Precision Silviculture Programme

FOREST GROWERS RESEARCH

# PlantMax Mechanical Planter: First year assessment of planting stock performance

**John Henry, Carol Rolando, Christine Todoroki**


**Date:** 22 May 2024

**Report No:** PSP-T029

FOREST GROWERS RESEARCH

# TABLE OF CONTENTS

**Disclaimer**

This report has been prepared by Scion for Forest Growers Research Ltd (FGR) subject to the terms and conditions of a research fund agreement dated 1 April 2014.

The opinions and information provided in this report have been provided in good faith and on the basis that every endeavour has been made to be accurate and not misleading and to exercise reasonable care, skill and judgement in providing such opinions and information.

Under the terms of the Services Agreement, Scion's liability to FGR in relation to the services provided to produce this report is limited to the value of those services. Neither Scion nor any of its employees, contractors, agents or other persons acting on its behalf or under its control accept any responsibility to any person or organisation in respect of any information or opinion provided in this report in excess of that amount.

supported by
forestgrowers
commodity levy

# EXECUTIVE SUMMARY

## Problem

Manual planting operations within New Zealand (NZ) forestry are facing challenges with potential labour shortages making it difficult for companies to establish new forests and to replant after harvesting. Where sufficient labour is available, wage growth is contributing to rising establishment costs.

Forest managers are increasingly looking to leverage technologies that augment efficient practices. Where accurate geospatial data are available, opportunities that allow for high-resolution stand management and emergent automation are also beginning to develop.

New mechanical planting platforms are becoming more commonplace overseas but challenges inherent in NZ forestry mean these types of machines have not yet been widely adopted. New Zealand typically differs in planting stock, establishment methodologies, and topography compared to the European forest environments where several high-tech planting platforms are being developed.

Unsurprisingly, the cost of adopting new technologies is problematic for forest owners and managers. With indicative costs of mechanical planting systems possibly exceeding $1 million, potential buyers need certainty that as-yet untested systems will perform under NZ conditions.

## This project

In collaboration with Scion, the Forest Growers Research Precision Silviculture Programme undertook to support Pan Pac Forest Products' testing of the PlantMax mechanical planter in NZ forestry.

Planting and trial setup were carried out in areas with contrasting site histories. On a grassed, ex-pasture stand, a trial was developed to test the impact of different seedling stock and planting variables on seedling success. Within previously harvested cut-over stands, a comparison between mechanically planted and manually planted seedlings was undertaken.

## Objectives

This project aims to assess the performance of the PlantMax on typical NZ forestry terrain while planting available seedling stock at densities commonly expected during forest establishment. Data gathered on seedling establishment will be used to inform future use of the PlantMax in NZ.

## Key Results

- The PlantMax performed well in the locations where it was assessed, but adjustments to the machine, to the seedling stocks, and to workflow planning will increase planting efficiency and success.
- When utilising the same stock, mechanically planted seedlings were as successful as manually planted seedlings.
- Experienced machine operators were necessary for precise and efficient planting.
- Seedlings planted into scarified areas outperformed seedlings planted into unscarified soil.
- Quality seedlings were critical to successful planting regardless of planting method.

# INTRODUCTION

## Background

The Planting and Establishment Workstream of the Precision Silviculture Programme (PSP) aims to increase forest value through reducing establishment costs and optimising forest establishment practices. Technology which facilitates mechanisation and leverages geospatial data is key to advancing these goals.

New Zealand forestry has a shortage of labour, and it's been recognised that finding the staff necessary to perform the physical work of planting is becoming problematic (Baker, 2018; NZIER, 2021). The scale of the issue for production forestry becomes clear from New Zealand Ministry for Primary Industries (MPI) figures which report that more than 91 million *Pinus radiata* seedlings were sold in 2021 (Martin, 2022).

Notwithstanding potential labour shortages, planting represents a significant investment for the NZ forestry industry. In 2019, labour costs in excess of $38 per hour contributed to total establishment costs sometimes exceeding $1,700/ha (Te Uru Rākau, 2022). A significant spend when applied across the ~90,000 ha of yearly radiata pine planting (Te Uru Rākau, 2022).

Using mechanised planting systems has the potential to mitigate labour shortages. While there are several mechanised planting systems now being used worldwide, all of these have been developed by international companies. Quantifying the performance of internationally developed mechanised tree planting systems in the NZ environment and finding solutions to optimise their performance for New Zealand forestry is a crucial element of the Planting Workstream. There are currently two platforms being tested in New Zealand: the M-Planter (M-Planter Oy, Paltamo, Finland) and the PlantMax (Plantma Forestry, Grangärde, Sweden), both developed in Scandinavia.

Pan Pac Forest Products (Pan Pac) imported the PlantMax mechanical planting machine to trial in their forest estate in winter 2023. The PlantMax, developed by Swedish company Plantma Forestry, is currently being utilised in Europe, Canada, and South America but the machine's operation during this trial series represents its first use in NZ.

This project, a partnership between Pan Pac, Forest Growers Research PSP Programme, and Scion was designed to support Pan Pac in their evaluation of the PlantMax to provide insights into the suitability of the PlantMax for NZ forestry. Through evaluations made during large-scale operational trials, assessments of PlantMax performance, and the performance of seedling stock planted with the PlantMax were undertaken.

## The PlantMax

The PlantMax (Figure 1A), a planting system consisting of an Eco Log 574E forwarder (Eco Log Sweden AB, Söderhamn, Sweden) (Figure 1B) and the Plantma planting module (Figure 1C), represents a state-of-the-art advancement in production planting. Requiring only two people on board, and with an ability to collect and store important planting data, the PlantMax could help overcome some of the planting challenges facing NZ forestry.

The PlantMax is a high throughput planting platform. With two planting arms, each capable of making a planting attempt every three seconds, the PlantMax has, under ideal conditions, demonstrated a planting rate of 2,800 seedlings per hour (Plantma Forestry, 2024d). The planting unit can store up to 20,000 seedlings (dependent on seedling sizes and packing methods) (Plantma Forestry, 2024a) which allows for extended planting periods without the need to stop and restock. Furthermore, extensive lighting provides the ability for the PlantMax to be operated at night (Plantma Forestry, 2024c), increasing the potential to optimise machine utilisation over the planting season.

The PlantMax requires two operators who divide tasks required to carry out planting (Plantma Forestry, 2022). The forwarder driver controls the machine's direction and speed. Additionally, the driver controls the Midiflex scarifiers (MidiFlex AB, Alfta, Sweden) (Figure 1D). Inside the planting unit, the second operator manually loads containerised seedlings into carousels (Figure 1E) which then release the seedlings into the planting arms (Figure 1C&F). This operator also has control of the planting arm variables.

**Figure 1. The Plantma Forestry PlantMax. A,** an overview of the PlantMax. **B,** the Eco Log 574E forwarder. **C,** the planting module. **D,** one of two Midiflex scarifiers. **E,** seedlings loaded in a carousel prior to being released into the planting arm. **F,** a planting arm head with mounted spray nozzles.

With a preset distance between seedlings (within rows) programmed, and the planting arms properly spaced (max distance 3.0 m), the machine is driven forward while the planting arms plant at a rate calculated to maintain a particular planting density. Scarification can be carried out intermittently or continuously, and depth of the scarification can be controlled. As the PlantMax moves forward, it compresses the prepared ground, and the seedlings can be planted anywhere into the scarified/mounded zone. Sensors in the planting tips evaluate the ground conditions and if assessed as too firm (e.g. rock/stump) or too soft (e.g. swamp) the planting is abandoned and the distances between remaining planting points are recalculated to maintain the required planting density (Plantma Forestry, 2024b). During planting, the planting tips force a pit in the ground then open to allow seedlings to fall into the prepared pit. The compactors then activate and compact the soil around the root system (Plantma Forestry, 2022). It falls to the planting operator to monitor the planting and adjust as necessary. An important component of this is selecting the correct planting (tip) pressure. In harder ground (ground hardness 1–8 where 1 is softest and 8 is hardest) higher pressures need to be selected to get the correct pit depth (Plantma Forestry, 2022).

## The PlantMax in NZ

The challenges posed by adapting the PlantMax to current NZ planting practices and the NZ forestry environment are not trivial. However, the PlantMax is capable of climbing and descending slopes of up to 20 degrees (37%) (Plantma Forestry, 2024c); operating limits that aren't inconsistent with reported figures for machine harvesting equipment in NZ forestry (Visser & Berkett, 2012). Of course, it must be recognised that a significant proportion of NZ forestry activities are carried out on land with slope exceeding 20 degrees (Raymond, 2010).

Increasing the functionality of the PlantMax in NZ could enhance efficiencies in early forest establishment. Prototypes have been fitted with spray equipment that provide capacity to apply fertiliser or herbicide simultaneously with planting (Plantma Forestry, 2024d). For example, release spraying ability would eliminate an immediate need for workers to carry out this function post-planting thereby reducing post-planting operations and increasing the economic performance of the PlantMax, by removing an additional manual operation.

A major benefit of the PlantMax is its ability to collect data. For each seedling planted, the PlantMax can record seedling position, planting pressure, and time of day. Geospatial data is particularly important for equipping managers with tools that enhance stand management (Keefe et al., 2022) and to leverage automation that could provide additional benefit over the whole silvicultural value chain.

## Objectives

The purpose of this project was to assess the performance of the PlantMax in two different NZ forestry conditions – an ex-pasture site of flat to rolling terrain and then a recently logged site that encompassed flat to steeper terrain. The primary objectives were to:

1. Evaluate the performance of the PlantMax on NZ terrain;
2. Compare performance of stock planted with the PlantMax with that planted manually; and,
3. Evaluate the effect of different machine settings on planting stock performance.

This report details the methodologies used to evaluate performance of the PlantMax, and to provide early results on seedling health and survival.

# METHODS

## Description of sites

Two contrasting sites (Figure 2) were selected by Pan Pac on which to test the PlantMax. Planting was carried out at the Roundhill Block of Mohaka Forest (Roundhill), and the machine was then transported to Gwavas Forest to continue operations. Roundhill—a newly purchased property located on Flat Hill Road, Putorino, Hawke's Bay—is former pastoral farmland being converted to production forestry. The land is typically flat to rolling grassland which still showed, at the time of planting, evidence of grazing. Gwavas Forest, located near Tikokino in Central Hawke's Bay, is an ex-State Forest with an extensive history of production forestry.

In July 2023, Scion and Pan Pac staff were on site to direct a planting trial at Roundhill, and therefore test different aspects and capabilities of the PlantMax within a defined area. However, at Gwavas Forest, the PlantMax was operated as would be typical in production setting. There was little opportunity for researchers to observe and direct the PlantMax at Gwavas Forest, so this meant that evaluation plots were instead installed once planting operations had ceased. Importantly, a technical expert from Plantma Forestry was on hand during the planting at Roundhill and during the early planting at Gwavas Forest.

At both sites, an attempt was made to compare the PlantMax planting quality with planting quality typically expected from manual planting. At Roundhill, space within the trial area was left unplanted by the PlantMax which was subsequently infilled with manual planting. At Gwavas Forest, areas within the forest stands that the PlantMax couldn't access were later completed through manual planting.

**Roundhill**

Within Roundhill, a terrace area, situated above a small stream (within Stand 1002.02) was used to set up the planting trial. With minimal slope and relatively uniform grass cover (Figure 3A), the site is designated as Land Use Capability (LUC) Class 4 (Manaaki Whenua - Landcare Research, 2020) with Podzolic Orthic Pumice Soils (Manaaki Whenua - Landcare Research, 2024). No site preparation was carried out prior to planting, but it should be noted that chemical releasing, using AGPRO Valzine Broadcast Granules (AGPRO NZ, Auckland, NZ), of seedlings was attempted approximately one month after planting through the application of granular herbicide.

**Gwavas Forest**

Evaluation plots were installed in two forest stands, exhibiting differences in topography, within Gwavas Forest. The PlantMax carried out planting in four Gwavas Forest stands (210.05, 217.06, 220.02, and 56.09). Early inspection of the stands indicated few observable differences except slope. Contrasting sites—Stand 210.05 (flat terrain; LUC Class 6; Typic Rocky Recent Soils) and Stand 56.09 (steep terrain; LUC Classes 3&4; Typic Orthic Recent Soils & Typic Orthic Allophanic Soils)—were initially selected for study. However, the topography of Stand 210.05 proved particularly conducive to the operation of the PlantMax and few areas remained requiring manual planting. Therefore, evaluation plots were instead installed within the secondary option of Stand 217.06 (LUC Class 6; Typic Rocky Recent Soils) replacing Stand 210.05.

All planting within Gwavas Forest took place in stands previously harvested (Figure 3B). Each stand had been aerially desiccated in early April 2023 using a herbicide mix of glyphosate (7 L/ha), metsulfuron-methyl (170 g/ha), and organosilicone penetrant (800 mL/ha). Logging debris was evident on each site, and some slash raking/windrowing had been performed in Stand 217.06 (R. Airey, personal communication, April 10, 2024).

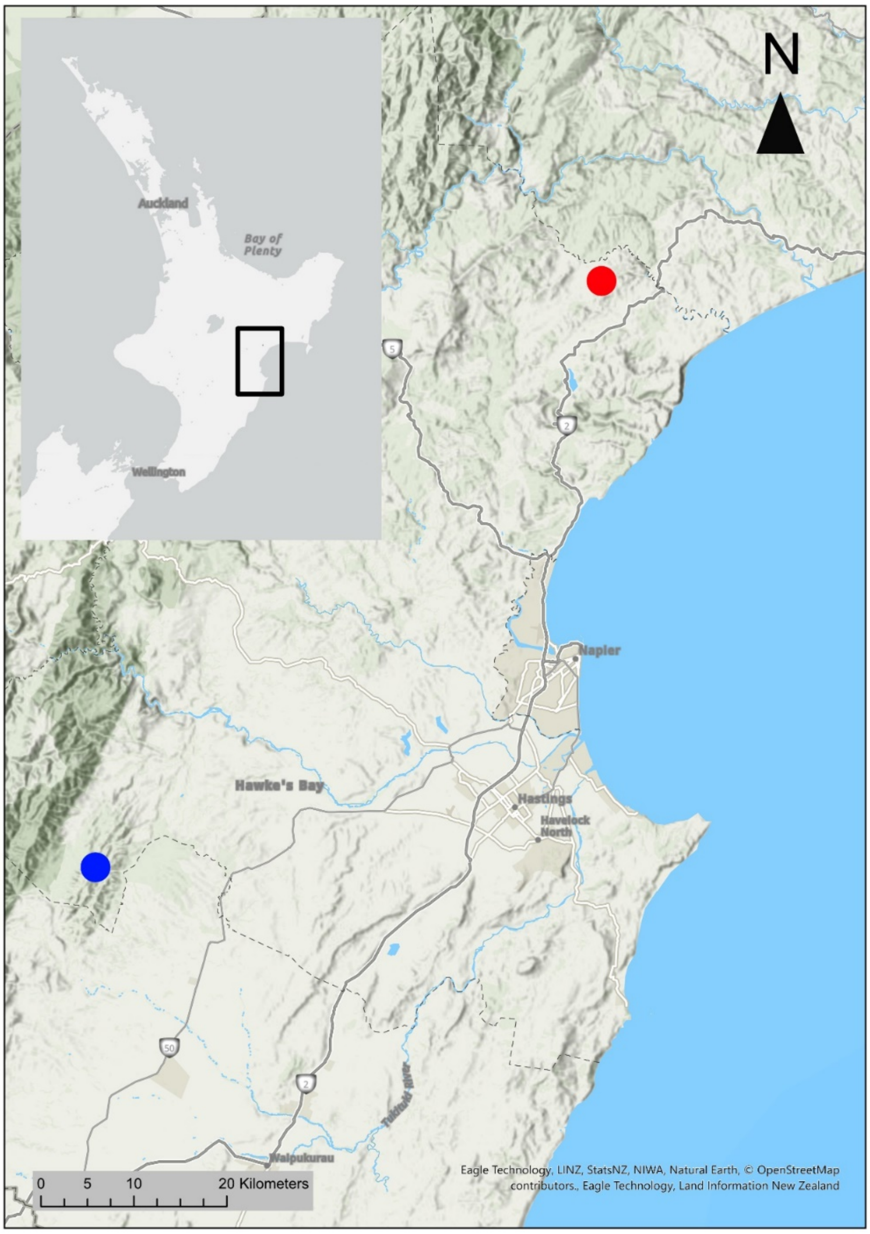


**Figure 2. PlantMax testing sites.** Roundhill (depicted with a red dot) is located in northern Hawke's Bay. Gwavas Forest (blue dot) is located in central Hawke's Bay close to the Ruahine Range.

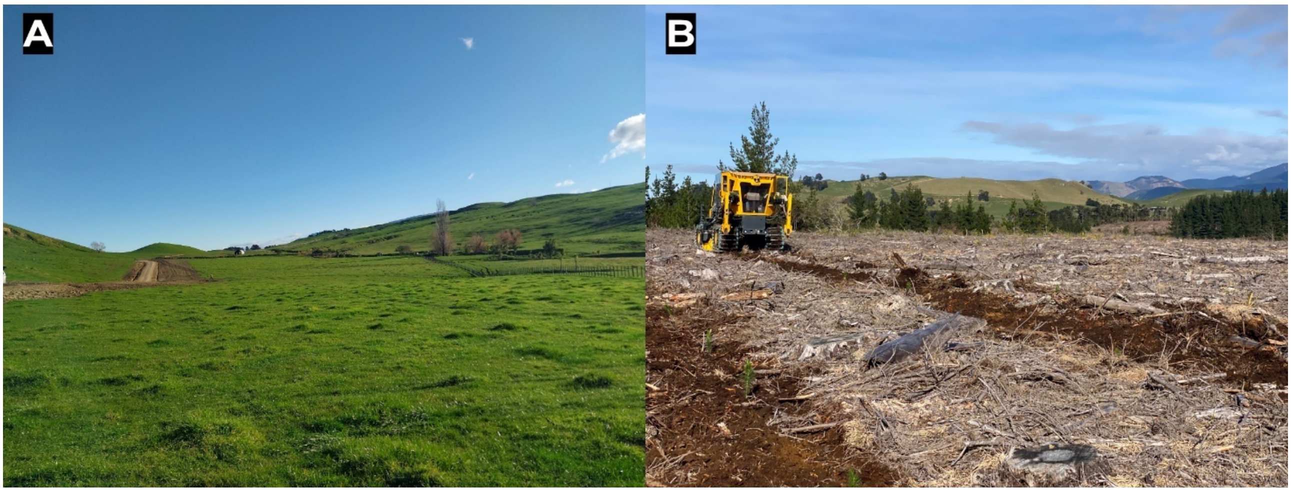


**Figure 3. Trial site conditions. A,** the recently grazed pasture that comprised the Roundhill trial area. **B,** previously logged land at Gwavas Forest on which the PlantMax operated.

## Trial implementation

With trial implementation being of secondary importance to Pan Pac's production considerations, the trial design was formulated to have minimal impact on planting efficiency. This meant that different plot designs were used at the different sites: ex-pasture and cutover.

### Roundhill

Trial planting was carried out during the morning of 19 July 2023. Two types of containerised seedings—Ellepot (paper pot) and plastic containerised (PC), sourced from the Te Teko nursery of ArborGen Australasia—were available at Roundhill during planting. These seedlings were planted at a spacing of 3.3 m within rows and 3.0 m between the planting arms, with approximately 3.0 m between machine runs, giving a planting density of ~1010 stems/ha. It is important to note that the high-accuracy GPS function available to the PlantMax was not operational during these trial series. Therefore, the forwarder driver had to estimate distances between machine runs and precise distances between runs may not have been achieved.

The trial layout was finalised after observing the PlantMax in operation and measuring the available planting area designated for the trial. Variables deemed important for assessment were determined on site through discussion between Pan Pac, Scion, and the Plantma Forestry technician. From these discussions, it was decided to test three variables:

1. Seedling container type (plastic; paper)
2. Planting pressure (high (8); medium (5))
3. Scarification (deep; none)

Using the above variables as a guide, a total of 16 strip plots were set up at Roundhill, resulting in a split-strip block design that encompassed scarification applied at the whole-plot level, planting pressure at the sub-plot level, and seedling container type at the sub-sub-plot level (Figure 4). Space within the trial area was sufficient for four replicates of each treatment. Each single-row plot was approximately 54 trees long. During planting, Ellepot seedlings were always planted using the left (looking forward) planting arm and PC seedlings were always planted using the right planting arm. Planting pressure (high = setting 8; medium = setting 5) was randomised across the site. However, because scarification involved significant alteration to site characteristics (Figure 5A), this was carried out in such a way as to minimise edge effects, as much as was possible within the constraints of the site.

A brief assessment of planting quality was carried out on the day of planting and two seedling assessments have been performed since planting. The first was carried out from 8–10 August 2023 and the second from 19–21 February 2024.

The plan was for PC seedlings to be manually planted in the space between the mechanically planted rows shortly after trial implementation (Figure 4). While the planting took place within the same week, unfortunately bare-root seedlings were manually planted. While not ideal for the trial, manual planting of bare-root seedlings is standard operational practice for Pan Pac forests and as such, still provided a valuable basis for comparison of performance with the mechanically planted seedlings.

### Gwavas Forest

Mechanical planting at Gwavas Forest commenced on 20 July 2023 and was completed on 28 August 2023. All planting (including manual planting) within the four forest stands which were mechanically planted was carried out using PC seedlings. Planting density of ~1075 stems/ha was targeted, with distance between the PlantMax planting arms of 3.0 m and seedling spacing within the rows of 3.1 m. All mechanical planting took place with the scarifiers in constant operation at maximum depth (Figure 5B), but planting pressures were altered as directed by the PlantMax technical advisor.

Manual planting was carried out to infill areas missed by the PlantMax from 14 August to 9 September 2023.

Optimal plot setup was not possible at Gwavas Forest. Initial planning was for a total of 16 rectangular (6 x 9 = 54 trees) evaluation plots to be installed. This number of plots would have allowed four replicates to capture data on the comparative performances of:

- PlantMax on flat cut-over terrain
- PlantMax on steep cut-over terrain
- Manual planting on flat cut-over terrain
- Manual planting on steep cut-over terrain

However, once mechanical planting operations had completed, there were not large areas remaining for manual planting. This resulted in only five plots set up to evaluate manual planting: three rectangular plots on steep terrain and two (>50 tree) strip plots on flat terrain. Where the rectangular plots were installed, plot sizes were measured so planting densities, stump densities, and debris loads could be estimated.

The initial site and seedling assessment took place during 19–21 September 2023. The follow-up assessment was conducted from 22–23 February 2024.

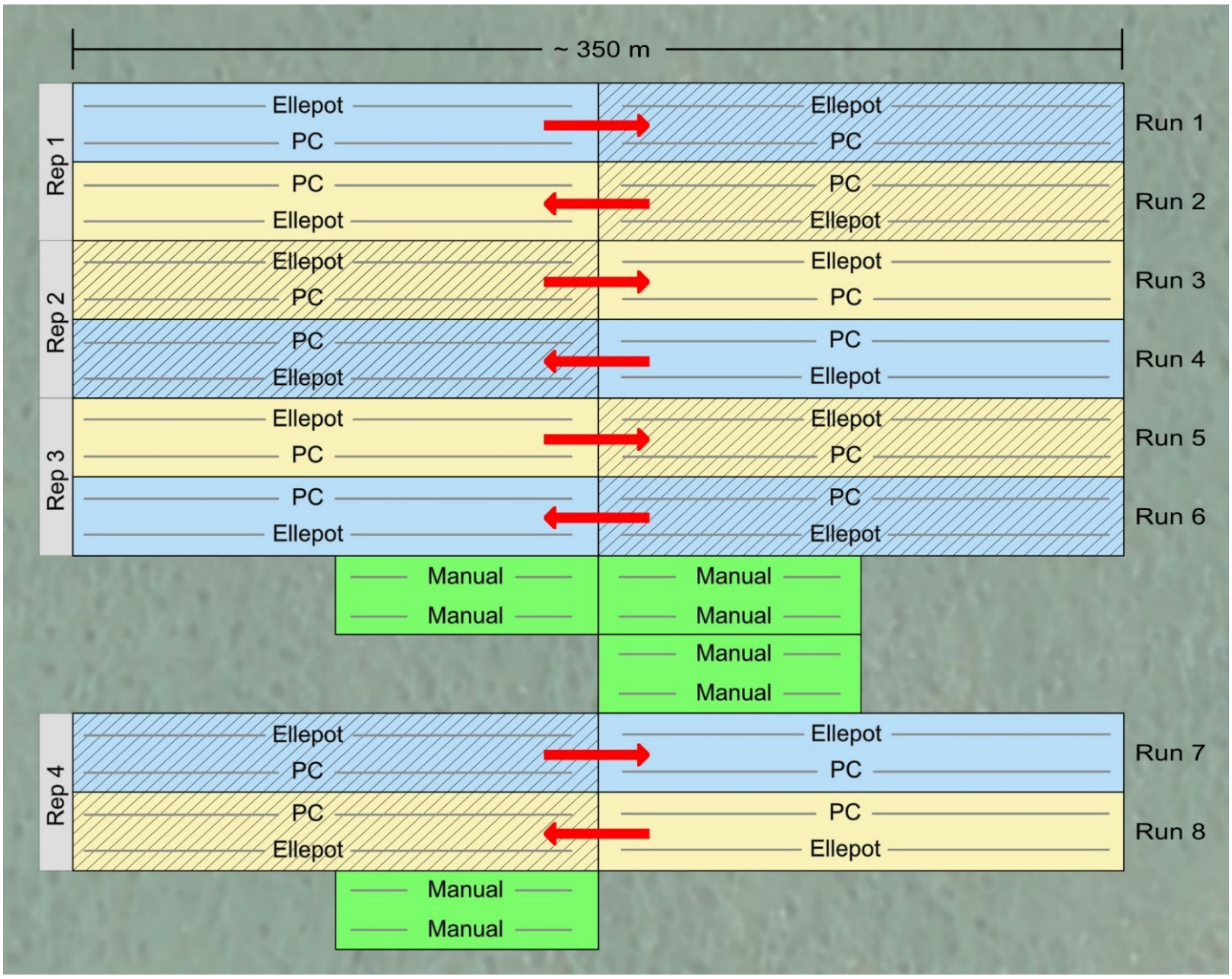

**Figure 4. Trial setup at Roundhill.** The PlantMax moved across the site arm (red arrows indicate direction of machine travel), planting Ellepot seedlings from the left planting arm and plastic containerised (PC) seedlings from the right planting arm. The machine would turn and plant in the reverse direction at the end of each run. Planting pressures (yellow = pressure 5, blue = pressure 8) were altered according to the randomisation protocol. Scarification (diagonal lines) was carried out in such a way as to minimise edge effects arising from only scarifying one planting run at a time. Manual planting took place later in areas that had been set aside between the machine rows, and four (~25 tree x two row) plots were set up in these areas.

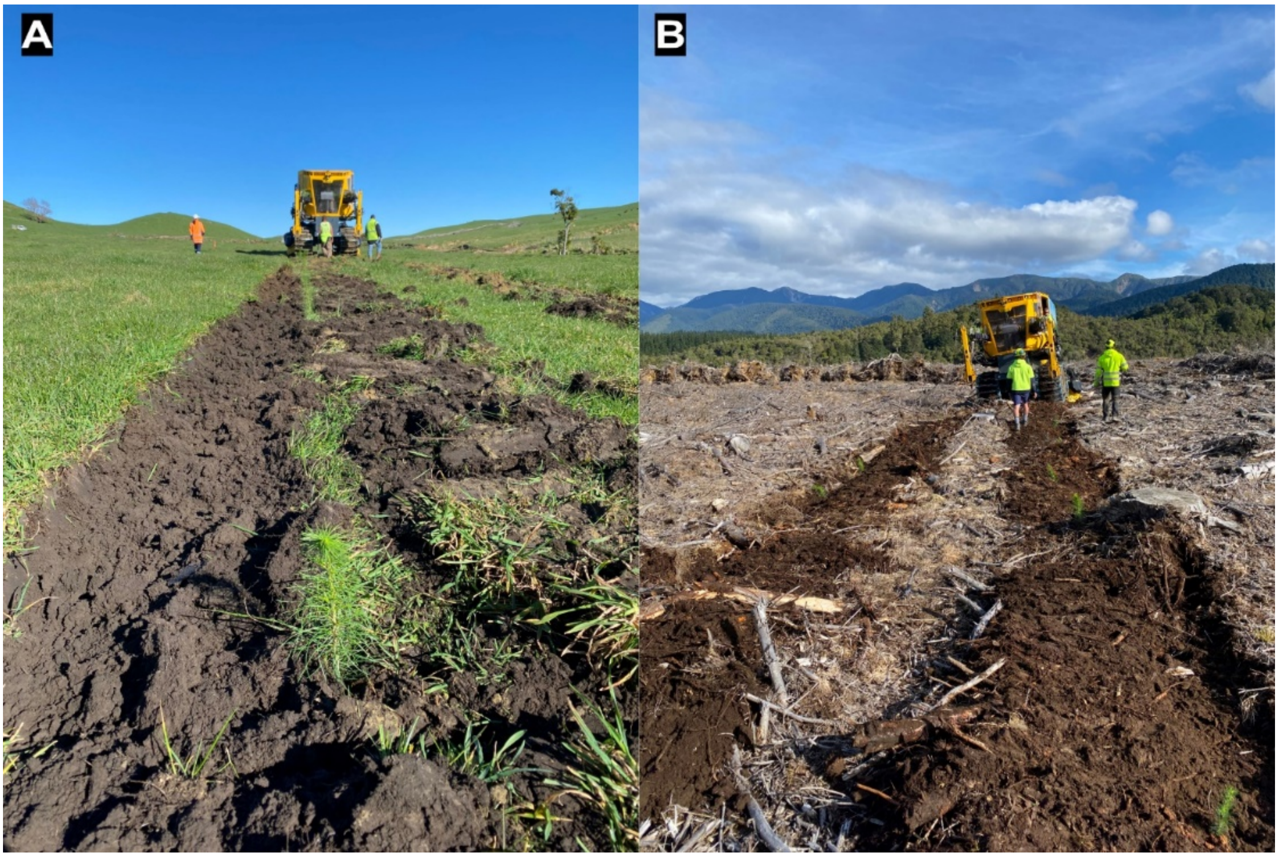

**Figure 5. Scarification during planting. A,** scarified line through grassed area at Roundhill. **B,** scarification through light debris at Gwavas Forest.

## Assessments

Observations and recordings were made during PlantMax operation through winter 2023 (July–September). Recordings of planting speeds were briefly carried out at both sites, and site characteristics such as slope, vegetation composition and slash levels were also noted. Physical seedling samples and soil samples were taken at Roundhill for measures of planting stock quality and soil moisture at the time of planting. Assessments of logging debris (slash) and stump densities were also made at Gwavas Forest. At both Roundhill and Gwavas Forest, approximately one month after planting, seedlings were measured and assessed for:

1. Health and survival (all trees in a plot)
2. Height (30 trees per plot)
3. Diameter at ground level (GLD) (30 trees per plot)
4. Straightness (vertical) of planting (30 trees per plot)
5. Planting quality (30 trees per plot)
6. Ground coverage of surrounding vegetation (15 trees per plot)

Seedling health was judged against a 1–4 scoring system:

1 = dead
2 = alive but unlikely to survive
3 = likely to survive but with some visible issues (such as needle browning)
4 = appears to be in perfect health

Seedling (vertical) straightness was judged against a 1–3 scoring system:

1 = tip is >10 cm off vertical
2 = tip is <10 cm off vertical but not completely straight
3 = tip appears vertical

Approximately six months after planting, a second extensive seedling assessment was undertaken at both sites.

## Statistical Analyses

Seedling plug integrity and planting failures were both compared using Fisher's Exact Test (Fisher, 1970). Differences in stump heights across slopes were tested using a Mann-Whitney U Test (Mann & Whitney, 1947). A chi-square test of independence (Pearson, 1900) was used to investigate differences between seedling vertical orientation at Roundhill.

Performance comparisons of PlantMax and manual plantings were evaluated using the non-parametric Kruskal-Wallis test (Kruskal & Wallis, 1952), with post-hoc analyses via Dunn's test (Dunn, 1964) for all pairwise comparisons, or Dunnett's test (Dunnett, 1955) for multiple comparisons with a control (e.g. Manual planting). Extended performance comparisons with additional variables such as seedling container type, planting pressure, scarification or slope, and comparisons of seedling mortality were evaluated using the same methods.

In addition, seedling mortality rates were modelled using beta regression analysis (Cribari-Neto & Zeileis, 2010). The full model comprised planting method, seedling type, planting pressure, and all two- and three-way interactions. To determine their importance (or lack of importance) in predicting seedling mortality, backwards stepwise regression (Garofalo & Garofalo, 2022) was invoked and the best reduced model derived.

All analyses were conducted using R Statistical Software (R Core Team, 2013) v4.2.2supplemented by packages 'tidyverse' (Wickham et al., 2019), 'janitor' (Firke, 2023), 'betareg' (Cribari-Neto & Zeileis, 2010) 'StepBeta' (Garofalo & Garofalo, 2022), 'DescTools' (Signorell), and 'FSA' (Ogle et al., 2023).

# RESULTS

## PlantMax operating observations

At Roundhill, the PlantMax was planting seedlings at approximately 1,800 trees per operation hour (based on nine 40-second observations). During four (20-second) observations made at Gwavas forest, on a flat cut-over area with low levels of slash, planting speed was calculated to be about 1,900 trees per operation hour. Anecdotally, it appeared machine performance improved as the operators gained familiarity with the system. Several seedlings, outside of the monitoring plots, were dug up and inspected. Although soil cultivation was more extensive for the manually planted seedlings, no damage or root orientation issues were observed for the mechanically planted seedlings.

Stocking density was only calculated at Gwavas Forest. However, from these data it appeared the mean seedling density was 963 stems/ha in the steep plots and 1052 stems/ha in the flat plots. Small sample sizes mean these data need to be treated with caution, but the mechanical planting appeared to be operating at close to the targeted 1075 stems/ha.

## Roundhill Trial

### Site conditions

As expected, the trial site at Roundhill was relatively flat with uniform grass cover. Five slope measurements made across the trial area ranged from 2.8 degrees to 5.6 degrees ($M$ = 4.4). Estimates of vegetation cover were made during planted seedling measurement but at the time of planting it was observed that pasture grasses covered nearly all the site (Figure 3A).

The soil was wet at the time of planting, yet soil moisture differed across the site. From the 10 points sampled, gravimetric soil moisture was found to be 25% in the drier areas and up to 51% in the wetter areas (Table 1). The soil moisture measurements demonstrate a heterogeneity of site conditions across a relatively small area and are therefore difficult to usefully interpret. However, soil data from the Hawke's Bay Regional Council weather station at Kotemaori (approximately 10 km away) show soil moisture on 19 July 2023 being 35%, very similar to the median soil moisture (33.7%) over the previous nine years (Hawke's Bay Regional Council, 2023). These data indicate that soil moisture conditions at the time of planting reflected those of a typical planting season.

### Seedling quality

Measurements taken of seedlings that were mechanically planted at Roundhill illustrated considerable differences between the Ellepot and PC seedlings (Figure 6A). While there was no significant difference ($p$ = .268) in RCD between seedling types, the Ellepot seedlings were significantly ($p$ < .001) taller ($M$ = 43.8 cm) than the PC seedlings ($M$ = 30.6 cm). This difference in heights was reflected in the masses of shoot material but the PC seedlings were found to have a greater root mass (Figure 6B; Table A1, Appendix). Of the other measurements taken, there was no significant differences in plug length ($p$ = .356), nor in plug width ($p$ = .146), but calculated stem volumes (where volume = $RCD^2$ x height) were unsurprisingly found to be significantly ($p$ = .003) larger for Ellepot seedlings (Table A1, Appendix).

| Table 1 Soil moisture at Roundhill during mechanical planting | | | |
|---|---|---|---|
| Sample | n | Mean | *SD* |
| 1 | 3 | 37.3 | 1.34 |
| 2 | 3 | 24.9 | 0.753 |
| 3 | 3 | 36.1 | 0.874 |
| 4 | 3 | 25.7 | 1.68 |
| 5 | 3 | 25.8 | 0.359 |
| 6 | 3 | 51.2 | 1.43 |
| 7 | 3 | 42.5 | 0.731 |
| 8 | 3 | 32.4 | 2.23 |
| 9 | 3 | 38.0 | 0.68 |
| 10 | 3 | 27.2 | 0.852 |

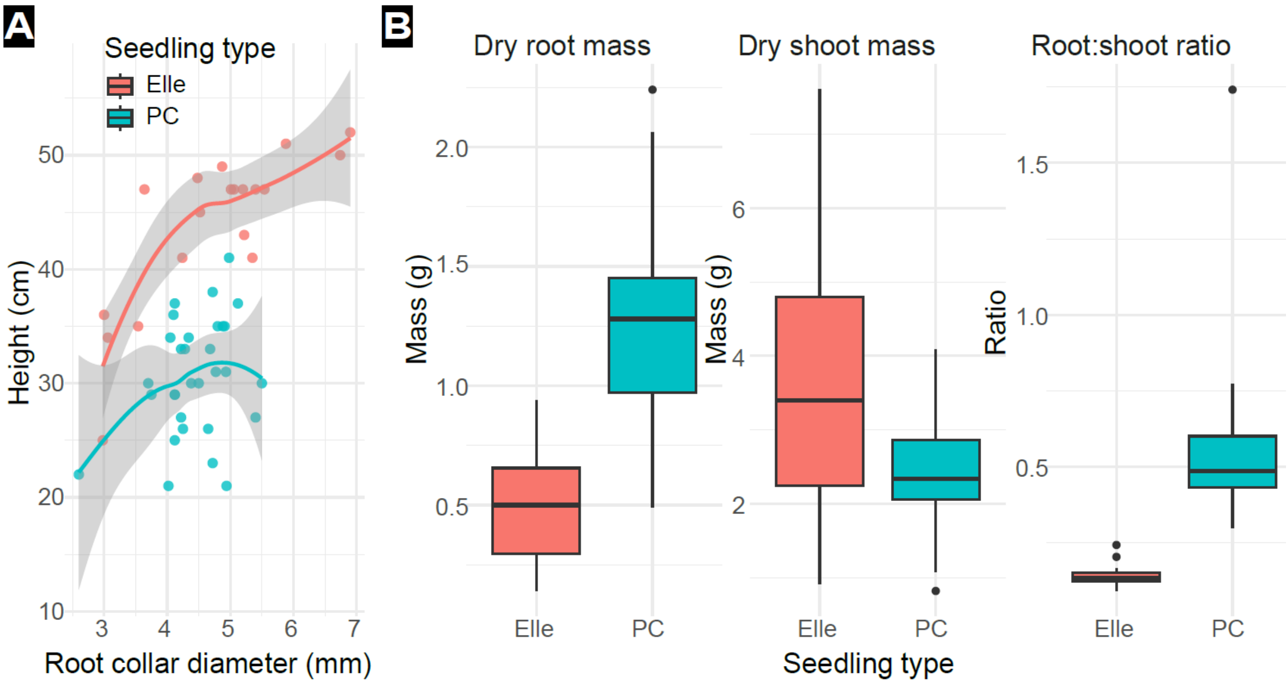


**Figure 6. Seedling quality measurements from Roundhill planting. A,** seedling heights plotted against root collar diameters (RCDs). Coloured dots show individual plants, coloured lines illustrate the relationship (trend) between height and RCD, and the shaded area surrounding the coloured trend lines indicate the 95% confidence interval of the relationship. **B,** box and whisker plots of dried shoot material masses, dried root material masses, and the ratios of these measurements.

Typically, integrity of the Ellepot seedlings plugs was better than that of PC seedling plugs at sampling. When the seedlings were removed from their containers, only five (16%) of the PC seedlings maintained all growth media. In contrast, 16 (84%) of the Ellepot seedlings did not lose growth media when handled. The difference was found to be significant using Fisher's exact test (two-tailed, $p < .001$). This result is surprising given the greater root mass of the PC seedlings. Figure 7 shows representative examples of plug integrity for the seedling types.


**Figure 7. Seedling plug integrity**. **A,** an Ellepot seedling with the growing medium still contained in the root plug. **B,** a plastic containerised (PC) seedling losing its growing medium early in handling.

**Planting quality on the day of planting**

Immediately after planting finished at Roundhill, an assessment was made of failed plantings: which included missing plants and 'not planted' where seedlings were not inserted into the ground. Overall, the number of failed plantings was low. Of the 840 assessed Ellepot seedlings, 17 (~2%) were determined to be failures, and the similar number of failed PC seedling plantings (22/840) meant that Fisher's exact test did not detect a significant difference (two-tailed, $p$ = 0.258) between seedling types.

Failed plantings do not reflect seedling type. Observations made during planting showed that taller (Ellepot) seedings were prone to becoming caught up in the planting tips. Furthermore, the planting operators felt the tapered plug shape of the PC seedlings was better suited to the feed mechanism of the PlantMax and, when remaining intact, resulted in fewer feed jams than the Ellepot seedlings. However, it was also noted that loss of soil from the PC seedlings meant these often failed to load properly. Overall, it was noted by the Plantma Forestry technical expert that the seedlings were too tall to efficiently pass through the PlantMax planting mechanism, with typically shorter and more robust seedlings used in Scandinavia.

**Vegetation cover**

Interestingly, although vegetation cover surrounding the seedlings varied at the time of planting according to planting method (scarified or not scarified), after seven months ground cover was assessed at 100% for all seedlings (Figure 8). Observations made during the remeasurements in February indicated that the dominant vegetation was the pasture grass remaining on site from the time of planting, and there was little evidence of other weed species occupying appreciable space around the planted seedlings.

At the first assessment, during early August 2023, mean ground cover percentage was found to be significantly lower for scarified mechanical planting (at 23%) than for manual planting (96%) and unscarified mechanical planting (93%) (Kruskal-Wallis $X^2$ = 400.91, $df$ = 2, $p$ < .001 between groups; with post-hoc Dunn test clarifying between-group differences).

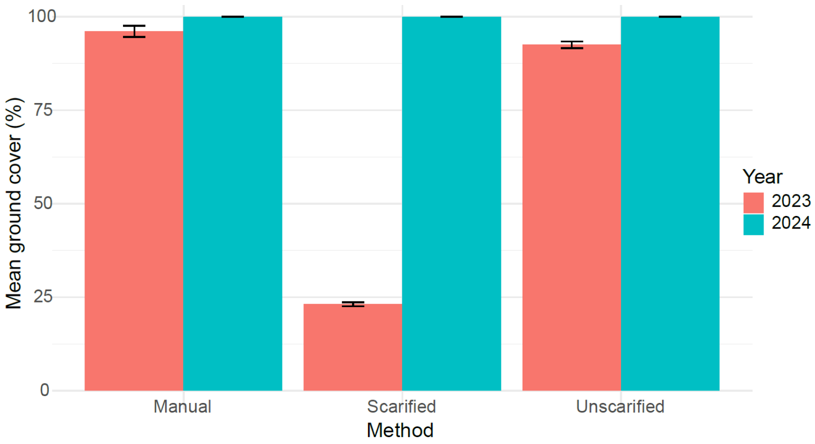


**Figure 8. Vegetation cover surrounding each seedling at Roundhill.** Mean vegetation ground cover (in a 1 m radius around each seedling) for two assessments, six months apart, is shown against the planting methods used. Error bars indicate standard error (*SE*).

## Seedling growth

There was little difference in seedling growth over the first eight months for the Ellepot and PC mechanically planted seedlings. The height and GLD growth increments were calculated over the period between the two seedling assessments undertaken in August 2023 and February 2024. The mechanically planted seedlings grew more in both height (Figure 9A) and stem diameter (Figure 9B) than the manually planted bare-root seedlings. However, while Figures 9A and 9B indicate slightly better growth in scarified plots, no significant differences (at a threshold of .05) were detected between these.

Interestingly, at the second measurement in February 2024, a Dunn test for multiple comparisons detected no significant differences in volume between scarified Ellepot seedlings ($M$ = 104 $cm^3$, $SD$ = 80.6 $cm^3$) and scarified PC seedlings ($M$ = 104 $cm^3$, $SD$ = 80.6 $cm^3$) ($p$ = .840) and no significant differences in volume between unscarified Ellepot seedlings ($M$ = 81.3 $cm^3$, $SD$ = 61.3 $cm^3$) and unscarified PC seedlings ($M$ = 81.9 $cm^3$, $SD$ = 71.0 $cm^3$) ($p$ = .947) (Figure A1, Appendix). There were, however, significant differences between scarified Ellepot seedlings and unscarified Ellepot seedlings ($p$ = .004) and between scarified PC seedlings and unscarified PC seedlings ($p$ = .023).

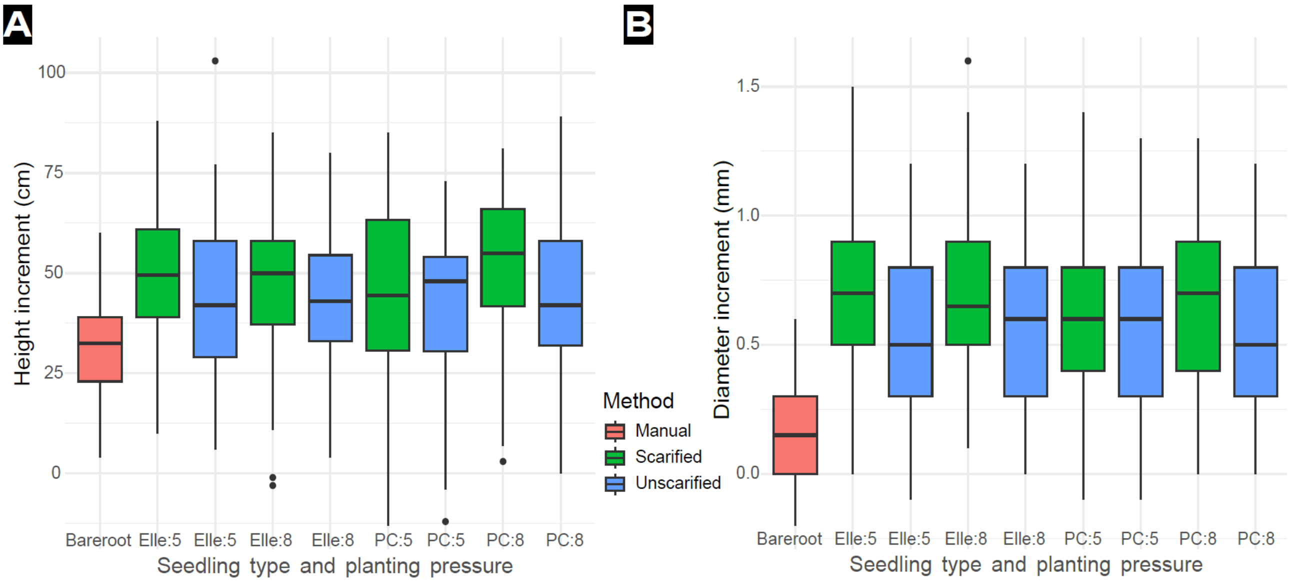


**Figure 9. Measured growth at Roundhill.** These plots show the increase in seedling size between the first measurement in August 2023 and February 2024. Negative growth increment values are ascribed to measurement error and seedling damage. **A,** seedling height increase. **B,** seedling diameter at ground level (GLD) increase.

### Seedling mortality and health

Planting method (scarified versus unscarified) and seedling type (PC versus Ellepot) were found to be significant predictor variables ($p = .013$ and $p < .001$ respectively) that were important to post-planting seedling mortality (Table A2, Appendix). After investigating all treatments, manually planted seedlings were excluded from the data to better understand the effects of the different PlantMax treatments on mortality. In this reduced dataset, there was no evidence of a three-way interaction between method, seedling type, and planting pressure.

Seven months after planting, the greatest mortality was associated with PC seedlings planted in the unscarified treatment (*M* = 49.9%, *SE* = 5.2%) and the lowest Ellepot seedlings planted in the scarified treatment (*M* = 17.1%, *SE* = 3.4%) (Figure 10). Intermediate levels of mortality were found for unscarified Ellepot seedlings which had a mean of 27.8% (*SE* = 4.4%), and for scarified PC seedlings which had a mean mortality of 34.8% (*SE* = 4.8%). Scarification, averaged over seedling type, had mortality of 25.0% (*SE* = 3.4%) in comparison to unscarified plots, where mortality was 31.3% (*SE* = 3.9%). For comparison, the mortality of the manually planted bare-root seedlings (*M* = 26.1%, *SE* = 5.1%) was similar to that of the Ellepot seedlings (averaged over different treatments).

When comparing all treatments against one another, PC seedlings planted at pressure five (P5) have significantly ($p = .04$) higher mortality than the manually planted bare-root seedlings (Figure 10).

Figure 11 illustrates the considerable changes in seedling health at Roundhill. Few seedlings were reported dead in 2023 and few were assessed as being in perfect health. Whereas, in 2024, most surviving seedlings were assigned a health score of four, which indicated they were healthy.

Notwithstanding their relatively high health scores at the first assessment, both the Ellepot and PC seedlings did not appear obviously robust at planting. Wilting and drooping was commonly observed amongst these seedlings, possibly reflective of the time they had spent at the planting site, including in the planting machine carousel before being planted.

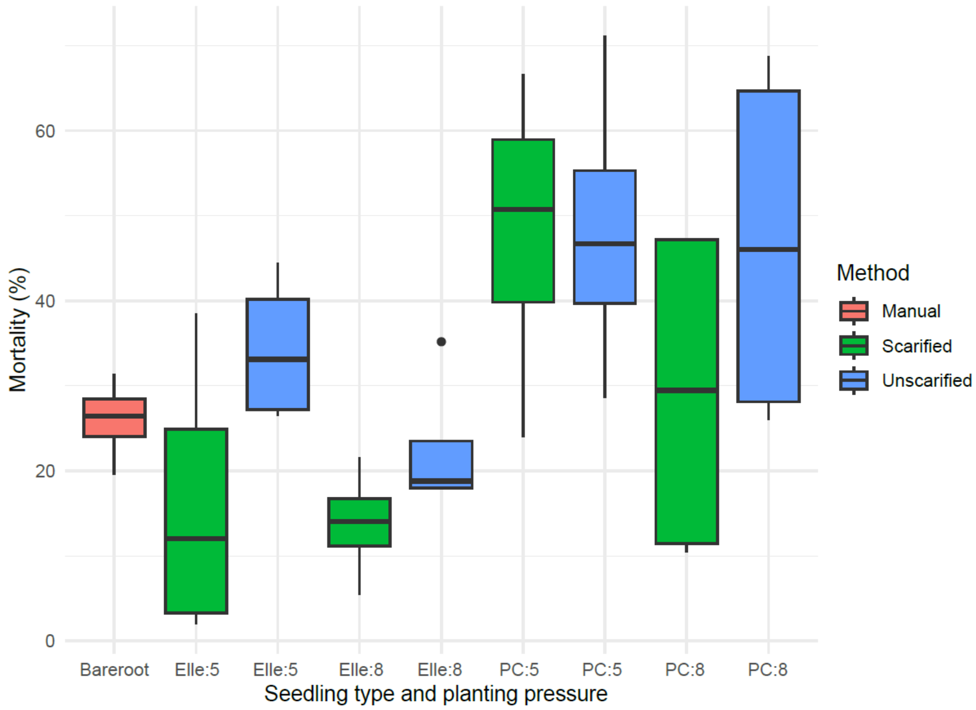


**Figure 10. Seedling mortality at Roundhill.** Mortality of seedlings at February 2024 for each treatment is plotted. Disregarding results for the manually planted bare-root seedlings, this box and whisker plot indicates lower mortality for Ellepot seedlings (left side of the graph) and lower mortality for seedlings in scarified plots (shown in green).


**Figure 11. Seedling health at Roundhill in 2023 and 2024.** Data from 2023 is shown along the top and data from 2024 along the bottom. Few dead seedlings (health score = 1) were found in 2023. However, in 2024, while there was considerable mortality, the visible health of the remaining seedlings typically increased towards being defect free (health score = 4).

## Gwavas Forest

### Site conditions

The evaluation plots installed at Gwavas Forest differed in slope but were otherwise relatively similar. Plots installed on ‘flat’ sites had an average gradient of 2.1 degrees (range 1.3–4.0 degrees) while the plots installed on ‘steep’ sites ranged from 9.9–21.3 degrees (*M* = 16.2 degrees). Harvest residues were assessed as typically being relatively light across the planted areas.

Stump measurements were made in each of the plots, but stump height did not appear to affect the PlantMax run spacing. The mean height of stumps avoided by the PlantMax (*M* = 36 cm, *SD* = 18 cm) was slightly larger than the mean height of stumps observed to have been run over by the machine (*M* = 30 cm, *SD* = 12 cm), but this difference was not found to be significant (Mann-Whitney U test, two-tailed, *p* = .34).

It was considered that site gradient could have an effect on the size of stumps remaining after harvest. However, there was no apparent correlation between site steepness and mean stump height (Figure 12A) nor between site steepness and mean stump diameter (Figure 12B).

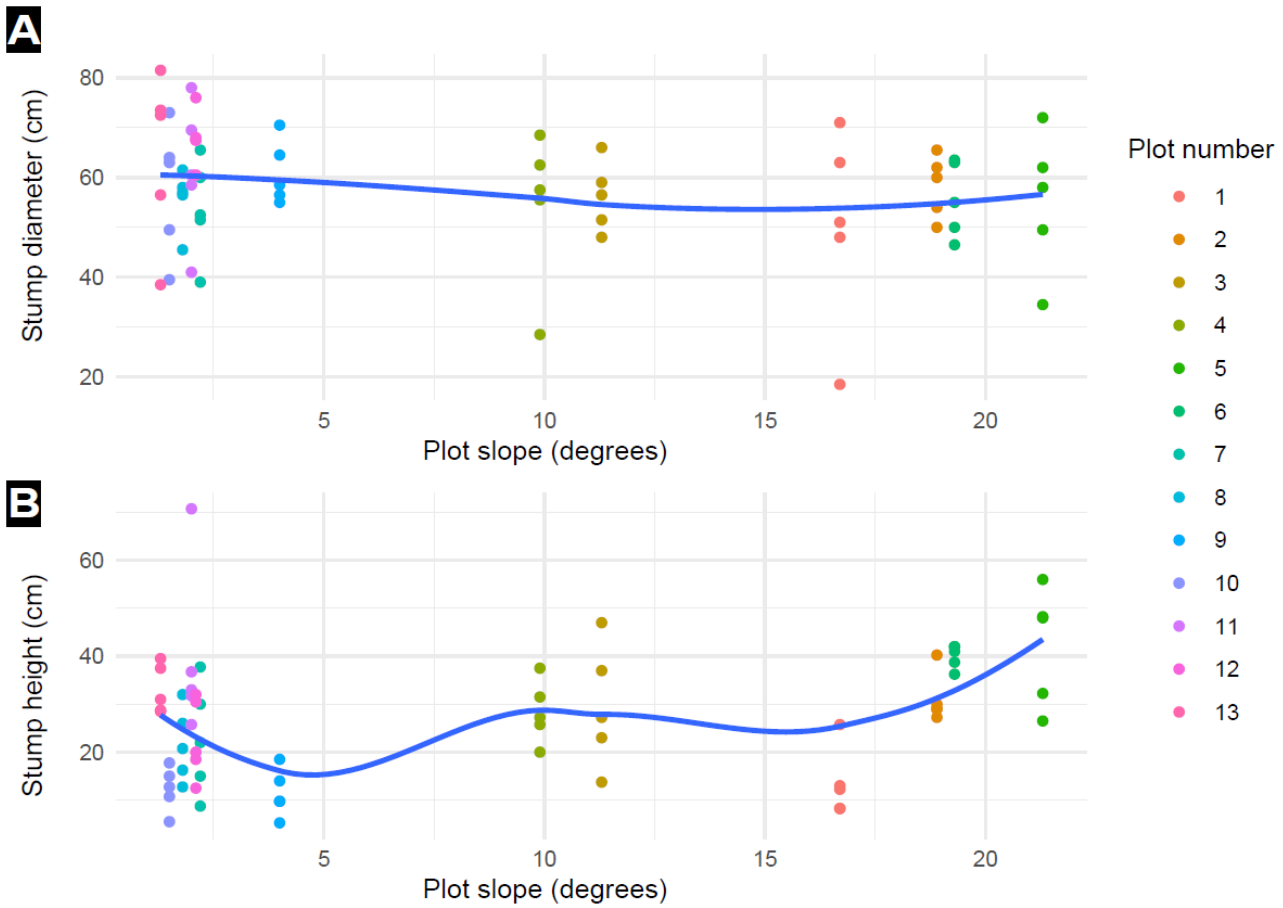


**Figure 12. Stump sizes at Gwavas Forest plotted against plot steepness.** Five stumps were measured per evaluation plot, and these (five) values have been plotted against the measured slope of the plot. Plot numbers have been included for completeness. The relatively horizontal dark blue lines, generated using locally weighted scatterplot smoothing (LOESS), illustrate the lack of relationship between plot gradient and stump size. **A,** stump diameters. **B,** stump heights.

### Vegetation cover

The scarification at Gwavas Forest had an interesting effect on the distribution of weeds. At this site, scarification was carried out for all planting with the PlantMax, and the effect of scarification was apparent at remeasurement. Although there was extensive growth of broad-leaved fleabane (*Conyza sumatrensis*) across the planting areas, the scarification lines were still visible due to being relatively weed-free (Figure 13). How a heavy fleabane infestation affects the survival and growth of the seedlings is outside the scope of this study, but chemical control of mature plants is known to be difficult (Massey University, 2024). The localised control of fleabane by PlantMax scarification was not duplicated in the manually planted plots, and vegetation ground cover in these was greater in both 2023 and 2024 assessments (Figure 14).

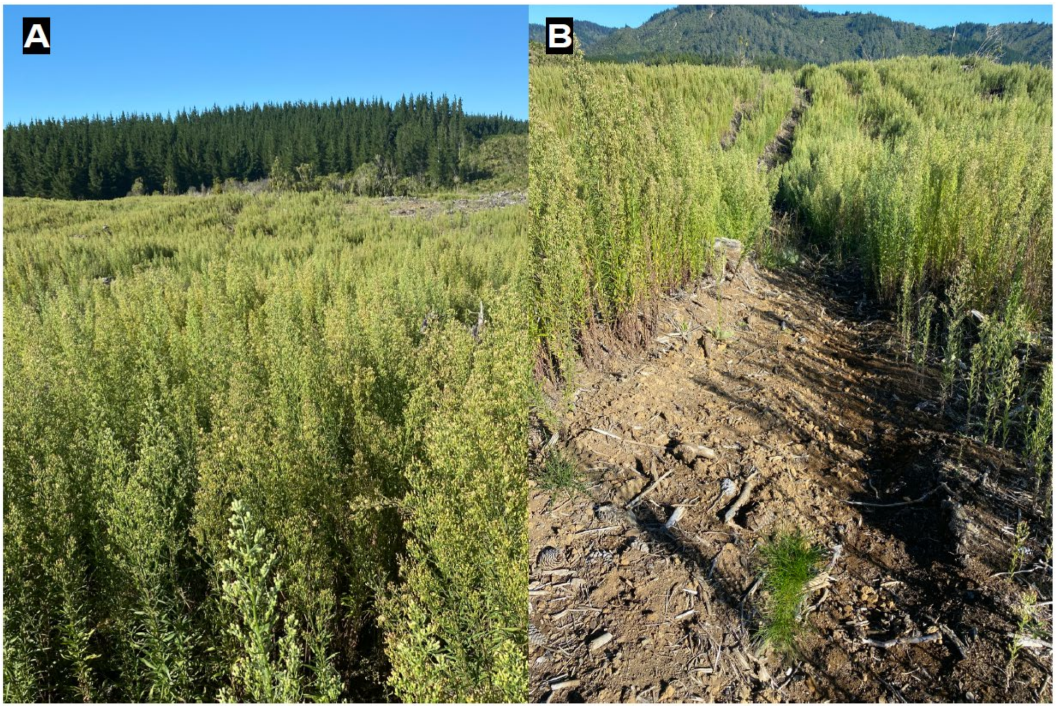


**Figure 13. Fleabane (*Conyza sumatrensis*) at Gwavas Forest. A,** overview of fleabane within the planted area. **B,** scarification line still visible, and relatively clear of weeds, approximately six months after planting. Note the planted pine seedling in the foreground.

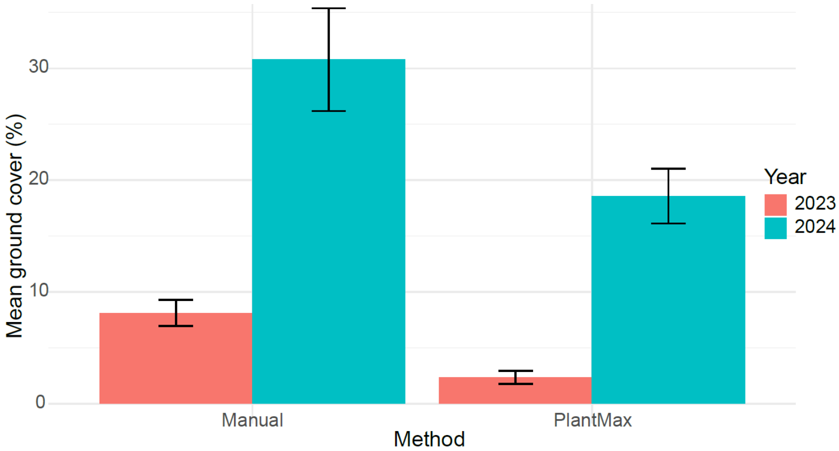


**Figure 14. Vegetation cover surrounding each seedling at Gwavas Forest.** Mean vegetation ground cover (in a 1 m radius around each seedling) for two assessments, five months apart, is shown against the planting methods used. Initial (2023) ground cover was predictably light due to pre-plant herbicide application. Error bars indicate standard error (*SE*).

## Seedling height at planting

The same types of seedlings (PC) were used for the manual and mechanised plantings at Gwavas Forest, so the height measurement of seedlings taken soon after planting was used to compare planting depths by method. Planting depth was not considerably different between mechanical and manual planting (Figure 15). Nevertheless, the plot does suggest that for both methods, there was a tendency for seedlings to be planted more shallowly on steeper slopes, and a significant difference between groups was detected (Kruskal-Wallis $X^2$ = 88.659, $df$ = 3, $p$ < .001). However, planting at Gwavas for this project took place over approximately two months, which means precise comparisons are difficult to make.

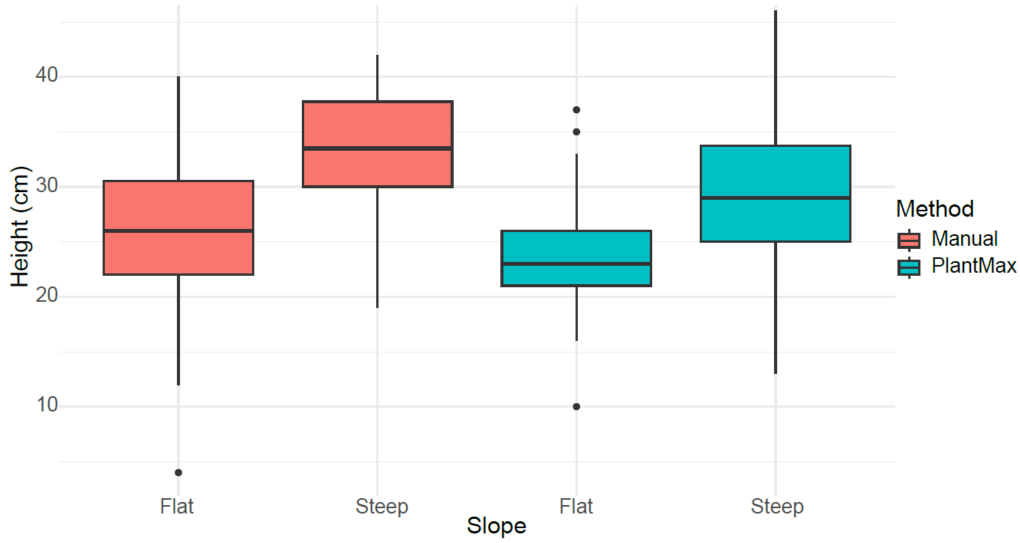


**Figure 15. Seedling heights at Gwavas Forest in 2023.** These data were collected approximately 1–2 months after plantings. Although the exact planting dates varied between sites and methods, there appears to be a trend whereby seedlings were planted more deeply on flatter land. However, there's little apparent difference between planting methods.

### Seedling vertical orientation

Planting the same seedling type also provided an opportunity to assess if the PlantMax maintained vertical orientation of the seedlings during planting.

Results from the 2024 assessment (Figure 16) show little difference in verticality between planting methods. The largest percentage (26%) of non-vertical plantings (categories one and two combined) occurred with mechanically planted seedlings on flat site. However, only one seedling in this group was seriously off vertical (category one). Furthermore, a chi-square test of independence of category three seedlings across all four method and slope groups detected no significant differences $X^2$ ($df$ = 3, $N$ = 257) = 3.80, $p$ = .28.

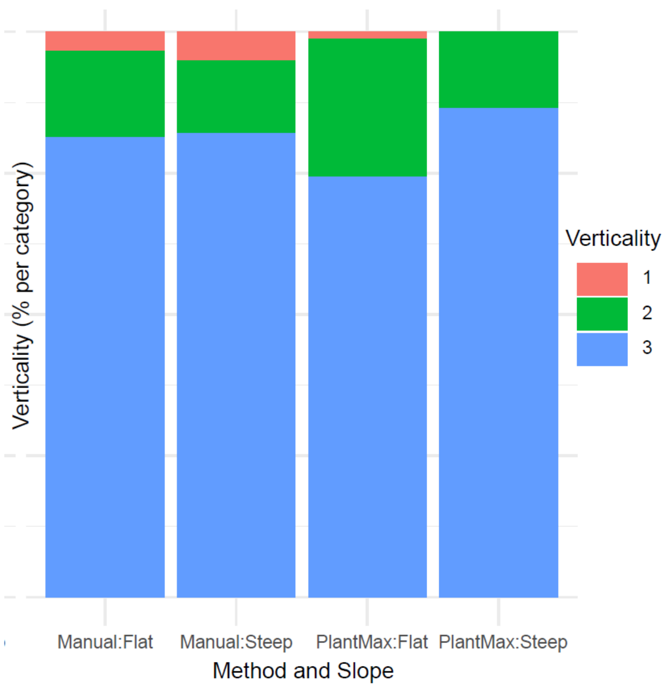


**Figure 16. Seedling vertical orientation at Gwavas Forest in 2024.** These data represent seedlings that were assessed as growing vertically (value = 3), growing slightly off vertical (value = 2), or badly off vertical (value = 1). This assessment was carried out at least five months after planting.

### Seedling growth

Height growth increment was, on average, greatest with mechanical planting on steep slopes and least with mechanical planting on flat slopes. However, there was a high degree of variability associated with mechanical planting on steep slopes, and more consistency with mechanical planting on flat slopes (Figure 17A). On average, diameter growth was also greatest with mechanical planting on steep slopes but was least with manual planting on steep slopes (Figure 17B).

Significant differences in height growth increment were detected between flat and steep slopes with mechanical planting ($p < .001$) for which height growth was greater on steep slopes. For manual planting, differences were not significant at a threshold of .05. On flat slopes, height growth was significantly greater with manual plantings, while on steep slopes the reverse was true (i.e. height growth was significantly greater with mechanical plantings).

Similarly, basal stem diameter growth increment differed significantly for flat and steep slopes with mechanical planting ($p < .001$), again with greater growth on steep slopes. With manual planting, growth differences between slopes were also significant ($p = .04$) but greater growth was on the flat slopes. On flat slopes, diameter growth was significantly greater with manual plantings, while on steep slopes the reverse was true (i.e. diameter growth was significantly greater with mechanical plantings).

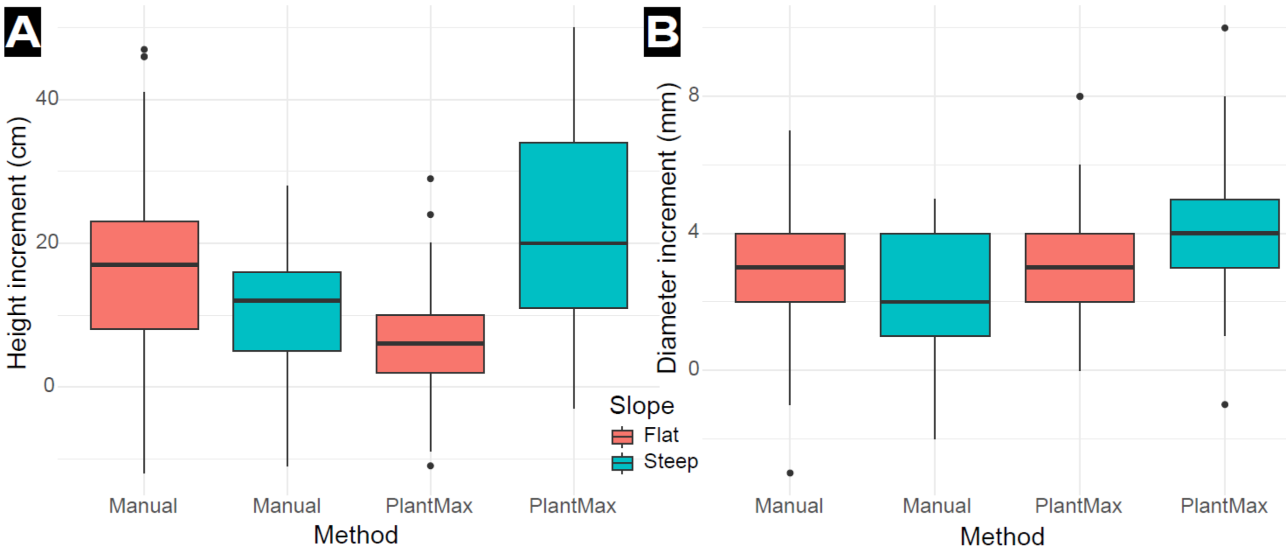


**Figure 17. Measured growth at Gwavas Forest.** These plots show the increase in seedling size between the first measurement in September 2023 and February 2024. Negative growth increment values are ascribed to measurement error and seedling damage. **A,** seedling height increase. **B,** seedling diameter at ground level (GLD) increase.

To ensure robust conclusions, the effect of negative growth increments was investigated. The instances of negative height increment (16) and negative diameter increment (6), ascribed to measurement error and seedling damage, were adjusted to zero to reflect natural growth expectations. The cleaned data were then analysed to determine if there were differences between the four treatments (2 x method (manual, mechanical) x 2 slope (flat, steep)) using the non-parametric Kruskal-Wallis test, with post-hoc analyses via Dunn's test. The conclusions are consistent for both the cleaned and the raw data.

### Seedling mortality and health

Although there was widespread mortality amongst seedlings assessed at Gwavas Forest in 2024, this did not appear to be dependent on planting method: manual or mechanised planting on flat or steep terrain. Mean mortality for mechanically planted seedlings was 35% (*SD* = 15%), while manually planted seedlings averaged 30% (*SD* = 15%) (Figure 18A). The lowest mortality of any plot occurred within a PlantMax plot on flat ground (16%) and the greatest mortality was observed in a steep PlantMax plot (52%). Beta regression analysis was used to test if method was a significant predictor of mortality, but differences were not significant due to high variability across the plots assessed ($p = .61$).

While there appeared to be a decline in mortality with increasing slope (Figure 18B), the effect of slope was not significant ($F(1, 24) = 1.0671$, $p = .31$).

As was noted at the Roundhill trial, the seedlings used for planting at Gwavas Forest appeared to be in below average condition. These health issues likely contributed to the high rates of seedling death. Probably exacerbating mortality at Gwavas Forest was the use of PC seedlings, which also had the highest mortality of all three seedling types used at the Roundhill trial.

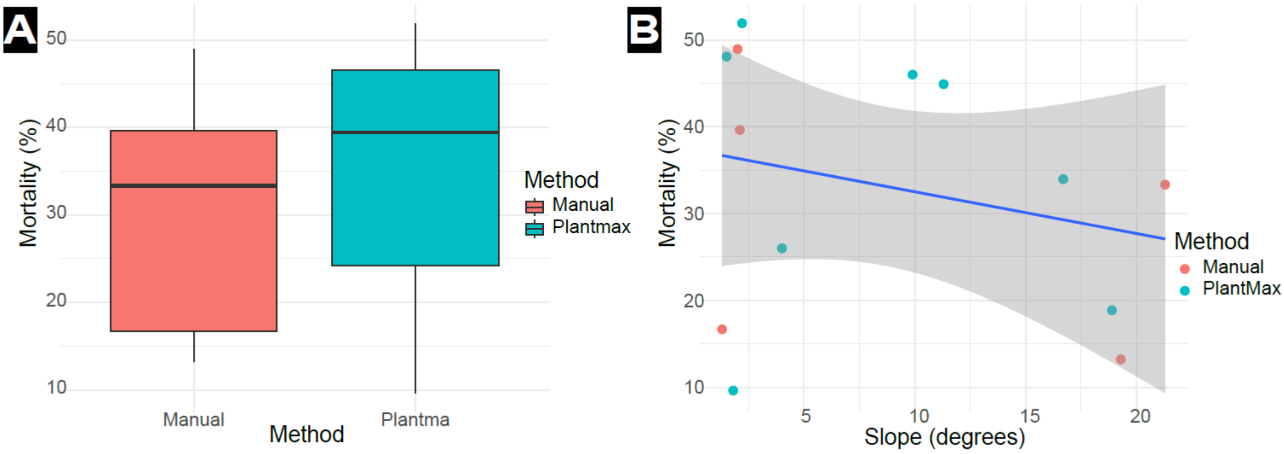


**Figure 18. Seedling mortality at Gwavas Forest. A,** mortality by planting method. **B,** mortality plotted against site slope. The negative relationship between site slope and percent mortality for each plot is weak and the 95% confidence interval (grey shading) of the regression line is large.

Figure 19 shows that a different seedling health trend occurred at Gwavas Forest to that observed at Roundhill. Similarly to Roundhill (Figure 11), mortality across all groups increased dramatically between the first and second seedling assessments. However, it does not appear that there was an overall increase in observed health amongst surviving seedlings, and a smaller proportion of seedlings were assigned a health score of four in 2024. The two trial sites are on very different sites, so this observation likely reflects site differences, notably cut-over versus ex-pasture, rather than planting variability.

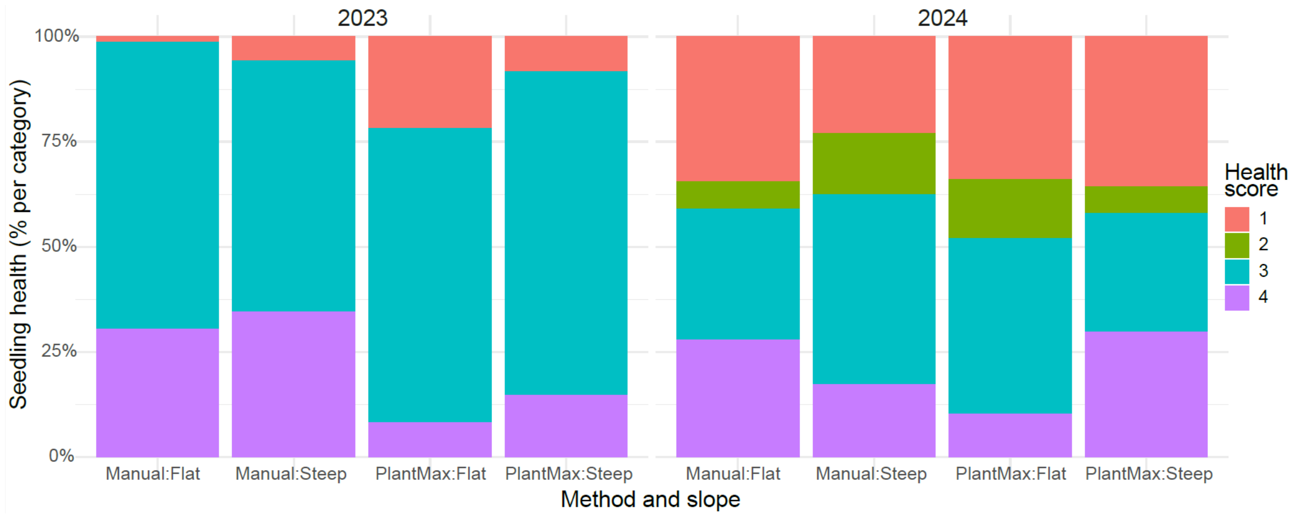


**Figure 19. Seedling health at Gwavas Forest in 2023 and 2024.** Left panel of stacked bars shows data from 2023, and data from 2024 is to the right. Considerable mortality (health score = 1) occurred between the 2023 assessment and the 2024 assessment. By 2024, the visible health of the remaining seedlings did not tend towards being defect free (health score = 4) as was observed at Roundhill.

# CONCLUSIONS AND RECOMMENDATIONS

These conclusions and recommendations are based on observations made during planting and on data gathered approximately six months after PlantMax operation. Therefore, these should be considered early results. Future seedling assessments from the current trial are scheduled, and Pan Pac has decided to maintain the PlantMax in NZ for further testing. This means that there are still opportunities to gather data and test the machine's capabilities across a range of terrain types.

One of the main limitations of this study is the high rates of seedling mortality that were unrelated to planting with the mechanised platform but more related to an issue of stock quality. This has reduced available sample sizes and likely resulted in smaller statistical power to detect true effects.

The extreme weather events and conditions of 2023 impacted implementation of this study. Firstly, the impacts of the Cyclone Gabrielle in February to Pan Pac operations affected their team's ability to focus on the evaluation of the PlantMax, with many staff being deployed to cleanup operations. Although this weather event did not appear to affect subsequent machine operation, planned early testing prior to the trial had to be truncated so operational planting could begin. Secondly, the wet summer of 2023 likely impacted seedling quality. It was commonly observed, during planting, that containerised seedling (both Ellepot and PC) quality was not as good as typically expected, and the seedlings were not the standardised dimensions ordered (R. Airey, personal communication, May 20, 2024). The similarly high rates of mortality for manually and mechanically planted PC seedlings at Gwavas Forest strengthens this hypothesis that better seedling quality would have improved planting outcomes. It is understood that across Pan Pac plantings in 2023, approximately three quarters of seedlings survived, and this poor survival could not be attributed to environmental conditions (R. Airey, personal communication, May 20, 2024).

Sturdier seedlings of a consistent size would improve the PlantMax performance. European tree planting typically utilises small, containerised seedlings planted at high densities (M. Peterson, personal communication, July 19, 2023). Recent figures indicate that only 12% of radiata pine seedlings sold (Bayne, 2021) are the containerised stock currently required by the PlantMax, so the availability of suitable seedlings could be a concern in the future, unless a way to plant bareroot seedlings with the Plantmax is developed. Despite the good plug integrity of the Ellepot seedlings, it was noted that the Ellepot root plug shape did not fit the PlantMax feed mechanism as well as the PC seedlings, the latter being tapered, and the former bring cylindrical. A further issue was the height of seedlings. Along with being prone to planting failures the taller seedlings caused feed jams when wind at the planting sites interfered with seedlings in the planting carousels. The planting crew had to mock up wind shields to alleviate this problem (Figure 20).

Planting operator skill and knowledge will affect success. Where planting pressure was trialled, although less significant than seedling type or scarification, it could influence seedling mortality. This finding reinforces the Plantma recommendation that the planting operator constantly monitor operations to optimise planting pressure and therefore depth. Additionally, the PlantMax planting module had a crew of two during most planting, but the PlantMax technical advisor demonstrated that with experience, planting could be handled by a sole operator.

There does not appear to be any advantage to planting into unscarified positions. At Roundhill, seedlings in scarified plots had better survival than seedlings in unscarified plots even though grass regrowth back into the scarification lines was rapid. The data collected also tentatively indicate that seedling growth was enhanced as a result of scarification. As an aside, the application of granular herbicide to seedlings one month after planting had a negligible releasing effect. At Gwavas Forest, scarification kept seedlings relatively weed free for several months. Although, it was observed during 2024 that pine seedlings regenerating from seed might be more prevalent in the scarification zone than outside it. The profusion of fleabane made this possibility difficult to confirm, and it requires further investigation. If regeneration is confirmed as an issue, then this could be addressed with intermittent, rather than continuous, scarification.

**Figure 20. Forester ingenuity.** To combat wind on the planting sites bending the seedlings and causing mechanism feeding issues, sections of planting box were cable tied against the seedling carousels to act as wind breaks.

Not tested during this trial, but with great promise for improving efficiency, was the mounted spray system. Figure 1F shows the spray nozzles mounted to a planting arm. If the spray system works as expected, then release spraying with a pre-emergent herbicide could be conducted simultaneously with planting. This would alleviate the cost of sending in ground workers later and would also mitigate the risk of seedlings being left unsprayed.

Testing the PlantMax on different slopes at Gwavas Forest generated useful information. It appears the machine successfully planted on gradients at the advertised operating limit of 20 degrees. Interestingly, there might be a trend in the data that tentatively implies seedling vertical orientation, seedling growth, seedling health, and seedling survival are slightly superior on the steeper slopes than on the lower gradient areas. However, further investigation would be needed to make any finding regarding this phenomenon. Furthermore, it must be noted that the Gwavas Forest plot with the best seedling survival (16%) was on flat ground planted with the PlantMax. Adjustments and refinements to the PlantMax would help optimise it for NZ conditions. Issues that arose during the trial included:

- Issues with seedling quality and size;
- A wide turning circle which limited the productivity of the machine in the hilly terrain;
- Constraints around the width between planting arms limiting the inter-row spacing, and;
- Failure of the GPS platform eliminating the opportunity to analyse data collected from the machine during planting (position, planting rate etc).

Planting difficulties have already been widely discussed but it should be reiterated that seedling type should be selected based on its utility for the PlantMax: sturdy with consolidated root plug. Alternatively, further investment could be made in altering the PlantMax planting module to suit the best seedling type, including an ability to plant bare-root seedlings.

One of the biggest issues with the PlantMax in smaller, or more topographically complex, planting sites was the relatively large area needed to turn around after finishing a planting run. Time spent turning was time not spent planting. Compounding this loss of efficiency was the cost of employing a manual planting crew to infill the missed areas. If possible, a more agile base unit could alleviate some of this problem or, potentially, new methods of strategising the planting operation could reduce non-productive time. Pan Pac are already investigating options to adapt the planting unit to a different base machine that has better manoeuvrability.

Typical NZ forestry planting densities (~1000 stems/ha) seem to be at the lower limit of the PlantMax capabilities. Because typically higher densities of seedlings are planted in European conditions, PlantMax planting arm spacing is normally adjusted between 2.5–2.7 m. In this trial, the arms were maximally spaced to 3.0 m apart, and this meant that planting operator vision of the planting heads was obstructed. Furthermore, because the planting arms had no adjustment remaining, seedlings could only be planted into the ditch formed by scarification. It was not possible to plant onto the formed mound, a potential limitation for planting on frost prone sites.

While the PlantMax should be a useful tool for precision forestry, unfortunately the GPS unit did not function during the trial. With a high-accuracy, real time kinematic (RTK) GPS system, it should be possible to capture precise location data and valuable planting condition data for all seedlings (Markus Peterson, personal communication, July 19, 2023). Properly functioning GPS would also have provided the driver with positional cues to optimise plant spacing and could be used to direct planting patterns.

The PlantMax shows promise for use in NZ forestry and indications are that the platform performs a quality and productive planting operation. Adjustments to the machine, to seedling supply, and to current work practices are needed to realise the full potential of this mechanised planting platform, and a full cost comparison with manual planting is still required. However, there are strong signals that given skilled operators and modification to existing processes, the PlantMax could be an important component in efficiently planting large areas of the forest estate.

# ACKNOWLEDGEMENTS

We thank Pan Pac Forest Products for importing the PlantMax and making it available for this trial; especially given the challenges imposed by the effects of Cyclone Gabrielle on the company. A special thanks is given to Richard Airey for safely accommodating the trial setup and measurement needs and for always being available to answer queries. Thank-you also to Sean Wright and Peter Campbell for their collaboration FGR and Scion in evaluating this platform. We also thank Markus Petterson of Plantma Forestry who provided technical advice for the PlantMax and provided valuable context on its use back in Sweden. Thanks are due to Ryan Vorster and Fiona Fields of Scion for processing seedling and soil samples. Finally, we would like to acknowledge the hard work put in by Richard Vili, Elijah Vili, Ngarimu Mana, and Kane Fleet from Scion who worked in occasionally unpleasant conditions to finalise the trial setups and take all the field measurements.

# REFERENCES

Baker, M. (2018). Mechanised silviculture: Opportunities and challenges for the New Zealand forest industry. *New Zealand: Kellog Rural Leadership Programme*.

Bayne, K. (2021). *Covid-19 : Extending the Planting Season – Industry Survey*. Te Uru Rākau – New Zealand Forest Service.

Cribari-Neto, F., & Zeileis, A. (2010). Beta regression in R. *Journal of Statistical Software*, *34*, 1-24.

Dunn, O. J. (1964). Multiple comparisons using rank sums. *Technometrics*, *6*(3), 241-252.

Dunnett, C. W. (1955). A multiple comparison procedure for comparing several treatments with a control. *Journal of the American statistical Association*, *50*(272), 1096-1121.

Firke, S. (2023). janitor: Simple tools for examining and cleaning dirty data. R package version 2.2.0. https://CRAN.R-project.org/package=janitor

Fisher, R. A. (1970). Statistical methods for research workers. In *Breakthroughs in statistics: Methodology and distribution* (pp. 66-70). Springer.

Garofalo, S., & Garofalo, M. S. (2022). StepBeta: Stepwise procedure for beta, beta-binomial and negative binomial regression models. R package version 2.1.0. https://CRAN.R-project.org/package=StepBeta

Hawke's Bay Regional Council. (2023). *Drought App*. Retrieved 8 May 2024 from https://www.hbrc.govt.nz/widgets/drought-app/drought_risk.php#

Keefe, R. F., Zimbelman, E. G., & Picchi, G. (2022). Use of Individual Tree and Product Level Data to Improve Operational Forestry. *Current Forestry Reports*, *8*(2), 148-165. https://doi.org/10.1007/s40725-022-00160-3

Kruskal, W. H., & Wallis, W. A. (1952). Use of ranks in one-criterion variance analysis. *Journal of the American statistical Association*, *47*(260), 583-621.

Manaaki Whenua - Landcare Research. (2020). *Our Environment - Land Atlas of New Zealand*. Retrieved 7 April 2024 from https://doi.org/10.26060/5ts6-hj98

Manaaki Whenua - Landcare Research. (2024). *S-Map Online*. Retrieved 14 May 2024 from https://smap.landcareresearch.co.nz/

Mann, H. B., & Whitney, D. R. (1947). On a test of whether one of two random variables is stochastically larger than the other. *The annals of mathematical statistics*, 50-60.

Martin, R. (2022). *Provisional estimates of tree stock sales and forest planting in 2021*. https://www.mpi.govt.nz/dmsdocument/44971-Provisional-estimates-of-tree-stock-sales-and-forest-planting-in-2021

Massey University. (2024). *Broad-leaved fleabane*. Retrieved 9 May 2024 from https://www.massey.ac.nz/about/colleges-schools-and-institutes/college-of-sciences/our-research/themes-and-research-strengths/plant-science-research/new-zealand-weeds-database/broad-leaved-fleabane/

NZIER. (2021). *Forestry and wood processing labour force survey - NZIER report to Ministry for Primary Industries*. New Zealand Institute of Economic Research.

Ogle, D., Doll, J., Wheeler, A., & Dinno, A. (2023). FSA: Simple fisheries stock assessment methods. R package version 0.9.5. https://CRAN.R-project.org/package=FSA

Pearson, K. (1900). X. On the criterion that a given system of deviations from the probable in the case of a correlated system of variables is such that it can be reasonably supposed to have arisen from random sampling. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, *50*(302), 157-175.

Plantma Forestry. (2022). *Operators Manual: Plantma - X*. Plantma Forestry.

Plantma Forestry. (2024a). *Main components of Plantma-X*. Retrieved 15 April 2024 from https://plantmaforestry.com/main-components-of-plantma-x/

Plantma Forestry. (2024b). *Operating the Plantma-X*. Retrieved 15 April 2024 from https://plantmaforestry.com/operating-the-plantma-x/

Plantma Forestry. (2024c). *Plantma Forestry*. https://plantmaforestry.com/

Plantma Forestry. (2024d). *What is PlantMax?* Retrieved 15 April 2024 from https://plantmaforestry.com/what-is-plantma-x/

R Core Team, R. (2013). R: A language and environment for statistical computing.

Raymond, K. (2010). *A step change harvesting research programme*. Forest Growers Research.

Signorell, A. DescTools: Tools for descriptive statistics. R package version 0.99.48. https://CRAN.R-project.org/package=DescTools

Te Uru Rākau. (2022). *Putting a value on the benefits of forestry*. https://www.canopy.govt.nz/assets/content-blocks/downloads/Putting-a-value-on-the-benefits-of-forestry.pdf

Visser, R., & Berkett, H. (2012). *Measuring Slope of Forestry Machines on Steep Terrain*. Forest Growers Research.

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L. D. A., François, R., Grolemund, G., Hayes, A., Henry, L., & Hester, J. (2019). Welcome to the Tidyverse. *Journal of open source software*, *4*(43), 1686.

# APPENDIX

**Table A1 Summary statistics of destructively sampled seedlings from Roundhill planting**

| | | Mean | *SD* | Median | Minimum | Maximum | Range | *SE* |
|---|---|---|---|---|---|---|---|---|
| Height (cm) | Ellepot | 43.79 | 6.95 | 47.00 | 25.00 | 52.00 | 27.00 | 1.59 |
| | PC | 30.58 | 5.16 | 30.00 | 21.00 | 41.00 | 20.00 | 0.93 |
| RCD (mm) | Ellepot | 4.77 | 1.15 | 5.01 | 2.98 | 6.90 | 3.92 | 0.26 |
| | PC | 4.45 | 0.57 | 4.38 | 2.60 | 5.50 | 2.90 | 0.10 |
| Stem volume ($cm^3$) | Ellepot | 110.68 | 61.41 | 117.17 | 22.20 | 247.57 | 225.37 | 14.09 |
| | PC | 62.11 | 19.54 | 60.45 | 14.87 | 101.68 | 86.81 | 3.51 |
| Plug Width (mm) | Ellepot | 39.32 | 2.36 | 40.00 | 35.00 | 43.00 | 8.00 | 0.54 |
| | PC | 37.94 | 4.24 | 38.00 | 28.00 | 47.00 | 19.00 | 0.76 |
| Plug length (mm) | Ellepot | 90.32 | 6.33 | 92.00 | 80.00 | 98.00 | 18.00 | 1.45 |
| | PC | 92.97 | 13.63 | 95.00 | 50.00 | 110.00 | 60.00 | 2.45 |
| Dry shoot mass (g) | Ellepot | 3.60 | 1.81 | 3.40 | 0.92 | 7.60 | 6.68 | 0.42 |
| | PC | 2.44 | 0.69 | 2.34 | 0.82 | 4.08 | 3.26 | 0.12 |
| Dry root mass (g) | Ellepot | 0.51 | 0.26 | 0.50 | 0.14 | 0.94 | 0.80 | 0.06 |
| | PC | 1.27 | 0.39 | 1.28 | 0.49 | 2.24 | 1.75 | 0.07 |
| Root:shoot ratio | Ellepot | 0.14 | 0.03 | 0.13 | 0.09 | 0.24 | 0.15 | 0.01 |
| | PC | 0.55 | 0.25 | 0.49 | 0.30 | 1.74 | 1.44 | 0.05 |

**Table A2 R output: Roundhill mortality - mechanical planting**

```
> Anova(reducedModel)
Analysis of Deviance Table (Type II tests)

Response:   propdead
              Df      Chisq    Pr(>Chisq)
Plant_type     1    14.0155    0.0001813  ***
Method         1     6.2168    0.0126543  *

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

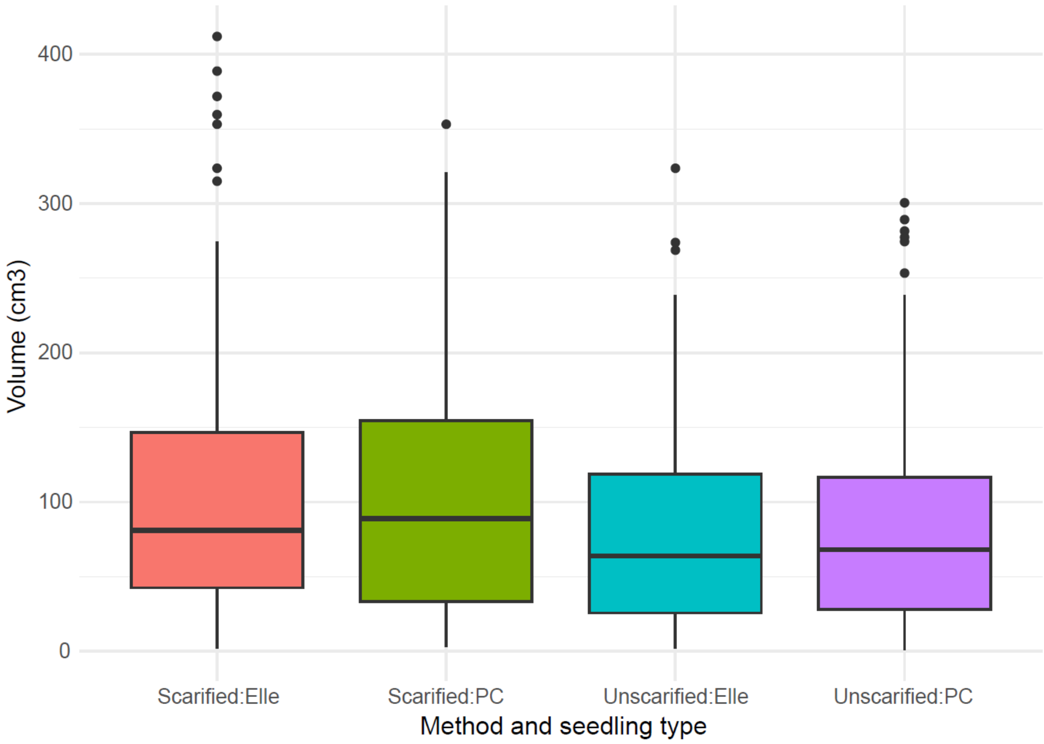


**Figure A1. Seedling volumes at Roundhill.** Stem volumes were calculated as root collar diameter (RCD)$^2$ multiplied by height. The plot indicates greater volume for seedlings that were planted into scarified lines. Manually planted bare-root seedlings omitted for clarity.