ruts, and erosion features over time at all sites.

Terrain factors influencing disturbance

Below, all 52,000 data points were analysed, except in the ANOVA test, which included only sites containing all four age classes. This exclusion removed Warrington, Lawrence, Ōpōtiki, and Wellsford, leaving ten sites for analysis. Various statistical methods, including ANOVA, t-tests, linear regression, and chi-square tests, were applied to different data sets. Significance was tested at $P<0.05$. Please refer to the full report (link in summary) for the full statistical analysis.

Site effect

Sites were very different to each other. To show this, all sites that had four age classes are displayed in Table . Following the rows along shows that some sites had many times the percentage coverage of certain disturbance classes than other sites. Almost every class has sites that are particularly high, and ones that are particularly low. This appeared to depend mostly on the soil and weather conditions in the forest, during the harvest and since.

Table 6: Percentage of each disturbance code for all sites with four age classes.

	Whangarei	Kawerau	Whangamata	Huntly	Raukumara	Waipaoa	Mohaka	Hunterville	Wakefield	Maitai
<15 cm deep rut	0.2%	0.7%	0.4%	0.5%	0.5%	0.4%	1.0%	0.4%	1.4%	0.4%
>15 cm deep rut	0.3%	1.1%	0.8%	1.9%	1.2%	1.2%	1.6%	0.2%	0.8%	0.8%
Vegetation	31.5%	26.5%	41.4%	22.3%	32.6%	63.7%	15.6%	44.6%	27.6%	42.4%
Erosion	1.9%	3.0%	2.9%	1.6%	4.2%	3.2%	2.9%	2.8%	0.2%	0.6%
Non-soil	0.4%	1.0%	1.1%	1.1%	0.4%	0.4%	1.2%	1.7%	1.6%	3.1%
Subsoil mixing	12.2%	15.4%	12.9%	18.7%	11.9%	5.3%	15.9%	6.7%	18.0%	6.3%
Slash	38.6%	30.7%	27.5%	37.7%	37.2%	21.6%	38.3%	29.3%	25.2%	30.4%
Topsoil mixing	0.1%	4.8%	4.6%	4.6%	3.3%	0.6%	4.1%	1.9%	2.7%	0.4%
Topsoil removed	14.4%	14.3%	6.7%	8.1%	6.9%	3.6%	17.5%	10.9%	20.3%	15.0%
Undisturbed	0.4%	2.4%	1.5%	3.4%	1.9%	0.1%	1.8%	1.4%	2.3%	0.6%

The Chi-square analysis revealed that forests were significantly different from each other across all disturbance codes. Below are the key findings from the analysis

- Undisturbed areas were more common in Whangarei, Waipaoa, Maitai, and Wellsford.
- Some sites had lower values in one rut category while being higher in the other, suggesting that site characteristics played a role in determining rut depth. Additionally, in certain locations, tracking may have been more concentrated, leading to fewer but deeper ruts.
- Topsoil disturbance was significantly higher in Huntly, Raukūmara, Kawerau, Warrington, Ōpōtiki, and Mohaka—sites characterised by thick topsoil or similar subsoil and topsoil.
- Non-soil presence was primarily influenced by stony soil conditions, with the highest occurrences observed in Maitai, Hunterville, and Lawrence.
- South Island sites, in particular, had lower erosion feature counts, averaging just 0.25% of points.
- Slash accumulation was significantly higher in Lawrence (a Douglas fir forest), Warrington (one Douglas fir site), Ōpōtiki, Mohaka, and Whangarei.
- Slash was more frequent in the bottom of valleys, and exposed soil most frequent on ridges, where flow accumulation was higher.
- Erosion features appeared more common on faces but also were noted around machine tracks and extraction corridors more frequently.

Linear regression analysis showed that higher elevations had increased slash accumulation, deep ruts, subsoil mixing, and topsoil removal. In contrast, lower elevations showed greater topsoil mixing and higher vegetation cover.

Steeper slopes were associated with an increase in erosion features, deep ruts, shallow ruts, subsoil mixing, non-soil surfaces, and topsoil removal. Conversely, steeper slopes led to a decrease in slash accumulation, vegetation cover, and undisturbed areas.

Shallow ruts, subsoil mixing, and topsoil removal were more common on convex land features. In contrast, concave land features had higher occurrences of slash accumulation, topsoil mixing, and vegetation cover.

Linear regression on the bearing direction of slopes indicated that aspect had a small but statistically significant effect on erosion features, vegetation, and soil mixing. This may or may not be useful, though, because high and low bearings (values of 359 and 0, both of which are in the same direction) are close to each other.

The aspect sampled into eight compass directions (using a chi-square analysis) showed the significant trends listed below.

- Undisturbed areas were lower on SE, S, and SW aspects.
- Vegetation showed no consistent relationship with aspect.
- Topsoil disturbance was slightly lower on N, NE, and NW aspects and slightly higher on SE and SW.
- Topsoil removal was lower on E and SE but higher on W, NW, and SW.
- No clear patterns were observed in subsoil mixing.
- Shallow ruts were more common on W aspects and less frequent on E and SE.
- Deep ruts showed no discernible trends.
- Slash accumulation was higher on S and SW aspects and lower on N, NE, NW, and SE.
- Erosion features yielded no clear patterns.

Disturbance changes over time

Linear regression indicated that all observation types, except erosion features, were significantly influenced by crop age. Age was the most significant factor differentiating sites, affecting all categories except erosion features. Soil disturbance and slash accumulation decreased over time, while vegetation cover increased. Topsoil mixing or non-soil areas showed a statistically significant, though slight, decline.

A t-test was conducted to assess differences between data collected immediately after harvest and three years post-harvest. This was conducted on the overall proportion of each disturbance code at each site. The linear regression, on the other hand, was conducted individual data points. Significant differences were observed for all categories except topsoil removal, erosion features and non-soil ($P < 0.002$ for each). This aligns with the linear regression.

When all categories involving exposed soil except ruts (topsoil mixing, topsoil removed, subsoil mixing, erosion features) were combined, a statistically significant decline was observed ($P < 0.003$). However, ground cover, including both slash and vegetation, did not show a significant increase over time in the t-test. This is because as vegetation was increasing, slash was decreasing.

The combined results indicate an average 50% reduction in exposed soil over the three years following harvest (although, as noted above this effect was not statistically significant). Vegetation cover increased ninefold to an average of 65% ground coverage. Unconsolidated soils declined over time as regrowth gradually covered them, while consolidated soils with exposed subsoil proved most resistant to regrowth. Subsoil disturbance was more common than topsoil disturbance, likely due to the depth of grousers exceeding typical topsoil depth.

Undisturbed ground was recorded when the surface appeared unchanged from the original forest floor. However, this classification was rare, as most areas had been subjected to vehicle traffic,

erosion, slash deposition, or log dragging. In some forests with minimal topsoil, the "subsoil exposed" classification may have been recorded instead of undisturbed. Over time, undisturbed points declined the fastest of the exposed soil categories, likely because intact topsoil provided an optimal environment for weed establishment and growth (Figure 12).

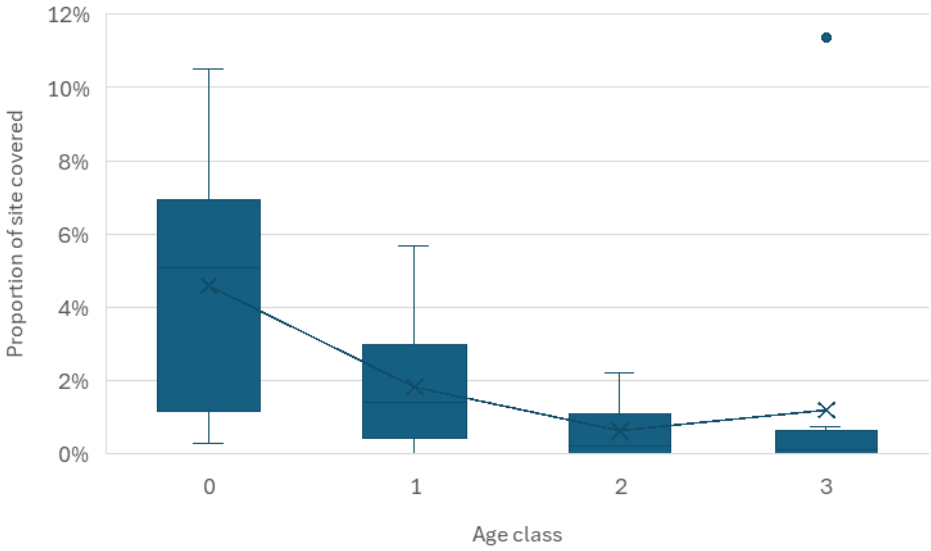


Figure 12: Undisturbed area across all sites over time.

Vegetation remained low during the first year after harvest, primarily due to the application of pre-plant desiccation spray. Although weed growth had occurred, it was effectively eliminated by the spraying process. Since data collection took place during the planting season, much of the first-year vegetation was already dead at the time of the survey. In the second year, vegetation growth increased rapidly (Figure 13).

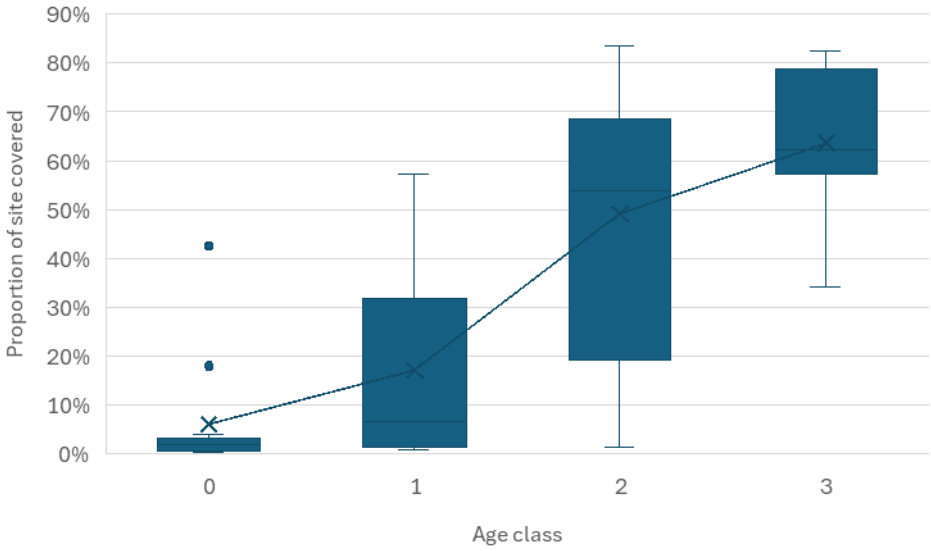


Figure 13: Vegetated area across all sites over time.

Slash cover steadily declined over time due to two primary factors: decomposition and vegetation growth. Immediately after harvest, slash was abundant, with needles still attached to branches, leaving little visible ground. By the end of the first year, all needles had fallen off. During the second year, branches up to 5 mm in diameter decomposed. During the third year, larger branches up to 3

cm broke down. By the end of the third year, anything under 10 cm in diameter could not support weight. This resulted in a decrease in the overall slash coverage (Figure 14). Additionally, vegetation growth increasingly obscured slash from view. In many cases, slash was still present underfoot but was not recorded because it was covered by thick vegetation, the vegetation being the primary ground cover. Consequently, the data indicate that slash cover was gradually replaced by vegetation over time.

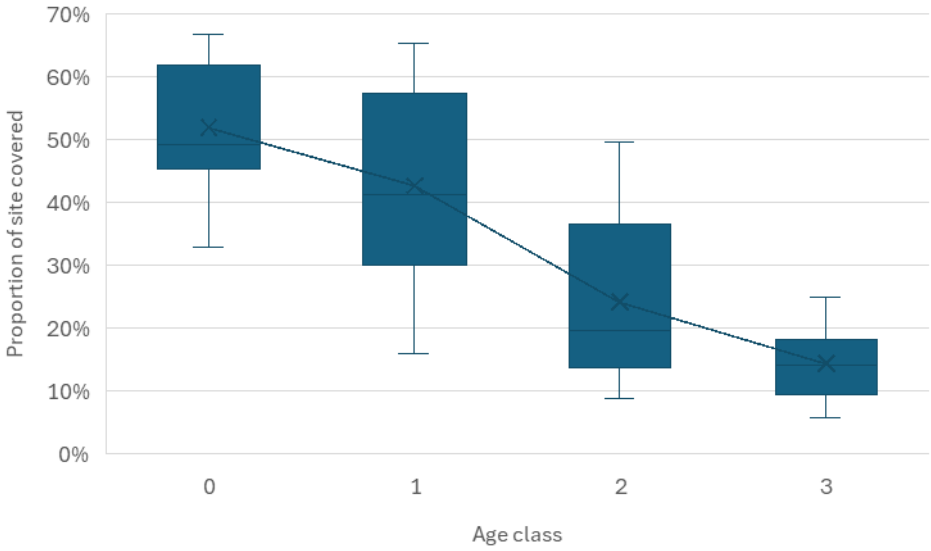


Figure 14: Area of slash across all sites over time.

Erosion features were the only disturbance class that did not show a clear trend over time (Figure 15). The occurrence of erosion was highly variable between forests and even among sites within the same forest. This variability was partly due to the number of slips encountered during surveys, as the recorded erosion features depended on their presence along transects. Also, the small proportion of erosion features meant that the numbers could be easily skewed.

In younger age classes, erosion features were predominantly rills and small slips, whereas older sites had more large slips. Soil type also influenced erosion patterns, with rills and small slips being more common in porous soils such as pumice, loam, and sand, while larger slips were more prevalent in silt and clay soils.

Erosion features were only recorded if they remained exposed and visibly active. Vegetated slips were not recorded, as the vegetation indicated stability. However, in some cases, erosion was occurring beneath surface vegetation, as observed in Whangamatā, where deep, sinkhole-like features persisted within the soil.

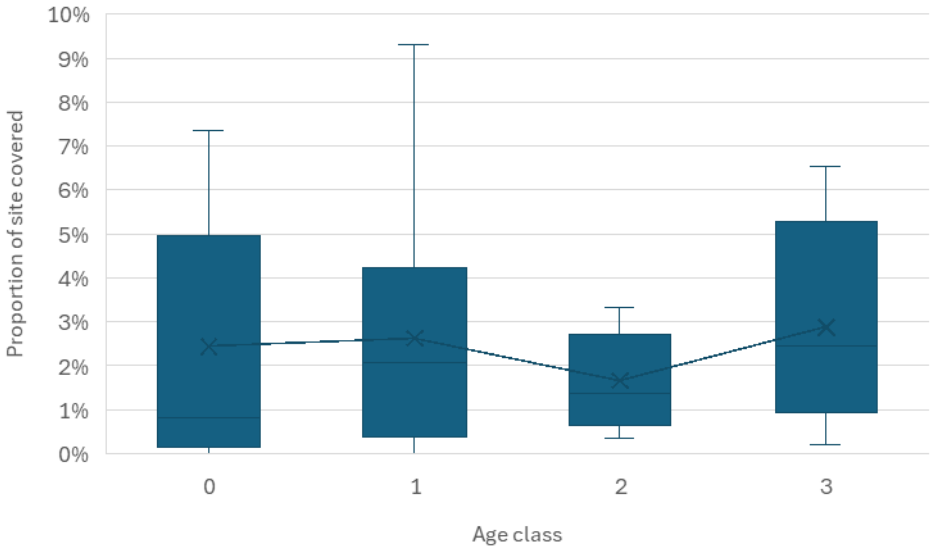


Figure 15: Area of erosion across all sites over time.

Most sites had similar amounts of non-soil, primarily due to the similar number of tree stumps across locations. The main outliers were rocky sites such as Wakefield and Maitai, where non-soil cover was higher. Most recorded non-soil points were tree stumps, which remained present throughout the three-year study period without much decomposition.

Rills were relatively high immediately after harvest, with the median number of rills remaining stable in the following year. However, the distribution became more spread, with more stable sites showing a reduction, while less stable sites—such as Hunterville, Mohaka, Ōpōtiki, Huntly, and Kawerau—increased. These sites generally had more granular soil, which may have contributed to this pattern.

The increase in rilling ceased by the second and third years (Figure 16), potentially due to the substantial increase in vegetation during this period.

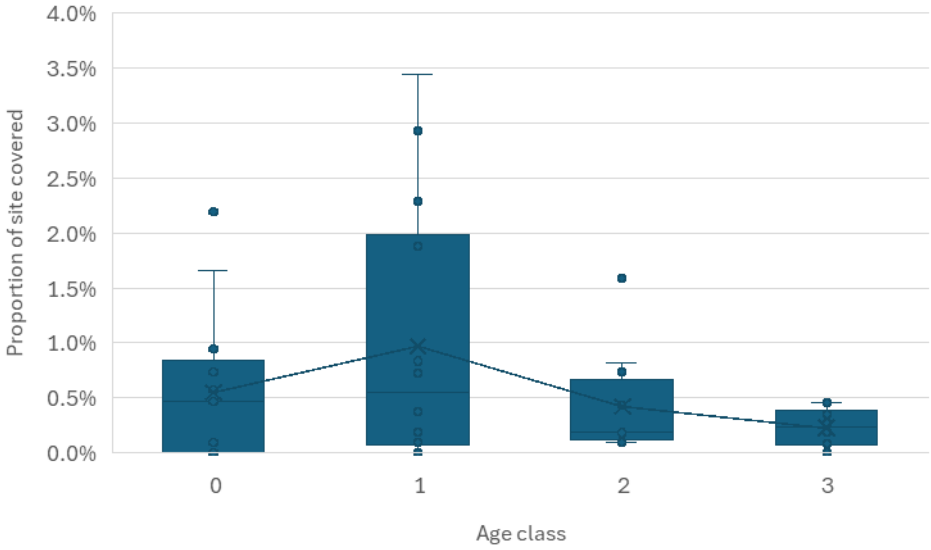


Figure 16: Rilling across all sites over time.

Slips, on the other hand, were highly variable and did not exhibit a consistent trend over time (Figure 17). According to field observations, slips developed independently of the erosion controls

implemented by harvesting crews. Their formation was more closely associated with factors such as soil type and weather events. In contrast, rills were predominantly found on unconsolidated ground, which was typically created by harvesting operations.

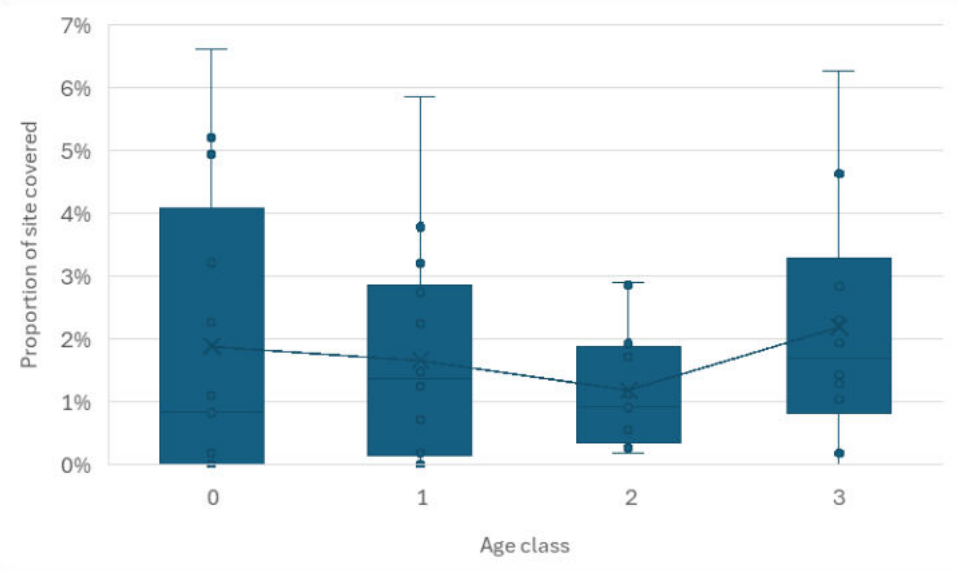


Figure 17: Slips across all sites over time.

Topsoil mixing, topsoil removed, subsoil mixing, and erosion features were combined to give Figure 18. The data indicate a general decline in exposed soil over time, though this trend was opposed by ongoing erosion and areas where topsoil had been removed. Despite the overall reduction, a considerable proportion of exposed soil remained on average. By the third year, most sites had thick vegetation cover that obscured the ground from a distance, though exposed soil was still visible when walking through the sites. The exceptions were areas lacking topsoil or with active erosion.

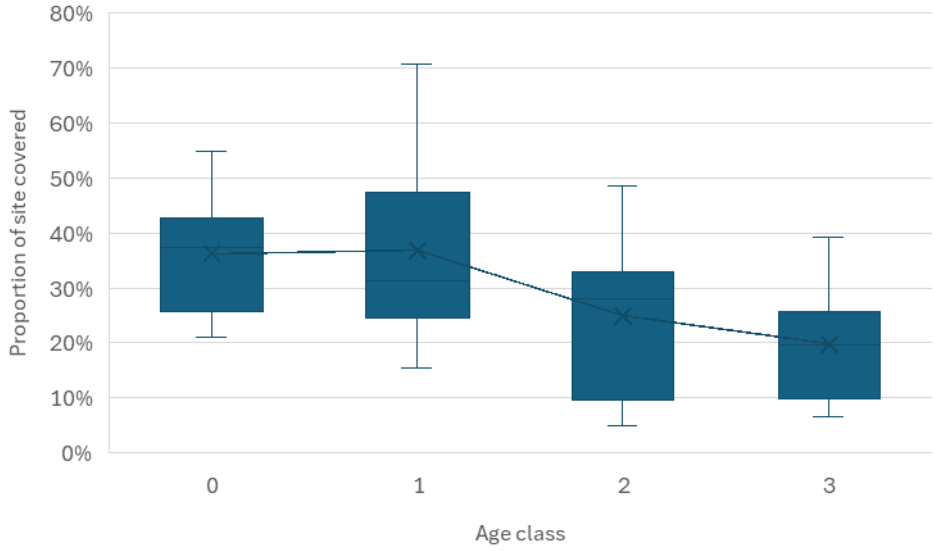


Figure 18: Area of exposed soil across all sites over time.

Shallow and deep ruts were combined to create Figure 19, which represents all ruts. Most of the observed decline in rutting was attributed to ruts being covered by vegetation. Some ruts may have transitioned into the erosion feature class, as it could be difficult to determine whether a rill originated from a rut. If the rill appeared to still be eroding, it was classified as an erosion feature, even if it began as a rut. Conversely, if a rut remained visible beneath the vegetation, it was still recorded as a rut. The reason for this is that if it was visible, it could still collect water and begin to erode.

Therefore, the decline in rutting suggests that ruts were either disappearing entirely or beginning to erode.

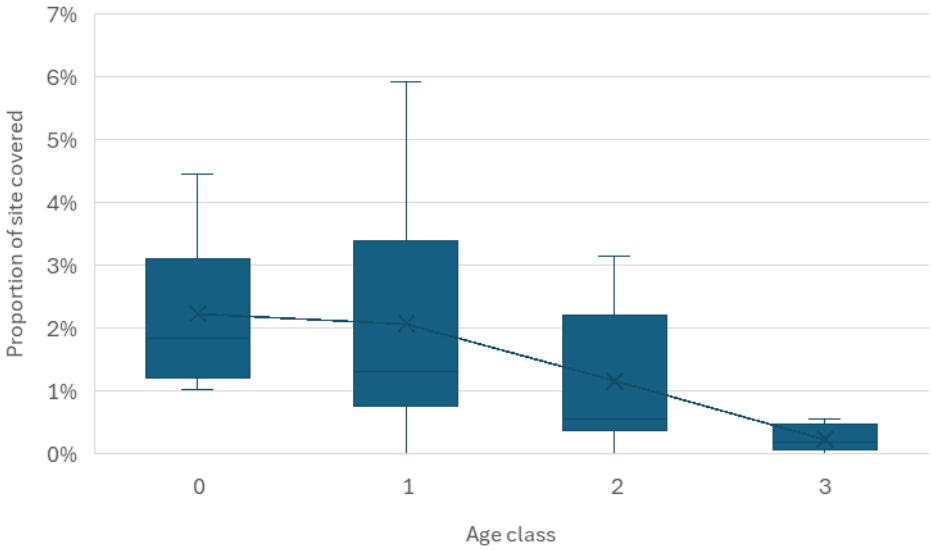


Figure 19: Area of ruts across all sites over time.

Different areas of the site predominantly displayed a single disturbance type. For instance, there could be a 100-metre section where 90% of the area was covered by slash, followed by a ridge where 60% of the area was exposed soil. This pattern is illustrated in Figure 20, where it is evident that disturbance codes occur in distinct blocks, with one disturbance type predominating in each area.

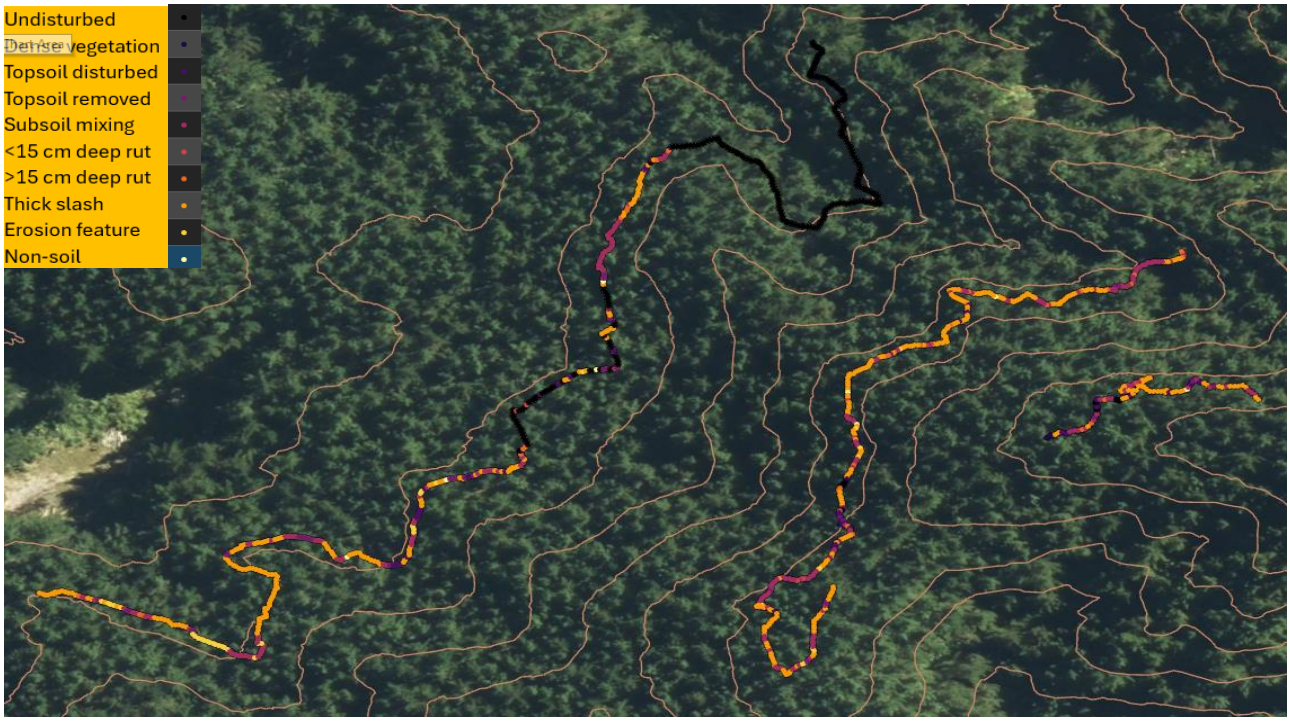


Figure 20: Example of distribution of disturbance across a site.

DISCUSSION

Recovery of sites over time

The results showed that all types of soil disturbance declined over time, except for erosion features, which remained constant. This is concerning, as erosion features are the primary pathways for sediment transport into waterways (Jones & Preston, 2012). The lack of a clear trend may be due to their localised nature and relatively low occurrence, where a single large slip can contribute significantly to the dataset. Therefore, a transect may have crossed a slip on one age class, but not another. Slips increased in number and size at certain sites. Erosion features are expected to stabilise as root interlock and canopy closure improve, likely a few years beyond this study's timeframe (Phillips et al., 2024). These larger soil features will still be visible into the future, though.

The lack of a statistically significant decline in areas categorised as "topsoil removed" could be attributed to compacted, exposed subsoil, which hinders seed establishment (Brown et al., 2017). However, given that this study did not survey the sites before harvest, there may not have been a significant increase in "topsoil removed" at harvest time. This would mean that recovery to baseline would not require a decline in this disturbance class. This is possible, especially at sites with very thin topsoil.

While rills declined over time, slips persisted, maintaining their proportional impact on site disturbance. This study could not determine the long-term stabilisation of slips. However, it is likely that slips will stabilise once vegetation regrowth improves soil cohesion, but this process extends beyond the three-year study period.

Differences between sites

Soil types across the study sites varied significantly, ranging from pumice sands (Napier, Rotorua) to clay (Northland), granite sands (Nelson), loams (Otago), and silts (Gisborne) (Manaaki Whenua - Landcare Research, 2019). Pumice and sandy soils were mostly stable, with almost no slips observed. However, rill formation was common, particularly in pumice-based sands. In contrast, other soil types experienced mid-slope slips, typically up to 10 metres in size, though some reached up to 50 metres. These larger slips were isolated events and generally did not intersect the transects, except for one instance in Raukūmara 3. Rill formation was present at all sites where soil was exposed or unconsolidated, except in Otago, where the combination of stable soils and low rainfall resulted in minimal surface erosion.

The terrain was consistently steep across all sites, except where otherwise noted, with gradients ranging from 50% to 110%. The tortuosity of the terrain varied significantly between forests and even within individual sites, with some areas exhibiting a much more gullied landscape. The average gradient within each forest remained similar due to consistent soil repose angles. Within each forest, slope length was generally uniform due to the similar size of hills. There were exceptions, namely Maitai, where the age class 0 stand had substantially smaller hills, and Waipaoa, where the terrain varied between sites. However, slope length varied considerably between locations, ranging from approximately 70 metres at Whangamatā to around 500 metres at Warrington.

Weather conditions within a forest should have been similar due to the close proximity of the sites. The greatest distances between sites within a forest were at Wakefield (7 km) and Whangamatā (12 km), though these were exceptions. Typically, sites were separated by a linear distance of less than 2 km. In many instances, one or more sites were directly adjacent to each other.

CONCLUSION

A study on harvest-related disturbance was conducted in 14 forests from Northland to South Otago, assessing sites immediately post-harvest and at 1, 2, and 3 years after harvesting. Surveys recorded soil disturbance or ground cover at one-metre intervals along transects. Surveys produced 2,100–4,400 geo-located observations per forest, totalling 52,541. Disturbance types included soil mixing, topsoil removal, rutting, and slash and vegetation cover. GIS mapping correlated this data with terrain features to analyse changes over time.

Age was the primary factor influencing site differences, with clear stabilisation trends over time. Slash cover declined, while weed cover increased, maintaining overall ground cover. Soil disturbance decreased as vegetation grew, and rills diminished. Slips remained variable, with larger ones appearing later. Steeper slopes increased soil disturbance and reduced slash and vegetation cover. Higher elevations had more disturbance and slash, likely due to proximity to landings, while lower elevations had more vegetation. Aspect influenced erosion, vegetation, and soil mixing. Slash and vegetation accumulated in gullies, whereas ruts, mixing, and scraping were more common on spurs. Steeper slopes saw more disturbance and less slash and vegetation.

This study improves understanding of soil disturbance and vegetation recovery after steep-slope harvesting, informing sustainable forest management, and provides a benchmark for future comparisons.

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APPENDICES

Appendix 1 – Understanding Local Relief Models (LRM)

LRMs are computational models used to enhance the visibility of small-scale elevation differences in terrain. They are calculated from high-resolution digital elevation models (DEMs) derived from LiDAR data. LRMs remove large-scale landscape forms, focusing on local, small-scale variations in elevation. This enables the direct measurement of relative elevations and volumes of small topographic features, making LRMs valuable for mapping of earthworks, roads, landings, quarries, and ruts. First, an accurate (e.g. LiDAR derived) DEM is produced. The DEM then is 'smoothed' using surrounding average gradients to remove small terrain features. The smoothed DEM is then subtracted from the original, leaving a DEM of only the small terrain features (Hesse, 2010).

Appendix 2 – Soil Characteristics of each site

Whangarei – No direct soil data available. The closest comparable data, from similar terrain, indicates deep, imperfectly drained clays, which aligns with the forest manager's comments and field observations.

Wellsford – No direct soil data available. The nearest comparable data describes deep clay with drainage varying from poor to well-drained. This aligns with field observations.

Huntly – Deep, moderately well-drained soils, consisting of silt over clay and clay.

Whangamatā – Well-drained loam near the coast, transitioning to deep, well-drained loam over sand closer to the mountains.

Kawerau – Deep, well-drained sand.

Ōpōtiki – No direct soil data available, but the nearest comparable data describes deep, well-drained sand. Soil conditions observed on-site were similar to Kawerau.

Raukūmara – No direct soil data available. The nearest comparable data indicates loams and loams over sands with variable drainage. The underlying geology includes crushed argillite and bentonitic mudstones (Hamilton, 1952).

Waipaoa – No direct soil data available, and the nearest comparable data is inconclusive (silts, sands, clays, and loams). Field observations suggest similarities to Raukūmara.

Mohaka – Shallow, moderately well-drained clay, and deep, well-drained sand.

Hunterville – No direct soil data available. The nearest comparable data indicates deep, well-drained sand. On site, this was shallow, with sedimentary rock directly underneath.

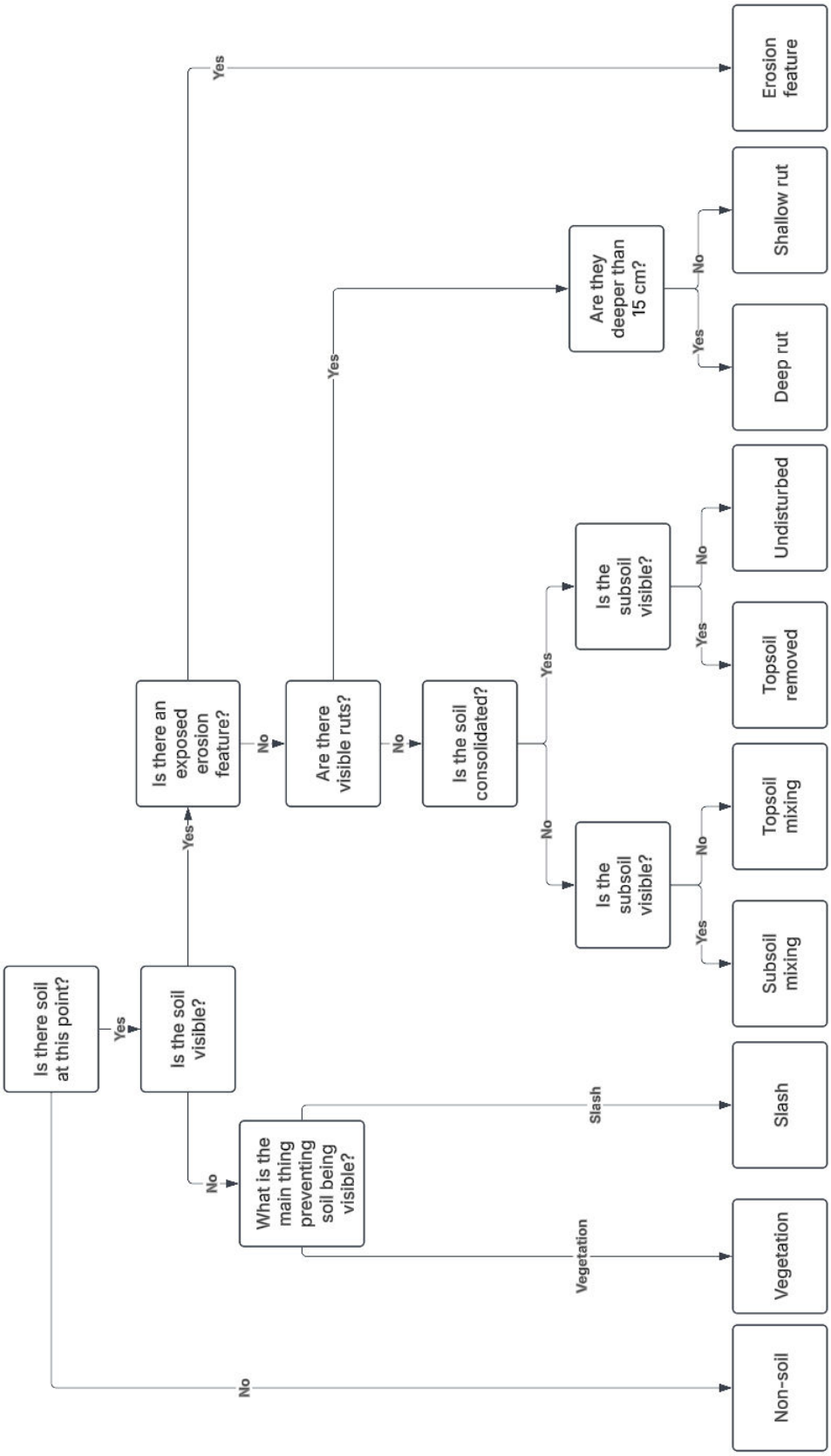
Wakefield – Shallow, moderately well-drained silts and loams.

Maitai – No direct or nearby soil data available. Field observations suggest similarity to Wakefield though rockier.

Warrington – Moderately deep, moderately well-drained silts and loams.

Lawrence – Moderately deep, imperfectly drained loams and silts.

Appendix 3 – Process for point classification



Appendix 4 – Results of Industry Surveys

Five harvesting contractors and eight harvest planners were surveyed. While some key factors for reducing site impact were widely recognised, most respondents provided at least one unique solution. The responses, along with the number of mentions, are listed below.

A. Harvest contractor survey

1. What do you do to minimise soil disturbance during harvesting operations?

Responses to this question varied widely. Many contractors emphasised water control on infrastructure as key to minimising impact. A major contrast was in disturbance management: some preferred spreading low-intensity disturbance across the site, while others concentrated it in specific areas, making it more severe but easier to rehabilitate while leaving other areas untouched.

- Spread disturbance out – Avoid repeated tracking of the same areas (3).
- Water controls on infrastructure (4).
- Increasing deflection (2).
- Remediate as you're going (2).
- Concentrate disturbance to tracks (2).
- Winch assist (3).
- Shovelling (1).
- Pulling away from rather than over waterways (1).
- Full suspension over waterways (1).
- Intermediate supports (1).
- Using tracks as few times as possible (1).
- Cutover has less impact than infrastructure (1).
- Stay out of high-risk areas (1).

2. How does the equipment you use reduce your impact on the site? Was this a consideration when buying it?

A common theme was that operating machinery on steep slopes increases disturbance. Contractors noted that these machines were introduced for safety, but at the cost of greater site impact. However, some equipment was recognised for its ability to reduce disturbance (see below).

- Winch assist reduces disturbance as compared to the same machine off-tether (4).
- Machinery increases disturbance in general – Purchased primarily for safety (3).
- Winch digger (2).
- Self-levelling machines – Weight is spread evenly across the track (1).
- Using a cable yarder reduces disturbance as opposed to ground-based extraction (1).
- Moving yarder closer to the edge of the landing– Increases deflection (1).
- Larger tower yarders increase deflection but require bigger landings, potentially causing more disturbance overall (1).
- Manual felling reduces rutting and soil tilling (1).
- Manual breaking out reduces slash left behind (1).
- Grousers reduce slippage (1).
- Winch enables more rehabilitation work (1).
- Slash grapples (1).

3. What do you do to prevent erosion on the cutover during and after harvesting activities?

Opinions on remediation varied. Some had felling machines repair their own tracks, while others used separate machines later. This choice depended on machine utilisation—if the felling machine had downtime, it handled remediation; otherwise, a specialised machine was more efficient.

- Excavators remediate tracks after harvesting (3).
- Felling machine remediates for itself (2).
- Limited erosion prevention on the cutover (2).
- Water controls – Primarily used on infrastructure rather than cutover (1).

4. How has the way you've managed the soil disturbance changed over time? What do you think you will have to change in the future?

All contractors agreed that environmental concerns are now a bigger priority. However, many were wary of regulations that overlook practical impacts. One contractor noted that stricter rutting rules would require full remediation of all tracks due to his machine's deep grousers. Others highlighted economic concerns, as fewer roads increase extraction distances and harvesting costs.

- Regulations have tightened a lot over time (5).
- Expected to continue tightening (4).
- Concern that restrictions may become excessive (2).
- Sediment ponds increasing in size (1).
- Increasingly avoiding streams altogether (1).
- More remediation of ruts (1).
- Changes in slash management rules – Uncertainty about impact during heavy rain events (1).
- Anecdotal reports of past processing and loading in riverbeds (1).

B. Harvest planner survey

Eight harvest planners were surveyed from five different companies. The answers they gave were extremely varied, reflecting the many ways that soil disturbance can be dealt with. All respondents placed a high importance on the environmental damage caused, but also the safety of the crews working on the hill, with many citing the difficulty of balancing these factors.

1. How do you assess soil and terrain characteristics before planning a harvest?

Companies and individual planners employed a variety of tools and methods to plan a harvest, with previous experience being the most commonly mentioned factor, cited by 75% of respondents. Many planners were working in second rotation forests, allowing them to leverage data from previous rotations, while others drew from experience with nearby sites.

Technology also played a significant role in the planning process. Companies utilized tools such as LiDAR, aerial and satellite imagery, soil maps, and erosion classifications. In one instance, a model was used that integrated all of these factors to aid in decision-making.

- Previous experience –From previous rotations or similar areas (6).
- Site walks – Conducted for new areas or all areas depending on the company (2).
- Company-made GIS tool – Predicts erosion risk based on slope, soil, ESC, harvest area, catchment area, weather, and downstream risk (2).
- LiDAR(2).
- S-Map – soil classifications (2).
- Drones imagery (2).
- ESC – Erosion Susceptibility Class (1).
- Stream levels – Monitored to assess risk (1).
- Aerial imagery (1).
- Earthflow maps – Used in Gisborne (1).

2. What techniques or equipment have you noticed reduce soil disturbance?

Machinery was frequently mentioned as a key factor in reducing soil disturbance, with the winch being highlighted as particularly effective in minimizing erosion. The cable yarder was also commonly referenced, with respondents noting various configurations that could reduce disturbance.

Operator performance was identified as a significant variable between sites. One manager emphasized that two otherwise identical sites could show vastly different levels of disturbance, depending solely on the operator. Effective techniques employed by skilled operators included laying slash in front of the machinery, creating their own cutouts in the tracks, and adhering to a straight-up-and-down travel pattern on slopes.

The planning phase was recognized as a crucial point for minimizing disturbance. Pre-planning activities, such as scheduling based on season and weather conditions, selecting track locations, and determining the appropriate harvest method, were noted as effective strategies for reducing both costs and environmental impact during the harvesting process.

- Winch – Helps reduce track/ wheel slip and therefore rutting (4).
- Cable yarder – reduces disturbance (as opposed to ground based) (3).
- Mechanisation – Generally increases soil disturbance (3).
- Drainage installed and maintained on infrastructure (2).
- Felling machine places its own corduroy – Reduces compaction and rutting (2).
- Changing harvest areas in different seasons (2).
- Forwarders with belts – Preferred over skidders (1).
- Maximising deflection (1).
- Intermediate spars – increases deflection and reduces high-leading (1).
- Manual falling (1).
- 2 staging in some scenarios (1).
- Tower yarders with skylines – Increases lift (1).
- Felling machine makes cutouts in its tracks as it goes (1).
- Concentrating soil disturbance in extraction corridors – Rehabilitating them afterward (1).
- Minimise felling machine turning on steep slopes (1).
- Machine operator care – Important in reducing disturbance (1).
- Different levels of rehabilitation – More required in sensitive areas (1).
- Limiting spraying in worst eroding areas – maintains vegetation cover, reducing erosion (1).

3. What details are provided to the contractor on allowable soil disturbance?

This factor varied significantly between companies. Some companies placed trust in the contractor's experience, while others provided detailed and specific guidelines for the contractor to follow. However, in general, it appeared that both parties worked closely together to determine the best solutions for minimising impact at each site.

- Contractors know acceptable damage- we don't provide that (2).
- Collaborative approach (2).
- Rules of thumb – e.g. rut depth (30 cm in one example, 50 cm in another) (2).
- Avoiding creeks (2).
- Rehabilitation requirements outlined for contractors (2).
- Varies by site – Particularly hard or wet conditions may have more lenience (1).
- Track locations provided to contractor (1).
- Any earthworks required consultation (1).

4. Does your company monitor the amount of disturbance after harvest?

- Formal post-harvest surveys – Mentioned by two companies, one company had sites nationwide so had four interviews.
- Formal survey –Photos and questions (2) including

- Slash location (1).
- Visible erosion (1).
- Track remediation (1).
- Drains and culverts installation (2).
- Removal of machine parts (1).
- Gouging and rutting (1).
- Water monitoring – Including sediment levels and clarity (1).
- Infrastructure checks – Focus on infrastructure rather than cutover areas (3).
- Post-harvest ripping – Used to remove compaction (1).
- Soil covering – Applied post-harvest (1).
- Mitigation of problems – Addressed when problems arise, rather than universally applied (1).
- Flagging areas for remediation (1).

Appendix 5 – Measuring soil disturbance with remote sensing techniques

Several papers have looked at measuring soil disturbance (in particular rutting) using remote sensing. Mohieddinne et al. (2023) conducted a study on rutting in managed forests using aerial LiDAR in Northern France. They compared a remotely derived rutting metric to the recovery of in-situ parameters including vegetation, soil texture and pH. They found that their index was useful to remotely assess soil recovery.

Rutting detection was achieved through a local relief model (LRM) (refer to Appendix 1) applied to the DTM, allowing visualisation of small-scale topographic variations and highlighting logging path ruts. Skid trails were manually digitised from the LRM images using a geographical information system (GIS). The cumulative length of ruts (CLR) within 400 m² plots was computed based on these digitised skid trails, providing a quantitative measure of soil rutting (Mohieddinne et al., 2023).

Advantages of LiDAR

- Accurate ground mapping.
- Terrain visible through canopy.
- Time efficient data collection.

Challenges of LiDAR

- Post processing of data (e.g. LRM).
- Cost.
- Complexity of flight planning.
- Unreliability due to weather.
- Unable to provide detailed disturbance information.

Other research proposes the use of photogrammetry from a handheld camera to accurately map small areas of ruts (Haas et al., 2016). The captured stereo photographs were processed into high-resolution 3D point clouds. Digital elevation models (DEMs) were created of the skid trail surfaces, providing information on rut depth, material displacement, and erosion-relevant parameters. Using map algebra techniques, assessment of rut depth, material mobilisation, and water retention characteristics across different tire configurations was possible (Haas et al., 2016).

Advantages of photogrammetry:

- Accurate 3D data for precise measurements.
- Time-efficient compared to traditional methods.
- Cost-effective compared to LiDAR.
- Comprehensive coverage for detailed analysis.

Challenges with photogrammetry:

- Need for accurate perpendicular measurements during setup.
- Post-processing complexity and software expertise required.
- Environmental factors like lighting affecting data quality.
- Manual allocation of spatial reference points during processing.
- Unable to provide detailed disturbance information.

Koren et al. (2015) focused on utilising terrestrial laser scanning (TLS) to analyse the spatial distribution of soil disturbance from skidding operations. The TLS data collection involved scanning the study site three times: before logging, after skidding, and after post-harvesting reinstatement.

The final DEM was useful for mapping terrain changes, specifically ruts and mounds caused by forestry activities, with a focus on skid trails.

Advantages of using TLS mentioned in the paper included:

- High sampling density providing detailed terrain imaging.
- Quick and flexible measurements over large areas.
- Accurate capture of geometric shapes and terrain changes.
- Detailed mapping of terrain alterations, especially in irregular spatial distributions.

Disadvantages discussed included challenges in:

- Separating points reflected by the terrain from other objects in point clouds.
- Identifying branches, harvesting residues, and complex objects in the forest.
- Correctly modelling stumps and other objects near skid trails, which can affect accuracy.
- Unable to provide detailed disturbance information.

Remote sensing methods all have the disadvantage of not providing detailed information on what is covering the ground or how much disturbance there is. This makes them challenging to deploy effectively for this research.