Mechanised Silviculture

Opportunities and Challenges for the New Zealand Forest Industry

KELLOGG RURAL LEADERSHIP PROGRAMME

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Contents

1 Executive Summary

The New Zealand plantation forest industry currently relies on manual labour to carry out silviculture operations, particularly planting, waste thinning and pruning. However, the industry is currently experiencing significant labour shortages. This is likely to be exacerbated for silviculture operations, particularly for planting in the short-term, with the commencement of the New Zealand Government's '1 Billion Tree' programme. A potential strategy to overcome the issues of labour shortages for silviculture operations is through mechanisation.

The aim of this study is to provide an insight into the opportunities and challenges of mechanised silviculture for the New Zealand forest industry, with a particular focus on planting, waste thinning and pruning. A review was carried out of the historical and current use of mechanised silviculture in New Zealand and internationally. A survey was also conducted of members of the New Zealand forest industry to attain their views on mechanisation of silviculture.

The review of current technologies showed that for:

- Planting, there are machines in Sweden, Finland, Canada and South Africa which have potential, though they would likely require adaption to operate effectively and efficiently in New Zealand conditions. Timberlands Ltd is currently trialling one of these machines in Kaingaroa forest.
- Waste thinning, there are currently some machines in operation in New Zealand, but they are limited to relatively gentle topography. There does not seem to be any other suitable technologies available, particularly for steeper terrain.
- Pruning, there does not seem to be any technologies that could be readily adopted for use in New Zealand forest conditions.

The results of the survey showed that:

- Over 90% of respondents had some or significant issues obtaining suitable labour or contractors for planting and thinning.
- Nearly 60% of respondents believed development and/or implementation of mechanisation for thinning was important for their organisation within the next 5 years. For planting and pruning, this figure was 45%.
- Over 63% of respondents thought a significant mechanised research and development programme should be developed for either planting, thinning or pruning within the next 5 years.
- The main benefit of mechanised silviculture for the New Zealand forest industry is that it could reduce the health and safety risk for workers, particularly on steep terrain.
- The most significant challenge for mechanised silviculture is operating machines on steep and variable terrain, as well as dealing with physical impediments (e.g. slash/logs).

The results of the review and survey indicate that the New Zealand forest industry has two options for implementing mechanisation of silviculture, particularly on steep terrain:

- Adapt some of the existing mechanised silviculture technologies to enable them to operate effectively and efficiently in New Zealand conditions.
- Investigate research and development of new technologies.

Implementation considerations include challenges and risks of technology development, the effect of potential labour supply changes on the viability of mechanisation, and social impacts.

It is recommended that the results of this study are presented to the Forest Owners Association's (FOA) Forest Research Committee to initiate discussion and determine the desire and feasibility of a forest industry mechanised silviculture research and development programme.

2 Introduction

The forest industry is New Zealand's 3rd largest primary industry with $5.5 billion of export revenue in 2017 (MPI 2017). The national plantation forest estate comprises of 1.7 million hectares, with 90% planted in radiata pine (FOA 2018a). The industry currently plants approximately 48 million trees per year (MPI 2018), but this is expected to increase to over 100 million per year by 2021 with the Government's '1 Billion Tree' programme (Te Uru Rakau 2018).

The New Zealand forest industry currently relies on manual labour to carry out a significant proportion of silviculture[1] operations, particularly planting, waste thinning and pruning. Therefore, the increase in forest establishment is going to increase the demand for labour for silviculture operations, particularly for planting in the short term.

However, in 2018, labour shortages are a significant issue for the New Zealand forest industry. A recent survey by the New Zealand Forest Owner's Association (FOA) showed that over the previous 12 months, 90% of respondents had some difficulty or major difficulty recruiting suitably skilled and qualified contractors or employees (FOA 2018b). This is resulting in increases in the cost of labour, and can also affect labour stability and the quality of work.

A potential strategy to overcome the issues of labour shortages in silviculture operations is by increasing labour productivity through mechanisation[2] (Poyry 2014). Mechanisation can also improve health and safety for workers, as well as improve the effectiveness of operations (Choudhry & O'Kelly 2018; Scott 1975).

Globally, it is estimated that less than 15 percent of forest establishment operations (e.g. land preparation, planting and releasing) are currently fully mechanised (Choudhry & O'Kelly 2018). Countries such as Sweden, Finland, Brazil, Canada, and South Africa are currently pursuing mechanisation of silviculture, with significant research and development programmes, particularly due to difficulties obtaining suitable labour. (Ersson 2014; Steenkamp 2018; FP Innovations 2017; Roothman 2014; da Costa 2018). New Zealand currently does not have a significant research and development programme for mechanisation of silviculture.

Therefore, in the current environment in New Zealand of actual or potential labour shortages it is deemed appropriate to review the potential of mechanisation of silviculture for the New Zealand forest industry.

3 Aim and Objectives

The aim of this study is to provide an insight into the opportunities and challenges of mechanised silviculture for the New Zealand forest industry, with a particular focus on planting, waste thinning and pruning.

The study has two research objectives to achieve this aim:

[1] Silviculture is defined as the practice of controlling the establishment, growth, composition, health, and quality of forests to meet diverse needs and values. In the New Zealand plantation forest industry, this includes site preparation, planting, post-plant weed control (releasing), thinning and pruning.

[2] Mechanisation is defined as the process of changing from working largely or exclusively by hand, to doing that work with machinery. In this report it refers to someone sitting in or indirectly operating a machine. It includes helicopter operations (e.g. for releasing). It does not include handheld tools (e.g. handheld chainsaws for waste thinning etc.).

1) Review what planting, thinning and pruning mechanisation has occurred in the past or is currently used in forestry operations in New Zealand and internationally.
    a. This will be based on a literature review as well as talking to relevant industry people in New Zealand and overseas (e.g. Australia, United States (US)) about their knowledge of mechanised silviculture. Due to the extensive nature and history of the subject, the aim of the review is to report on mechanised silviculture relevant to New Zealand. However, due to the reliance on predominantly published material, it is accepted that this review may not include all relevant:
        i. Historical examples of mechanised silviculture.
        ii. Current examples of mechanised silviculture, particularly technologies that are being research or developed overseas, as these may not be published or widely known.

2) Survey the forest industry to understand their perspectives on:
    a. The importance of mechanised silviculture
    b. Research and development into mechanised silviculture
    c. The key opportunities and benefits of mechanised silviculture in New Zealand.
    d. The key risks and challenges of mechanised silviculture in New Zealand.

4 Background

4.1 History of Mechanised Silviculture

4.1.1 Planting

Ever since the invention of the first tree planting machine (a horse drawn-rig) in Nebraska, USA in 1886 (Hallonborg 1996), tree planting has been performed either manually or mechanically. (Ersson 2014).

Over the next 80 years, various planting machines were developed that were based on principles borrowed from agriculture using continuously ploughing (continuous furrow). These machines required a person to at least place the tree into the ground (Scott 1975; Ersson 2010). By 1960 there were over 40 types of continuous ploughing planting machines in use in the United States and Canada alone (Scott 1975). These machines were developed to operate on relatively gentle terrain and on soils free from obstacles (Hallonborg 1996). Due to their method of continuous ploughing they were generally cost competitive with manual planting.

In New Zealand, forests with relatively gentle topography such as Aupouri, Woodhill, Tarawera and parts of Kaingaroa were established or expanded in the 1960s and 1970s using continuous ploughing machines such as the Lowther planter (Figure 1) (Rigby 1999; Restall 1964; Manktelow 1967; Anon 1966; Chavasse 1981). There was also an example, in the early 1970s, of these machines being used in very steep country in New Zealand, where a stationary tractor was used to control the lowering of the planting tractor down the slope and to assist it to reverse back up the slope (Chavasse 1973).

The use of these type of planting machines subsequently reduced in New Zealand due to a reduction in availability of suitable terrain and sites. However, they were continued to be used in New Zealand into at least the 1990s (e.g. the Mackay tree planter in the MacKenzie Basin (Ledgard and Davis 1994)).

Internationally, continuous ploughing machines are still used in places such as Chile (Arauco 2015) and the Southeast USA, where approximately 35% of the annual establishment area is mechanically planted (Maggard and Barlow 2018).

Figure 1. Double unit Lowther planters hauled by a crawler tractor, Tarawera forest, 1960s (left). Rear view of similar planting machine in USA (right)

As an increasing proportion of New Zealand's annual planting programme in the 1970s was scheduled to take place amidst the slash and stumps of pine cutovers, there was a need to develop a more adaptable planting machine. Therefore, in 1975 New Zealand Forest Research Institute (FRI) imported a 'Quickwood Intermittent Tree Planter' from Austria for testing (Coates 1980).

This machine was based on a method of intermittent plough planting, a technology which was developed in the 1960s in mostly Sweden, Finland, Germany and the United States (Scott 1975; Ersson 2010). The machine had a planting mechanism which was designed to ride over obstacles, and to create slots into which the seedlings were planted. FRI soon found that the 'Intermittent Tree Planter' had limitations, though the intermittent principle seemed well-suited to cutover sites. This led to FRI developing the FRI Intermittent Planter (FRIIP) in the late 1970s (Figure 2) (Coates 1980).

Figure 2. The FRI intermittent tree planter (FRIIP) developed in the late 1970s.

However, the FRIIP was restricted to relatively flat to rolling terrain and, more importantly, couldn't compete with the cost of manual labour in cutover sites. Therefore, it was not operationally deployed by the New Zealand forest industry (Euan Mason *pers comm*, 19 September 2018).

The beginning of the 1980s was deemed to be the climax of mechanised tree planting research and development in both North America and the Nordic countries. Several symposia on the mechanisation of forest regeneration were held in North America, and no less than 16 varieties of tree planting machines had either been developed, were in development or were commercially available in Canada at that time (Ersson 2010).

The 1980s also saw the first commercially intermittently advancing planting machine developed in Sweden. This was followed by the first successful boom-tip scarifying and planting head using containerised treestocks. This evolved into the Bracke planter, which is now one of 3 modern intermittent planting machines produced out of Sweden (Bracke) and Finland (M-Planter; Risutec) (Figure 3) (Ersson 2010).

Figure 3. Modern planting heads on excavators. The Bracke tree planter from Sweden (left) and the M-Planter from Finland (right)

These machines have the ability to scarify, cultivate, fertilise, irrigate and apply herbicide and insecticide. In Sweden, apart from scarifying and cultivation, the other applications of these machines is either prohibited (e.g. insecticide/herbicides) or considered uneconomical (Ersson 2014).

Despite plenty of research and development work to promote mechanised planting in Sweden and Finland, uptake has been and is currently low. The proportion of mechanised planting, particularly in Finland, has in fact stagnated or even slightly decreased over the last few years. For example, in 2013, these machines were used to plant less than 1% of the annual treestock requirements in Sweden, with fewer than 10 planting machines operating. In Finland, this figure was considered to be less than 5%, with up to 35 tree planting machines operating in 2013 (Ersson *et al.* 2018).

The reason why the growth of mechanised tree planting in Finland and Sweden is struggling is because of the lack of cost-competitiveness compared to manual planting. This is due to (Ersson *et al.* 2018):

- Low productivity, which originates from operator experience. E.g. up to a 65% difference in productivity between operators has been reported (Rantala *et al.* 2010)
- Quality of sites e.g. stones, slash and stumps decrease productivity
- The size and spatial distribution of sites e.g. smaller and more dispersed sites increases relocation costs.
- The relatively low number of treestocks in the planting head, which requires frequent manual reloading by the machine operator.

Despite the lack of uptake in Finland and Sweden, these machines can be cost-competitive in other countries due to their ability to provide added value to tree plantings. For example, Bracke machines in China, Indonesia and Brazil often water and fertilise Eucalyptus seedlings simultaneously. Because low-wage regions normally call for low-tech forest machines, it is these added services which makes these planting machines economical even in these relatively low-wage countries (Ersson 2014).

The Bracke machine has also been operated or trialled in Ireland, Scotland, Wales, Canada and Australia (Keane 2006; Bracke 2014; Berry 2015; Stjernberg 2004; Ian Last *pers comm*, 9 November 2018).

The Risutec machines are also being used in Chile. For example, one contractor states that it has 14 excavators operating with Risutec planting heads (LogInFor 2018).

In New Zealand, Timberlands Limited has recently imported a M-Planter (planting head) from Finland to trial in Kaingaroa forest. The ability of this machine to provide added value, such as fertilising, along with adaption of the cultivation mechanism to enable spot (rip) mounding (and perhaps the ability to windrow), could make it cost-effective (Dean Witehira *pers comm*, 9 November 2018).

In South Africa and Canada, planting machines using the same techniques as the machines in Sweden and Finland (i.e. planting head/s on an excavator) have recently been developed.

For example, in South Africa, Novelquip Forestry has developed the 'ProPlant 1', which plants containerised treestocks and also offers added value such as cultivation, fertilising and herbicide applications (Figure 4) (Novelquip 2017).

In Canada, Tim C. Van Horlick Forestry Inc. has developed the 'Van Horlick's Cultivator Planter' (Figure 4). This has 3 planting heads and can plant bare-rooted treestocks (which is the pre-dominant type of treestock planted in New Zealand). While the machine is claimed to be cost effective, as it is a recent development, there does not seem to be information available on its actual efficiency in an operational context (Van Horlick 2016; Van Horlick 2018).

Figure 4. The Novelquip 'Proplant 1' from South Africa (left) and the 'Van Horlick's Cultivator Planter' from Canada (right)

The 'Tree Rover', a planting robot, was also developed in Canada in 2015, by 2 students from University of Victoria (IOTA Technologies 2015). However, the robot would be impractical for New Zealand forestry conditions.

In France, a report was published in 2016 describing the development of an automatic tree planting machine, which is attached to a tractor, for use on relatively gentle topography (Appavoo *et al.* 2016).

In 2018, Scion (a New Zealand Crown Research Institute), in conjunction with New Zealand forest industry members and technology providers, has initiated a proposal for research and development of an automated planting machine ('Planterbot').

Another method of planting is by using aerial techniques. For example, aerial direct seeding was carried out with fixed wing aircraft and helicopters in Kaingaroa forest in New Zealand in the 1960s and 70s. However, it was ceased due to the uncertainty of the results. Either too many trees were produced causing expensive thinning, or too few resulting in blanking costs. (Levack 1973; Chavasse 1981). Planting using tree bullets from aircraft was also used in the US in the 1960s/70s and was discussed as having potential for application in steep country in New Zealand in the early 1970s (Chavasse 1973).

More recently companies such as droneseed (www.droneseed.co) and BioCarbon engineering (www.biocarbonengineering.com) have been developing techniques to do aerial planting via direct seeding using Unmanned Aerial Vehicles (UAVs or drones). Droneseed has been working with timber companies in the US, including looking at post-fire establishment. BioCarbon engineering is focused on large-scale ecosystem projects. For example, it has demonstrated its potential for mangrove renewal in Myanmar and rehabilitation of former open coal mines in Australia.

4.1.2 Thinning

Production thinning (otherwise known as commercial thinning) was partially mechanised (i.e. extraction and loading) in New Zealand at least 60 years ago (e.g. Grayburn 1976; Chandler 1976) and has been fully mechanised (i.e. mechanised felling) since at least the late 1990s/early 2000s (Les Russell *pers comm*, 14 October 2018). This compares with waste thinning (otherwise known as pre-commercial thinning), which, in New Zealand, still relies significantly on motor-manual operations (i.e. handheld chainsaws).

Production thinning is currently carried out in areas with relatively gentle topography (e.g. <25 degrees). Production thinning on steep slopes was attempted in New Zealand, for example in the 1980s, but it wasn't cost effective (Les Russell *pers comm*, 14 October 2018).

There is minimal published evidence (that the author could find) of mechanised waste thinning occurring in New Zealand. In a relatively unique case, fire (1946) regenerated radiata pine stands at Tahorakuri forest were tractor crushed in the early 1960s to reduce the stocking of the stands from 1 million stems/ha to 500-600 stems/ha (Grayburn 1976). While in the late 1990s/early 2000s, Carter Holt Harvey implemented mechanised waste thinning for a period of time in Kinleith forest with the use of Bell loggers (Russell Dale *pers comm*, 8 October 2018).

Recently, mechanised waste thinning operations have been implemented in New Zealand in some forests that have relatively gentle topography. One of these operations uses 14 tonne excavators with a shear head, while another uses small Bobcats (Figure 5).

Scion, in conjunction with University of Canterbury has recently developed a proof of concept tree to tree locomotion robot ('Stick Insect') (Parker *et al.* 2016). It is envisaged by the developers that with further work this could potentially be used for thinning and pruning.

Over the last 50 years there has also been technology developed in other countries for waste thinning. For example, in the 1970s, a method of mechanical waste thinning was developed in Western Australia for thinning *Pinus pinaster*. This involved a hydraulic driven power saw mounted on an agricultural tractor (Figure 5) (Kerruish 1976; Black 1977).

Figure 5. Mechanised waste thinning machines: Developed in Australia in early 1970s (left) and currently in use in New Zealand (right).

In Sweden and Finland, mechanised 'early cleaning' or waste thinning has been introduced, though a lack of cost competitiveness (versus manual brushcutting) has limited the uptake. For example, in Finland, it accounted for less than 1% of waste thinning in 2015 (Strandstrom 2016). However, this operation does not have much applicability to New Zealand, as it involves thinning of trees that are typically 2 to 3cm in diameter. This compares with New Zealand, where waste thinning generally involves trees that are 10-30cm in diameter.

4.1.3 Pruning

Mechanisation of pruning has been attempted for at least over 50 years, with predominantly 2 types of mechanised pruning techniques focused on (excluding mechanised hand-tools and platforms/cherrypickers).

The first technique relied on a machine being physically carried to the tree. For example, the 'Tree Monkey' was originally developed in Europe in the mid-1960s. It was trialled in New Zealand in the early 1970s and again in the 1980s, after further development by two Japanese companies, Sumitomo Corporation and Kioritz (FRI 1985; Wilkes and Bren 1986). However, it wasn't successful with radiata pine in New Zealand due to a number of factors. For example, a major problem with the machine was that it couldn't cope with knobbly whorls, resulting in excessive tree damage. It was also heavy and could not cut branches greater than 50mm, or be used for first-lift pruning as it required a portion of clear stem to which it could be attached (FRI 1985; Wilkes and Bren 1986).

Other machines which have been developed that use a similar technique to the 'Tree Monkey' are:

- The Clouston Tree Shaver from USA (Young 2002),
- 'WOODY', developed by the Sugano Lab at Waseda University in Japan (Campbell *et al.* 2013)
- A tree pruning robot developed at the Kawasaki & Mouri Lab of Gifu University in Japan (Ishigure *et al.* 2013).
- The automatic pruning machine 'YAMABIKO' made by Seirei Industry Co. Ltd (Ishigure *et al.* 2010; Campbell *et al.* 2013)
- The mechanical delimber 'Patas' developed by advaligno from Germany (Advaligno 2018)

The first three were only described as being a prototype. 'YAMABIKO' was described as the only commercial article of its type (Figure 6). However, it was not used very much because of its weight and branch bite problems (Ishigure *et al.* 2010). The 'Patas' is a recent development with sales planned for 2019 (Figure 6). However, it looks like it would have similar limitations to the 'Tree Monkey' when working with New Zealand radiata pine e.g. it can only cut branches up to 35mm.

The other pruning technique involved full mechanisation with a mechanised pruner attached to a machine. The 'Paterson Pruner', which was initially developed by the CSIRO Division of Forest Research in Australia in the mid-1970s, was the first known attempt at full mechanised pruning (Figure 6). However, a major problem with the machine, like the 'Tree Monkey', was excessive stem damage (CSIRO 1977; Wilkes & Bren 1986). The SAMUEL pruner seems to be a more recent iteration of this machine (Uebergang 2010).

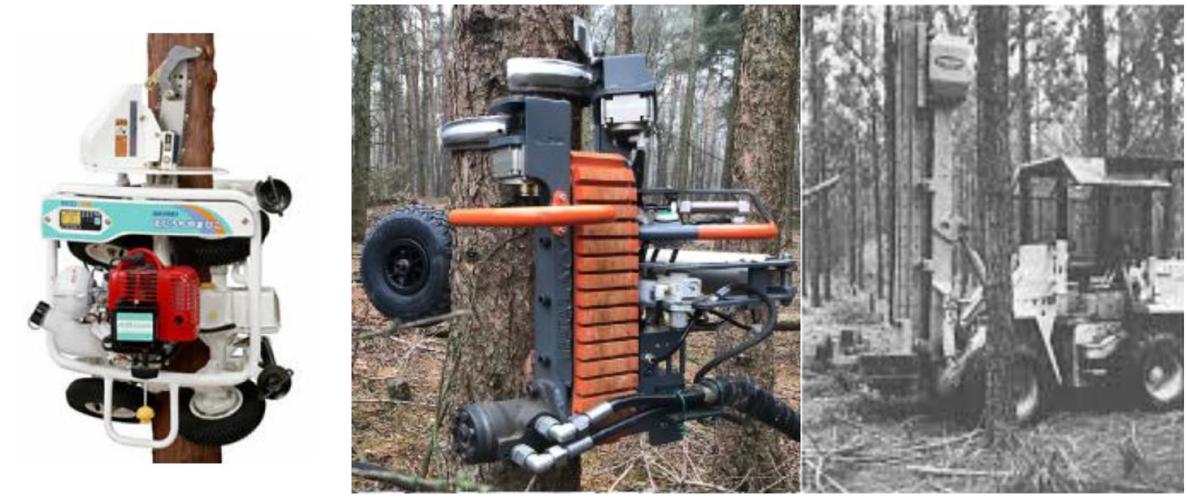


Figure 6. Mechanised pruning machines. The 'YAMABIKO' (left), the 'Patas' (middle), and the 'Paterson Pruner' (right).

In the late 1980s, Weyerhaeuser in the United States (US) also developed a pruning machine similar to CSIRO's 'Paterson Pruner' (United States Patent 1988). It is understood that this was at least used in production in the Southeast US to successfully treat a 'backlog' of stands in the early 1990s. However, Weyerhaeuser subsequently reverted to manual pruning because this produced a better quality pruned stem (Dave Lowry *pers comm*, 19 September 2018).

In New Zealand, a 2 year research project initiated in 2016 as a proof of concept, and carried out by the University of Canterbury, was looking at autonomous pruning using a UAV (University of Canterbury 2016). There are no published reports available, so far, on the outcomes of this project. At Massey University, researchers have also recently developed a 'novel tree climbing mechanism', which they suggest can be used as a platform for a tree pruning robot (though they suggest further work needs to be done) (Gui *et al.* 2017).

4.1.4 Research and development programmes

In New Zealand, between the 1960s and 1980s, there was significant interest in mechanisation of silviculture predominantly due to actual or feared labour shortages, and rising labour costs.

For example, in New Zealand, a 1972 FRI Symposium on 'Mechanization of nursery production, forest establishment and tending in New Zealand', which attracted 181 people, identified that a then trend of increased mechanisation of forest operations was being driven by (Chavasse 1973):

- A desire to reduce the unit costs of various operations.
- A recognition that there was a probability that labour for forest work will become increasingly difficult to obtain.

In the late 1970s, further development of mechanised planting was pursued by the New Zealand forest industry (e.g. FRI's Intermittent Planter) because of variations in quality of manual planting and labour costs rising steadily (Coates 1980). While, in 1985, a field day on manual and mechanical pruning equipment that attracted 115 people, stated that the primary reasons for investigating mechanisation of pruning were a shortage of labour, and the resulting unstable nature of the workforce, and poor quality of work (FRI 1985).

Over this period, there were significant research and development programmes in New Zealand. For example, there was a Silvicultural Equipment Development Committee headed by industry personnel that acted as a steering committee for FRI's Silviculture Equipment Research Group (SERG) (FRI 1985). This programme was quite successful in developing silviculture technologies, particularly in relation to nurseries and land preparation. However, not long after the dis-establishment of the New Zealand Forest Service in 1987, and with a reduction in establishment in the late 1980s, SERG was disbanded (Euan Mason *pers comm*, 19 September 2018).

Subsequently there seems to have been little in the way of an industry research and development programme for mechanised silviculture, apart from projects in relation to land preparation in the 1990s (e.g. Hall 1995).

In the absence of a dedicated research and development programme in New Zealand, initiatives, such as mechanised waste thinning, have been implemented by individual companies and contractors (e.g. see Section 4.1.2). This method of contractor innovation has also been notable in New Zealand harvesting operations over the last 15 years, particularly in relation to steep slope harvesting (e.g. HFM NZ 2015). Plantation tree nursery managers have also invested in developing mechanisation and automation technologies in recent years (Duke *et al.* 2016; Smaille 2018).

While there has been a gap of 30 years of significant mechanised silviculture research and development in New Zealand, other countries have been continuing to progress.

For example, in Finland, Metaseho Oy is a company owned by the forest industry organisations and companies, and is focused on research and development. It currently has a vision of 'Efficient wood supply 2025'. Mechanisation and automation/robotics is a key focus of this programme. For example:

- Utilisation of automation and sensor technologies and robotics technology
    - Planting
        - Developing a continuously operating planting machine
        - Autonomous planting spot detection
    - Mechanised early waste thinning
        - Locate and visualise trees for the operator as well as move the boom and the processing head (Metsateho 2018)

In Brazil, a consortium of leading Brazilian plantation companies was established in 2013 to tackle the issue of mechanisation of silviculture. They are cooperating with selected equipment suppliers, universities and institutes to develop a "multi-task machine". The aim is to reduce plantation establishment costs by planning, designing and reshaping the whole production processes of the first two years from planting. This multi-task machine will eliminate labour intensive processes by combining several forest operations into one (e.g. planting, fertilising, weed & insect protection) (Poyry 2014).

In Canada, FP Innovations are currently evaluating the effectiveness and productivity of mechanical planting machines as part of their 2017/18 collaborative research programme (FP Innovations 2017).

In South Africa, companies such as Sappi and Mondi are investigating and investing in semi-mechanised or fully mechanised establishment operations (Roothman 2014; da Costa 2017).

Information could not be found on any research and development programmes in Chile.

5 Methodology

A survey was conducted of members of the New Zealand plantation forest industry to help understand the industry's view on mechanisation of silviculture. 23 survey responses were obtained from representatives involved in forest management or silviculture positions from 14 of the largest forestry companies in New Zealand. Multiple responses were obtained from some companies due to their extensive geographic coverage (e.g. separate regional offices). The 14 companies surveyed represent over 55% of the total plantation forest area in New Zealand (FOA 2018a).

A survey was sent to individuals within each of the 14 companies using the website 'Survey Monkey'. The survey comprised of 10 questions, which were predominantly multi-choice/matrix type questions, with the opportunity for respondents to provide comments to help further describe their answers. Responses were anonymous. The survey questions are shown in Appendix 1.

The survey focused on predominantly the following stand establishment and tending operations:

- Spot (rip) mounding
- Windrowing/Slash raking
- Planting
- Releasing (e.g. post-plant herbicide application)
- Thinning
- Pruning

The aim of the survey was to understand:

1. The current use of mechanisation for silviculture operations in New Zealand. (6.1)
2. Whether obtaining and retaining contractors/labour was a current issue for silviculture operations? (6.2)
3. Whether the (further) development and/or implementation of mechanised silviculture or automation/robotics was deemed important for their organisation? (6.3)
4. Whether the New Zealand forest industry should develop a significant research and/or development programme for mechanisation or automation/robotics for silviculture? If so, how should it be funded and managed? (6.4)
5. What are some of the key opportunities and benefits of developing and/or implementing mechanisation and/or automation/robotics? (11 opportunities/benefits were provided for rating, with the opportunity for the respondent to provide others). (6.5)
6. What are some of the key challenges and risks of developing and/or implementing mechanisation and/or automation/robotics for silviculture in New Zealand? (13 challenges/risks were provided for rating, with the opportunity for the respondent to provide others). (6.6)

The following definitions were used in the survey:

- Mechanisation: The use of machinery that requires direct operation by a person/people. This includes helicopter operations (e.g. for releasing). It does not include handheld tools (e.g. handheld chainsaws for waste thinning etc.).
- Automation/Robotics: Machinery or robotics that does not require direct operation by people (includes tele-operation, UAVs)

6 Results

6.1 Current use of mechanisation

Out of the six silviculture operations focused on in the survey, only the land preparation operations, spot (rip) mounding and windrowing/slash raking, are fully mechanised. These operations are typically carried out using excavators with appropriate attachments. Over 75% and 85% of respondents indicated that they carry out at least some spot (rip) mounding or windrowing/slash raking respectively. The percentage of each respondent's annual establishment programme treated via these methods varies depending on local forest conditions (e.g. soil type, soil compaction, risk of frost, topography).

The extent of mechanisation currently used for planting, releasing, thinning and pruning are shown in Figure 7.

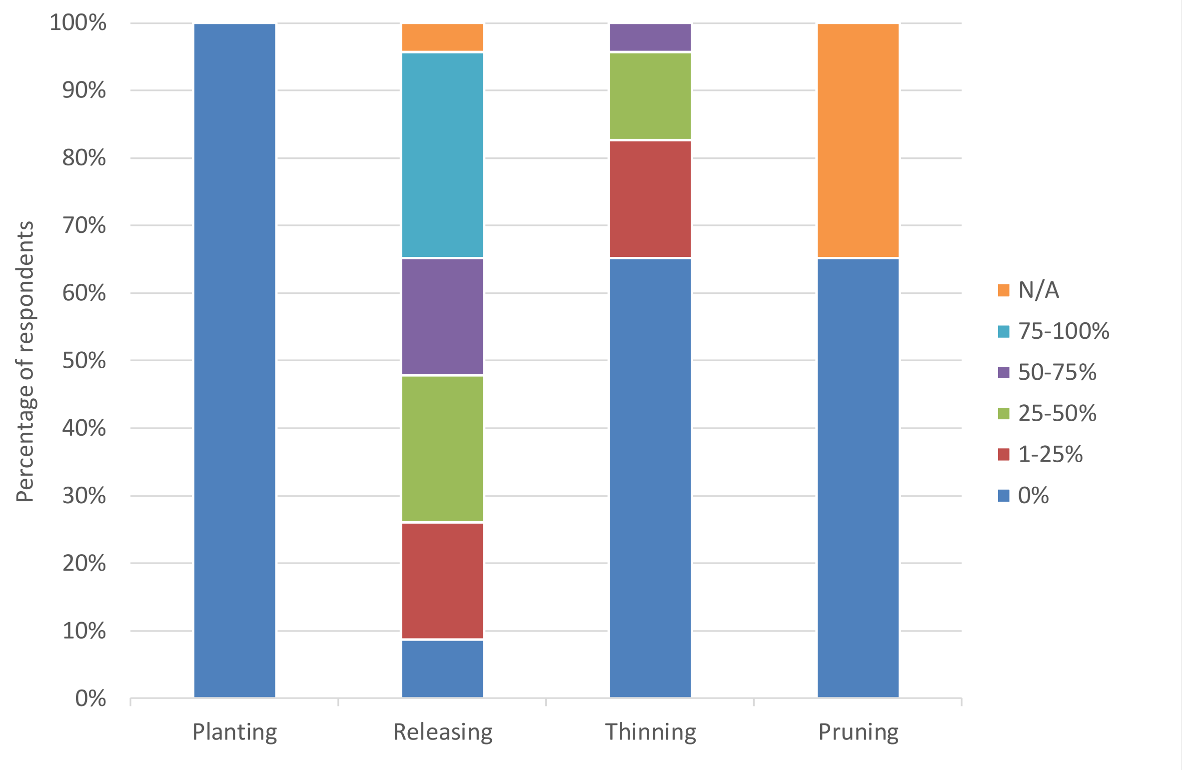


Figure 7. Percentage of operation's annual programme that is mechanised[3]

Planting and pruning operations are currently carried out using 100% manual labour with hand tools (e.g. planting spades, pruning loppers).

Mechanised post-plant herbicide releasing (e.g. aerial releasing using helicopters) can be a significant proportion of an organisation's programme, particularly because of:

- The terrain (e.g. steep hill country), which, from a health and safety perspective, is not suitable for manual herbicide releasing and/or
- The limited time to complete large areas, combined with a lack of labour

Manual herbicide releasing, such as spot spraying by hand, is used as an alternative to aerial releasing, and is used to varying degrees by different organisations. For example, where there is suitable topography; in areas that have been oversown; or in sensitive areas/boundaries. The

[3] Thinning includes both waste thinning and production thinning.

availability of labour can also play a large part in the extent of manual herbicide releasing that is used.

Mechanised thinning is used to varying extents by 35% of respondents. Production thinning is the main type of mechanised thinning, with a small percentage of respondents using mechanised waste thinning in some parts of their estate. Both of these operations occur in areas that are flat or with relatively gentle slopes (e.g. <25 degrees).

6.2 Obtaining and retaining suitable contractors/labour

Obtaining and retaining suitable contractors/labour for planting, thinning and pruning is currently an issue for a significant number of respondents (Figure 8).

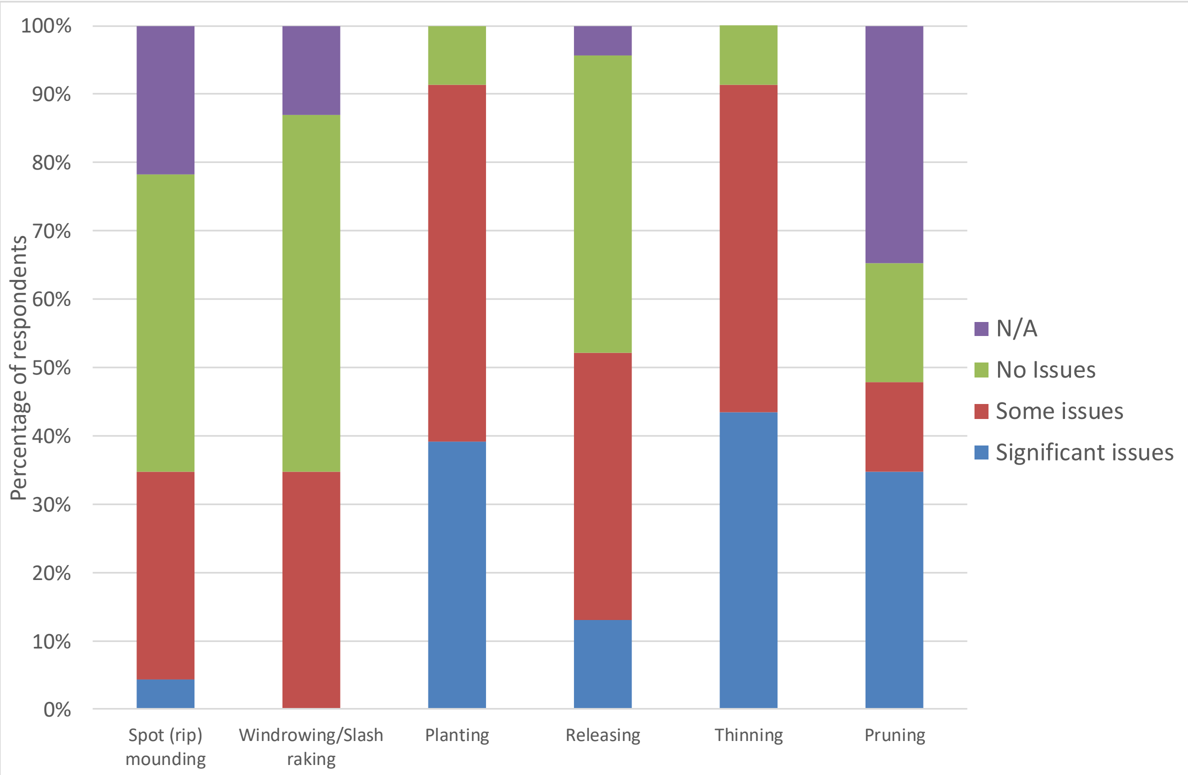


Figure 8. Is obtaining and retaining suitable contractors/labour a current issue?[4]

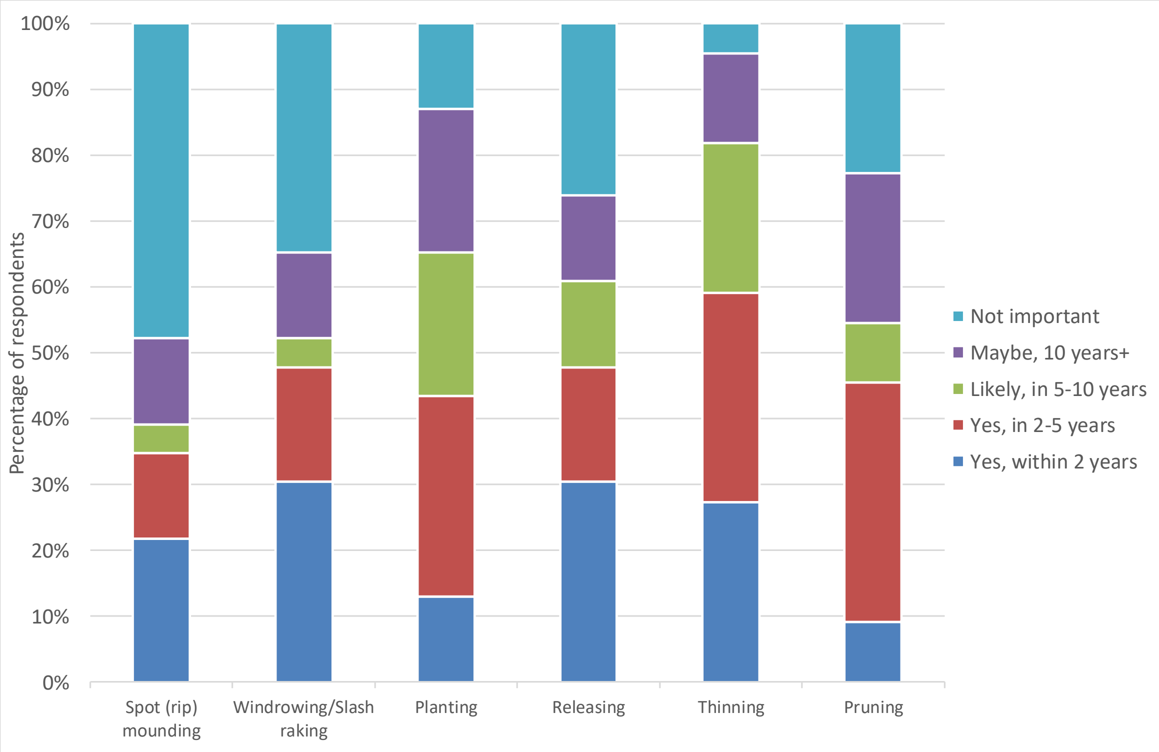
This has been developing over recent years, and for some respondents it is now affecting the quality of their operations and/or their ability to complete their work programmes. Manual waste thinning (i.e. with handheld chainsaws) is particularly an issue, as it is a common operation across most forestry organisations, requiring skilled and, preferably, experienced operators. Notable operational cost increases have occurred for some organisations this year.

Some organisations are also experiencing issues with obtaining and retaining suitable contractors/labour for manual herbicide releasing (e.g. spot spraying), particularly as many of the contractors/labour are the same used for either planting and/or thinning or pruning. For some organisations, this has resulted in an increase, and potentially further increases, in their use of aerial herbicide releasing (see Figure 9).

[4] Note: For the pruning 'No issues' category, it is difficult to determine from the survey responses whether 3 out of the 4 respondents in this category actually have 'No issues' or should be in the N/A category.

6.3 The importance of (further) development and/or implementation of mechanisation or automation/robotics

Planting, thinning (e.g. waste thinning) and pruning are deemed the most important operations for (further) development and/or implementation of mechanisation or automation/robotics (Figure 9). This is not surprising considering the current issues of obtaining and retaining suitable contractors/labour for these operations (as shown in Figure 8).



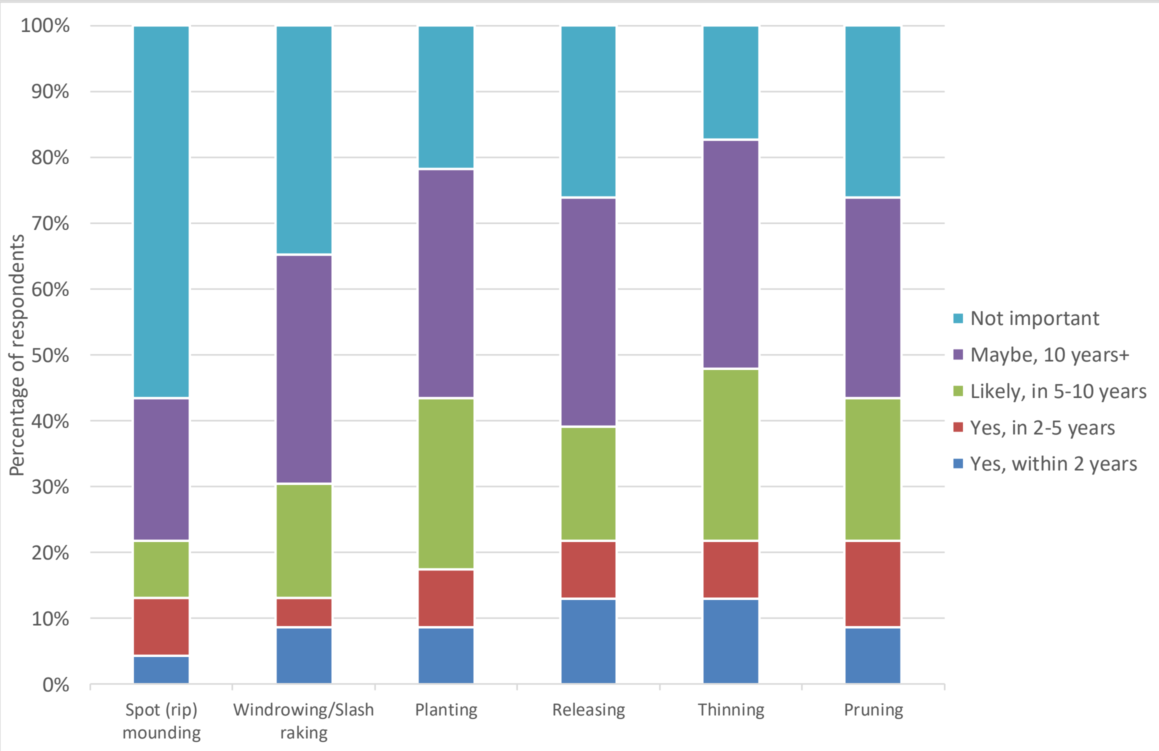


Figure 9. Is the (further) development and/or implementation of mechanisation (top) and automation/robotics (bottom) for silviculture important for your organisation?

Mechanised waste thinning is currently carried out by a small percentage of respondents. However, it was indicated that there was a strong incentive to at least (further) mechanise waste thinning, due to the health and safety risk of manual thinning operations, particularly on steep slopes, along with the current labour supply/demand pressures and the skills and experience required for manual thinning operations.

Spot (rip) mounding and windrowing/slash raking are already fully mechanised, as well as a significant proportion of herbicide releasing for some organisations (i.e. aerial helicopter operations). Therefore, the results shown in Figure 9 for these operations are either for further implementation (e.g. more slash raking or aerial releasing) and/or further development of the operations.

6.4 Development of a significant research and/or development programme

Planting, thinning and pruning had the highest proportion of respondents indicating that the development of a significant research and/or development programme should be implemented by the New Zealand forest industry (Figures 10 & 11). This aligns with the results from sections 6.2 and 6.3. The level of interest between the development of a mechanised or automation research and development programme is relatively similar.

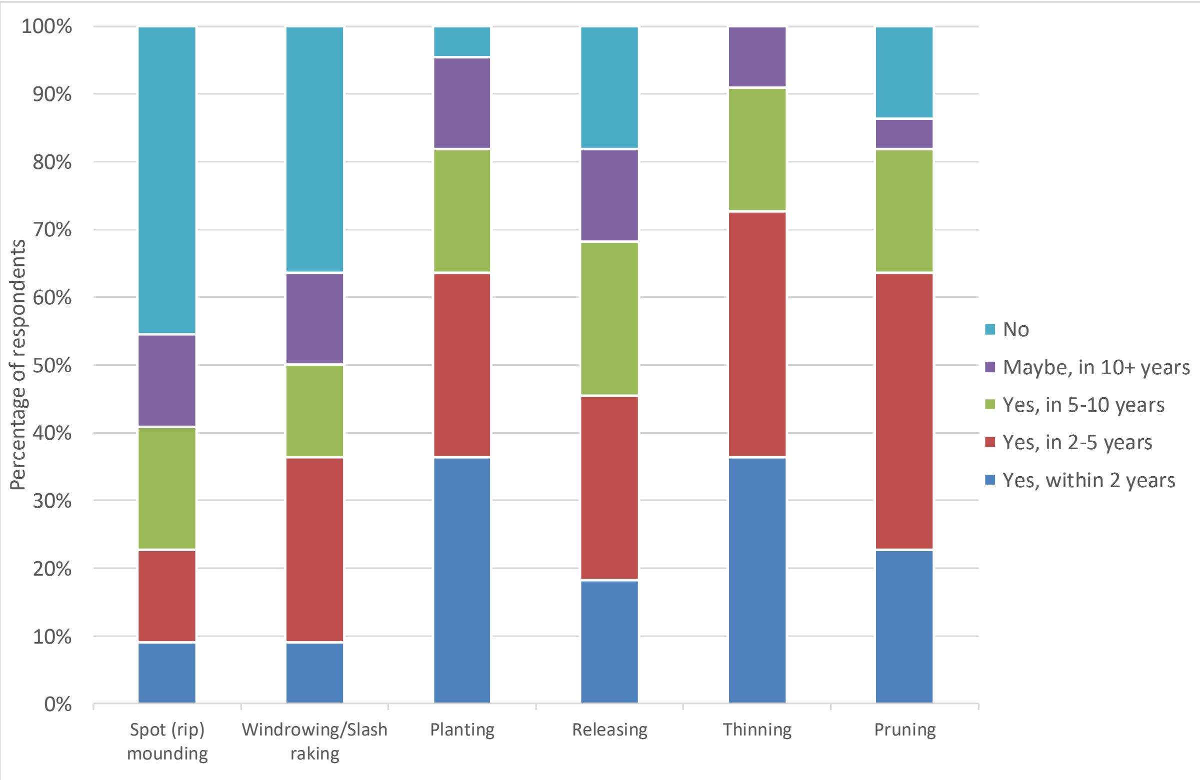


Figure 10. Should the New Zealand forest industry develop a significant research and/or development programme for mechanisation of silviculture?

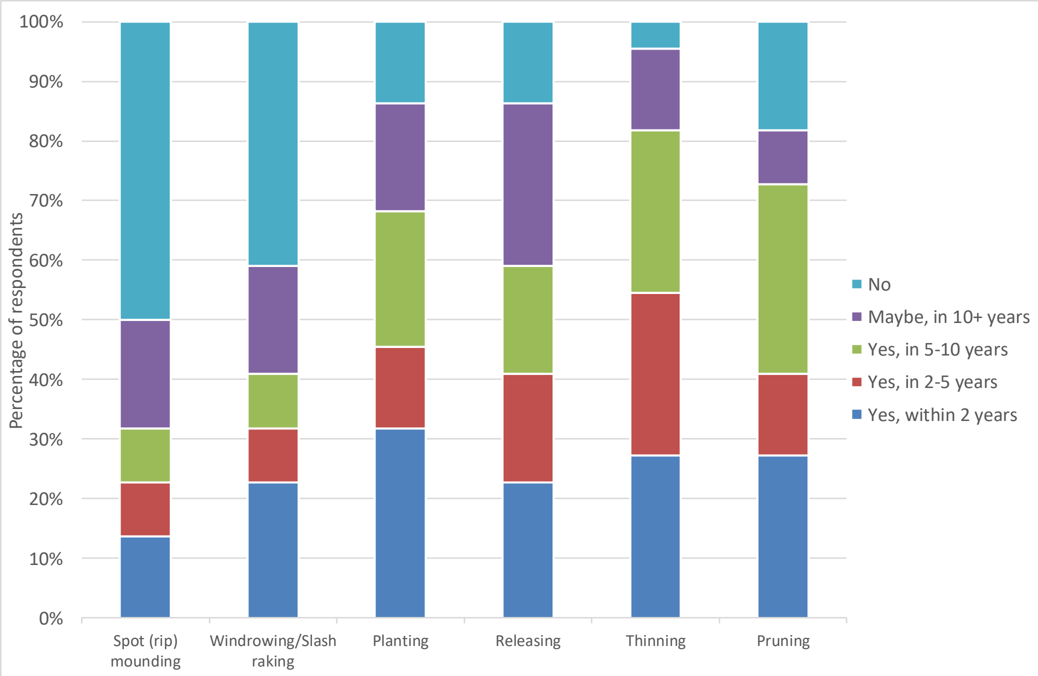


Figure 11. Should the New Zealand forest industry develop a significant research and/or development programme for automation/robotics for silviculture?

The most favoured method for funding and managing any research, as identified by survey respondents, is through a joint industry and government programme (Figure 12).

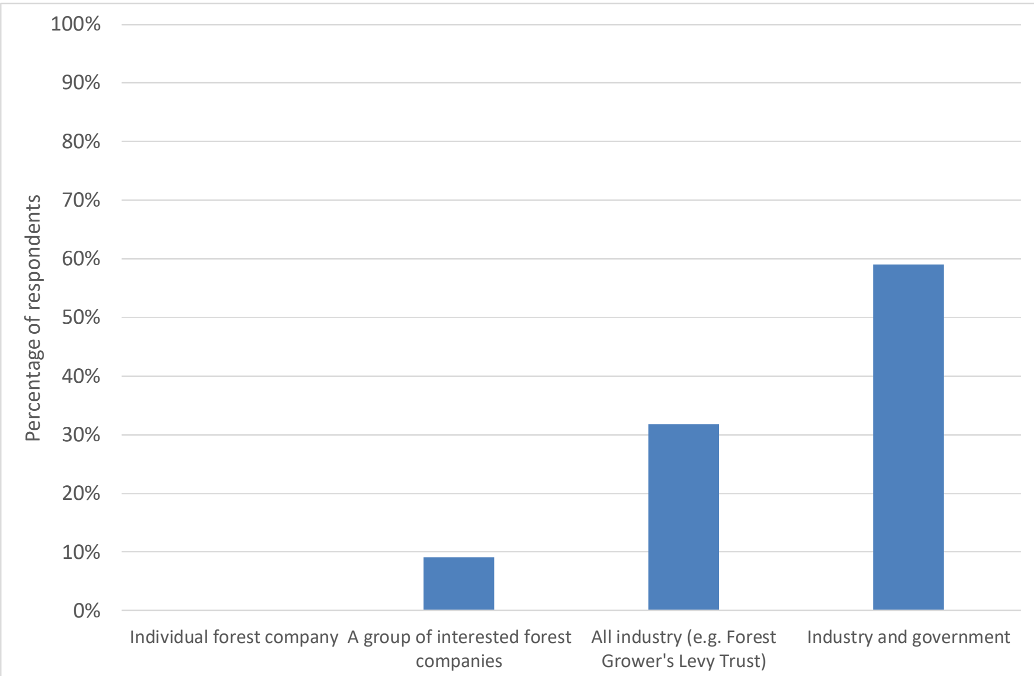


Figure 12. How should a research and development programme be funded and managed?

6.5 Opportunities and benefits of mechanisation & automation/ robotics

The most significant benefit of mechanisation and/or automation/robotics for the majority of survey respondents is the opportunity to reduce the health and safety risk for manual workers (Figure 13). The next 2 most significant benefits for respondents were providing a more attractive and skilled work environment to attract labour, and enabling multiple operations to occur with the one machine (e.g. planting, spot (rip) mounding and fertiliser applications).

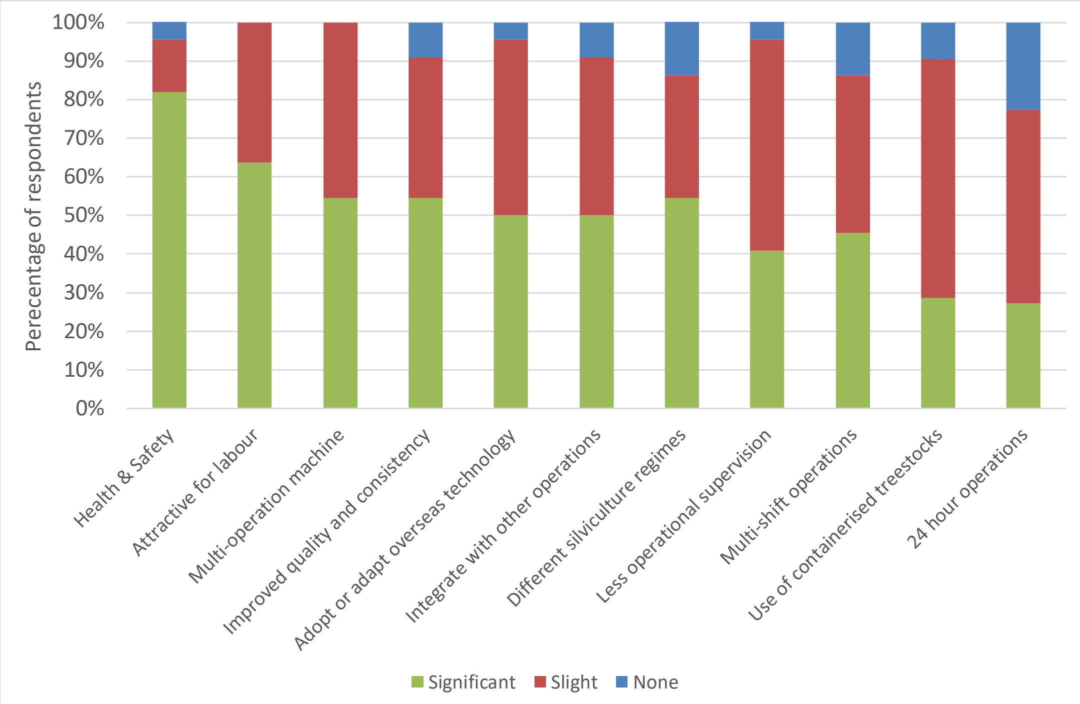


Figure 13. Opportunities and benefits of mechanisation and automation/robotics

6.6 Risk and challenges of mechanisation & automation/ robotics

The most significant challenges indicated by survey respondents for any mechanised or automated silviculture operation is working on steep and variable terrain, and dealing with physical impediments (e.g. slash) (Figure 14). The cost competitiveness of mechanised operations versus the manual alternative was deemed the third most significant challenge.

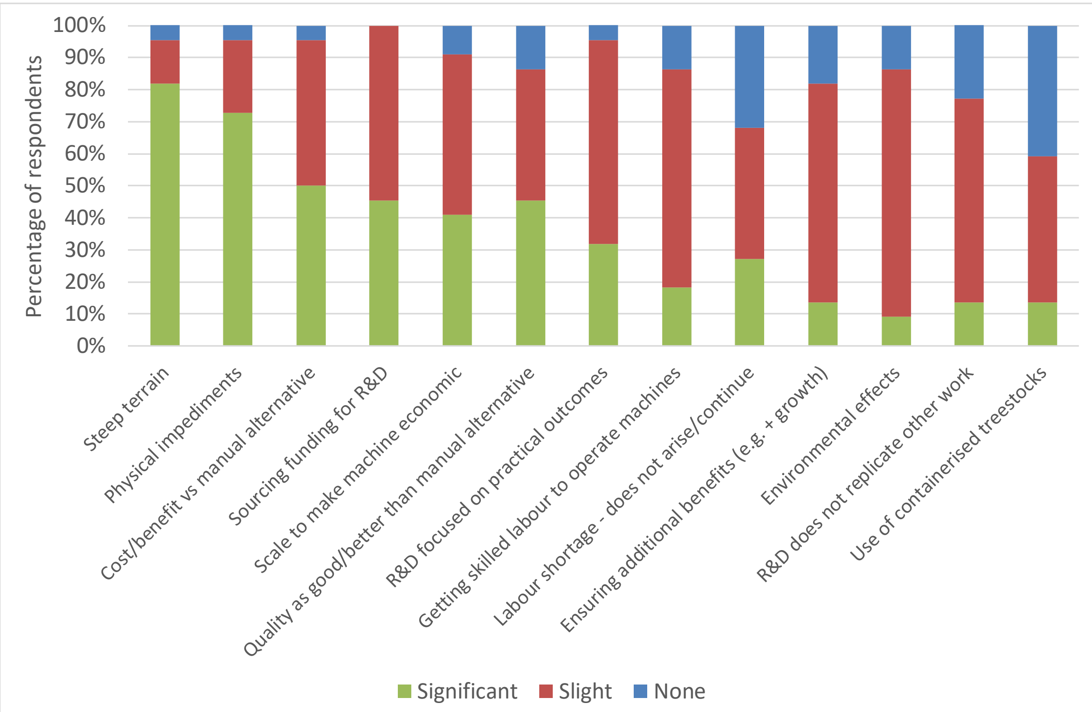


Figure 14. Risks and challenges of mechanisation and automation/robotics

7 Discussion

7.1 Current technologies

The review of current technologies showed that there does not seem to be any that can be readily adopted by the New Zealand forest industry for planting, waste thinning or pruning.

- Planting
  - The mechanised planting machines (planting head/s on an excavator) from Sweden (Bracke), Finland (M-Planter, Risutec), Canada (VHCP) and South Africa (Proplant 1) look to have potential, though they would likely require adaption to work effectively in New Zealand conditions. The ability of these machines (except the VHCP) to carry out other operations (e.g. cultivation, apply fertiliser & herbicide) could help make them cost-effective. However:
    - They are built to work on relatively gentle topography. In their current form they would have a limited market due to the lack of large contiguous areas in the current New Zealand plantation estate. The machines could be evaluated for tethering on steep slopes in New Zealand, but would require adaption. The cost-effectiveness of this would need to be evaluated.
    - The machines from Sweden, Finland and South Africa only deploy containerised treestocks, while the New Zealand forest industry currently uses predominantly bareroot treestocks.
    - The cultivation mechanism of these machines may require some re-configuring to be suitable for New Zealand soils and conditions (e.g. spot (rip) mounding).
- Waste thinning
  - There are currently some machines in operation in New Zealand but they are limited to relatively gentle topography. There does not seem to be any other suitable technologies available, particularly for steeper terrain.
- Pruning
  - Despite many prototypes and commercial machines, there does not seem to be any current technology that can be readily applied into New Zealand forest conditions.

7.2 Industry survey

The results of the industry survey show that there is interest in mechanisation of silviculture operations. For example:

- 43%, 59% and 45% of respondents, respectively, believed (further) development and/or implementation of mechanisation for planting, thinning and pruning was important for their organisation within the next 5 years.
- 64%, 73% and 64% of respondents, respectively, thought a significant research and development programme should be developed for planting, thinning and pruning within the next 5 years.

The most significant benefit of mechanised silviculture for the New Zealand forest industry, for the majority of survey respondents, is the opportunity to reduce the health and safety risk for manual workers. For example, mechanisation can reduce the exposure to hazards encountered in manual waste thinning, such as tree falling and operating of chainsaws. This is important, as, for example, over the 12 months until June 2018, there were at least 16 Lost Time Injuries (LTIs) associated with planting, thinning or pruning recorded in New Zealand's Forest Industry Safety Council's IRIS database.

However, one respondent mentioned that while exposure is reduced for manual workers, new hazards are introduced when working with machines. Another respondent also mentioned that 'there are definite potential health and safety gains from taking people off the hill, but you also "dumb down" the skill levels required. So when a situation arises when a machine cannot do the operation, we have increased the risk because the human element no longer has the skill or experience'.

The other main opportunities/benefits identified in the survey were that it could help attract labour, improve quality and consistency of operations, and potentially enable multiple operations to occur with the one machine.

The most significant challenges, as identified in the survey, are working on steep and variable terrain, as well as dealing with physical impediments. This is important as it is estimated that 55% of New Zealand's current harvest area (i.e. subsequent re-planting area) consists of steep terrain (>20 degrees slope), with this area expected to increase in the future. (Raymond 2010). Related to these challenges, is the cost competitiveness of mechanised operations versus the manual alternative, which was deemed the third most significant challenge.

7.3 Implementation of mechanised silviculture

The results of the review and survey indicate that the New Zealand forest industry has two options for implementing mechanisation of silviculture, particularly on steep terrain:

- Adapt some of the existing mechanised silviculture technologies to enable them to operate effectively and efficiently in New Zealand conditions.
- Investigate research and development of new technologies.

A number of factors need to be considered before progressing with these two options. Particularly as significant innovation and investment would be required to adapt or develop new mechanised silviculture technology, while ensuring it is operationally effective and cost competitive. This is particularly important in relation to overcoming the challenge of operating in steep and variable terrain in New Zealand.

7.3.1 Research scope, funding and capability

Scope

A mechanised silviculture research and development programme needs to determine whether it includes:

- All silviculture operations, or focuses on a few priorities (e.g. planting, waste thinning).
- Partial mechanisation
    - Labour productivity can be improved through mechanisation of hand tools (i.e. partial mechanisation). For example, mechanised pruning hand tools have been explored in New Zealand extensively in the past (FRI 1985). However, at the time nothing was found to be as effective or practical as a person with a pair of pruning loppers. More recently, the potential of battery powered chainsaws have been demonstrated for waste thinning.
- Nurseries
    - Nurseries were part of the previous industry mechanised silviculture research and development programme over 30 years ago. Since then, there has been no industry mechanised research and development programme for nurseries. In recent years, many of the technologies developed in nurseries have been instigated and funded by individual nurseries, with labour shortages driving many of the initiatives (e.g. Duke *et al.* 2016; Smaille 2018). It would seem timely and appropriate, considering the importance of nurseries to the forest value and

supply chain, to investigate the inclusion of nurseries in a mechanised silviculture research and development programme.

Funding

In the absence of an industry mechanised research and development programme, individual contractors and companies have been responsible for some of the recent mechanised innovations in silviculture (and nurseries) in New Zealand (e.g. waste thinning, see Section 4.1.4).

Individual contractors and companies are unlikely to be in a position to provide the level of investment required, as well willing to take on the risk, to provide multiple solutions to what could be considered an industry wide issue (i.e. planting, waste thinning and pruning, particularly on steep and variable terrain). Therefore, an industry funded research and development programme (with possible government co-funding) seems the most viable option for any future mechanised silviculture in New Zealand.

The requirements, cost and level of commitment (time wise) to establish and fund a New Zealand research programme will have to be investigated. A review of the status of current overseas research programmes including their level of success and funding requirements, can assist in this process. Potential sources of funding will have to be explored. For example, the Forest Growers Levy Trust and appropriate New Zealand government research funding (e.g. MBIE, MPI).

Capability

The New Zealand forest industry will need to partner with a range of research and development providers to ensure that it can obtain the appropriate capability. For example, Crown Research Institutes, Universities, private technology companies and potentially overseas organisations with existing expertise and recent or current experience in this area (if they are willing to participate).

7.3.2 Technology and effective outcomes

Over the last 50 years, there have been many examples where investment in mechanised silviculture did not result in technology that was operationally effective and/or cost competitive (i.e. was either never operationally deployed or only deployed for a period of time).

For example, the Swedish and Finnish research programmes have produced a range of planting machines over this period, many which never became fully operationalised. An example is the 'Silva Nova' planting machine from Sweden, which involved over 20 years of development and cost over 150 million SEK (equivalent to approximately to $NZ25 million) (Figure 15). While it was an impressive planting machine, and was used in production for a number of years, it ceased to be used in 2002 for a number of reasons. One of these was that the investment costs (circa 4.5 million SEK ($NZ770,000) per machine in 1995) could not be offset by productivity improvements versus manual planting (Ersson 2010).

Even the modern planting machines (i.e. Bracke, M-Planter, Risutec) are still not cost competitive versus manual planting in Sweden and Finland because of low productivity (see Section 4.1.1).

The New Zealand forest industry has also trialled, implemented or adapted a number of silviculture technologies, particularly those developed in North America and Europe between the 1960s and 1980s. While some of these technologies lasted longer than others in New Zealand (e.g. continuous ploughing planters), many didn't survive due to (for example):

- Cost-competiveness compared with the manual alternative (e.g. intermittent planters)
- Lack (or reduction) of suitable conditions (e.g. continuous ploughing planters, which required relatively gentle topography and cutover with little or no physical impediments)

- Machine's applicability to New Zealand conditions and radiata pine e.g. The 'Tree Monkey' pruner (see Section 4.1.3).

Many other mechanised forestry technologies have been developed which ultimately became redundant. For example, the 'Paterson Pruner' in Australia (see Section 4.1.3), the 'Reforester' planting machine in Canada (Larson *et al.* 1980; Ersson 2010), and the 'PlusJack', a walking harvester that had extensive (and expensive) development, which was never put into serial production. One (of 3 machines) now resides in a museum in Finland (Figure 15) (Avril 2012).

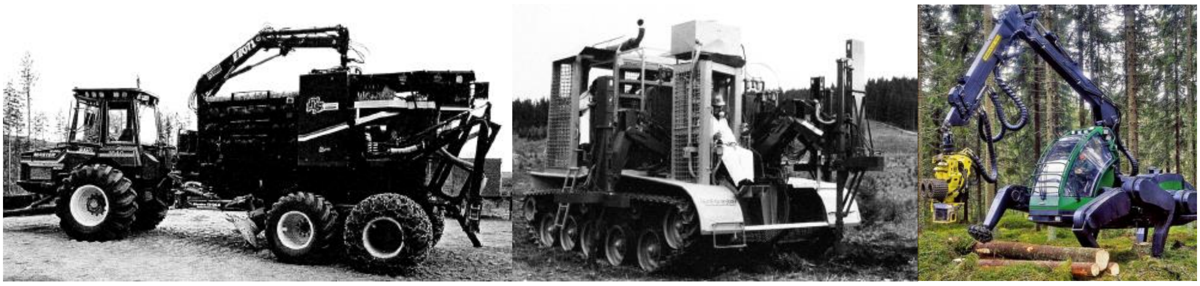


Figure 15. Examples of significant investment in technology that either was never, or is no longer, operationalised: The Silva Nova (left), ReForester prototype automatic injection planting machine (middle), and the PlusJack (walking harvester) (right).

7.3.3 Innovation

The modern planting machines (e.g. Bracke planter) are based on techniques developed over 30 years ago, while the modern pruning machines (YAMBIKO, Patas) are based off techniques similar to those developed over 50 years ago. Therefore, is there an innovative way to look at these operations? As one survey respondent mentioned 'we are dealing with small material (seedlings, branches). Do we need big machines?'

For example, Droneseed and Biocarbon engineering are using remote sensing and UAVs/drones for aerial seeding (see Section 4.1.1). Can this technology be developed to plant seedlings? This idea is not new. In the 1960s/1970s planting using tree bullets from aircraft was used in the US. The New Zealand forest industry also discussed the potential of this technology for steep topography in the early 1970s (Chavasse 1973).

7.3.4 Labour supply

Historically, mechanisation of silviculture has been pursued predominantly due to actual or feared labour shortages. For example, in Sweden since the 1960s, and in New Zealand between the 1960s and 1980s. However, these shortages have not continued or eventuated as silviculture has continued to be carried out by predominantly manual labour in these countries.

Therefore, a key risk for mechanisation is whether the current labour shortage in New Zealand will continue? For example, has there been a structural change in the labour market, so that labour will continue to be in short supply (e.g. urbanisation and/or people just don't want to do physically hard work)? If the labour shortage continues, what is the probability of labour costs increasing to a point where manual labour becomes uneconomic and/or mechanisation is attractive and/or cost-competitive?

Or will the supply of labour improve in the short to medium term (e.g. 3-10 years)? For example, through training, promotion of the industry and remuneration. Also will labour be able to be sourced through the New Zealand Government's Recognised Seasonal Employer (RSE) scheme or will macro-economic conditions change to increase the pool of available labour?

If mechanisation is pursued in New Zealand, then this will require a different skill set from manual labour operations. Therefore, will skilled, dedicated and motivated labour be able to be obtained to operate mechanised technology? Operator ability has been shown to have a significant effect on the productivity of mechanised technology. For example, up to a 65% difference in productivity between planting machine operators has been reported in Sweden and Finland (Rantala *et al.* 2010).

7.3.5 Social impact

In 2012, a survey of New Zealand forest industry personnel, showed that they were concerned that robotic introduction could lead to a reduction in employment. However, Parker (2012) suggested it may lead to changed roles, and a greater support service sector for the mechanised equipment. Mechanisation could also be seen at odds to the New Zealand Government's '1 Billion Tree' programme, which aims to create jobs in the regions (Te Uru Rakau 2018).

One respondent from this current study summarised '(We) need to keep moving with technology and labour issues may push us towards this sooner than later. The negative impacts on the social aspects of our society need to be measured and accounted for if this will put further existing workers out of work'.

Therefore, an assessment of the social impact of any potential mechanisation should be completed. For example, the effect on the availability of year round work for forestry workers, and the effect on seasonal workers.

8 Conclusion

A review of mechanised silviculture showed that there does not seem to be many options that could be readily adopted for planting, waste thinning or pruning in New Zealand.

The mechanised planting machines from Sweden, Finland, Canada, and South Africa look to have potential, but there are limitations in their current form (e.g. developed for relatively gentle topography; most of them use containerised treestocks). The ability of these machines to provide added value, such as fertilising, along with cultivation (with adaption), could make them cost-effective. The machines could be evaluated for tethering on steep slopes in New Zealand, but would require adaption.

For waste thinning, there are currently some machines in operation in New Zealand but they are limited to relatively gentle topography. There doesn't seem to be any other suitable technologies available, particularly for steeper terrain.

The survey of members of the New Zealand forest industry, showed that:

- Over 90% of respondents had some or significant issues obtaining suitable labour or contractors for planting and thinning. For pruning, over 70% of respondents had some or significant issues.
- Nearly 60% of respondents believed development and/or implementation of mechanisation for thinning was important for their organisation within the next 5 years. For planting and pruning, this figure was 45%.
- Over 63% of respondents, thought a significant mechanised research and development programme should be developed for either planting, thinning or pruning within the next 5 years.
- The main benefit of mechanised silviculture for the New Zealand forest industry, is that it could reduce the health and safety risk for workers, particularly on steep terrain.
- The most significant challenge for mechanised silviculture is operating machines on steep and variable terrain, as well as dealing with physical impediments.

If the New Zealand forest industry wants to implement mechanisation of silviculture operations, particularly on steep slopes, then it will have to:

- Adapt some of the existing mechanised silviculture technologies to enable them to operate effectively and efficiently in New Zealand conditions.
- Investigate research and development of new technologies.

Mechanised silviculture implementation requires a cautious and considered approach. Significant innovation and investment would be required to adapt or develop new mechanised silviculture technology, while ensuring it is operationally effective and cost competitive. This is particularly important in relation to overcoming the challenge of operating in steep and variable terrain in New Zealand. The scope, funding and capability of any research and development programme will need to be determined. The challenges and risks of technology development will also need to be evaluated, along with the effect of potential labour supply changes on the viability of mechanisation. The social impacts of mechanisation should also be assessed.

As stated in a Canadian paper published in 1975 (a statement which is still pertinent today): *'The key question is, are the benefits really there?.....While mechanised silviculture offers great hope as an answer to some of the problems of forest management, without careful consideration…….mechanisation of silviculture may end up as a graveyard for silviculture dollars'* (Scott 1975).

9 Recommendations

This study shows that there is interest from the forest industry for the implementation of mechanised silviculture, as well as a research and development programme for particularly planting, thinning and pruning. It is recommended to:

- Present the results of this study to the Forest Owners Association's (FOA) Forest Research Committee to initiate discussion and determine the desire and feasibility of a forest industry mechanised silviculture research and development programme.

If there is interest from the FOA's Forest Research Committee, then it is recommended that the following is considered:

- Determine the scope of a research and development programme. For example shall the programme include all or some silviculture operations, partial mechanisation or nursery operations?
- Determine the potential funding required for a research and development programme and sources of funding. For example, the Forest Growers Levy Trust and appropriate New Zealand government research funding (e.g. MBIE, MPI).
- Evaluate overseas research programmes, if possible, to determine the content and level of investment in their programmes.
- Identify research and development capabilities available in New Zealand and overseas to determine if a research programme could be adequately resourced.
- Critically evaluate the potential operational and cost effectiveness of any proposed technology and the estimated development cost.
- Review other technologies, in and outside the forest industry, to see if there are innovative ways of carrying out silviculture operations.
- Evaluate the future labour demand and supply and the probability of labour costs increasing to a point where manual labour becomes uneconomic and/or mechanisation is attractive and/or cost-competitive.
- Evaluate the potential social impacts of mechanisation.

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11 References

Advaligno 2018. Accessed 3 November 2018. https://www.advaligno.com/en/advaligno-eng/

Anon. 1966. New Zealand National Film Unit. Film information sheet No. 271.

Appavoo, I, Marionneau, A., Berducat, M., Merckx, B., Olivier N. & Cotton, L. 2016. A high yield automatic tree planting machine. 5th International Conference on Machine Control Guidance MCG 2016, Oct 2016, Vichy, France. Facing complex outdoor challenges by interdisciplinary research, 5 p., 2016.

Arauco. 2015. Plantadora Mecanizada. Accessed 5 September 2018. https://www.youtube.com/watch?v=4aHwnSNCT6k

Avril, J.M. 2012. Museum of Lusto in Finland: Forest Machinery. Accessed 19 October 2018. http://www.unusuallocomotion.com/pages/museums/museum-of-lusto-in-finland-forest-machinery.html

Berry, A. 2015. Bracke trials. Forestry Journal. 7/15. Accessed 23 September 2018. https://www.forestryjournal.co.uk/media/uploads/cat-247/bracke-planter-forestry-journal-july-2015.pdf

Black, R. J. 1977. Mechanisation of production thinning. A dissertation for the degree of B(For)Sc. University of Canterbury.

Bracke. 2014. A new Bracke P11.a planter to Scotland. Accessed 23 September 2018. http://www.brackeforest.com/news/products/193-new-bracke-p11-a-planter-to-scotland

Campbell, I., Cobane, E., Giovacchini, R., & Murray, T. 2013. Design and construction of a tree-climbing robot. Project report. Worcester Polytechnic Institute.

Chandler, K.C. 1976. Extraction thinning operations in young radiata pine at Kaingaroa forest. New Zealand Journal of Forestry Science 6(2): 193-199

Chavasse, C.G.R. 1973. Mechanization of nursery production, forest establishment and tending in New Zealand. FRI symposium No. 13

Chavasse, C.G.R. 1981. Forest nursery and establishment practice in New Zealand. FRI symposium No. 22

Choudhry, H., & O'Kelly, G. 2018. Precision forestry: A revolution in the woods. McKinsey & Company.

Coates, P. 1980. The development of an intermittent planting machine. What's New in Forest Research No. 81, Forest Research Institute.

CSIRO 1977. CSIRO Twenty-ninth annual report 1976/77. Commonwealth Scientific and Industrial Research Organisation, Australia

Da Costa, D. 2017. Modernising silviculture. Mondi. Accessed 7 June 2018. www.cmogroup.net/focus-presentations-2017/silviculture/

Duke, M., McGuinness, B., & Kunnemeyer, R. 2016. Development of mechatronic dibbling machine for improving the quality of forestry seedlings. Acta Technica Corviniensis, IX(3), 51–56.

Ersson, B.T. 2010. Possible concepts for mechanised tree planting in Southern Sweden - An introductory essay on forest technology.

Ersson, B.T. 2014. Concepts for mechanised tree planting in Southern Sweden. Doctoral Thesis. Swedish University of Agricultural Sciences.

Ersson, B.T., Laine, T., and Saksa, T. 2018. Mechanised tree planting in Sweden and Finland: Current state and key factors for future growth. Forests 9(7):370

FOA. 2018a. Facts and Figures 2016/17. New Zealand plantation forest industry. New Zealand Forest Owners Association (FOA).

FOA. 2018b. Plantation forestry labour and skills survey summary. June 2018. New Zealand Forest Owners Association (FOA).

FP Innovations 2017. Forest Operations 2017–2018 collaborative research program April 2017

FRI. 1985. Field day on manual and mechanical pruning equipment. Lectures and demonstrations. 2 July 1985. Silviculture Equipment Research Group. Forest Research Institute.

Grayburn, A.W. 1976. Kinleith thinning operations of N.Z. Forest Products Limited. New Zealand Journal of Forestry Science 6(2): 214-220

Gui, P., Tang, L., & Mukhopadhyay, S. 2017. A novel robotic tree climbing mechanism with anti-falling functionality for tree pruning. Journal of Mechanisms and Robotics 10(1)

Hall, P. 1995. A comparison of continuous ripping–mounding with spot ripping-mounding. Logging Industry Research Organisation 20(5)

Hallonborg, U. 1996. Limiting factors in mechanised tree-planting. Journal of Forest Engineering 7(2): 35-41

Hallongren, H., Laine, T., Rantala, J., Saarinen, V., Strandstrom, M., Hamalainen, J., & Poikela, A. 2014. Competitiveness of mechanised planting in Finland. Scandinavian Journal of Forest Research, DOI: 10.1080/02827581.2014.881542

HFM NZ. 2015. Winch assisted harvesting brings safety & environmental benefits. Hancock Forest Views. Issue 13, July 2015. Hancock Forest Management. Accessed 10 October 2018. http://hfm.nz/wp-content/uploads/sites/6/2017/08/Hancock-Forest-Views-Issue-13.pdf

IOTA Technologies. 2015. 'Tree Rover'. Accessed 9 September 2018. https://iotatechnologies.wordpress.com/

Ishigure, Y., Kachi, H., Mori, Y., & Kawasaki, H. 2010. Pruning machine with a mechanism for preventing branch bite. FORMEC 2010. Forest Engineering: Meeting the Needs of the Society and the Environment July 11 – 14, 2010, Padova – Italy

Ishigure, Y., Hirai, K., & Kawasaki, H. 2013. A pruning robot with a power-saving chainsaw drive. Presented at IEEE International Conference on Mechatronics and Automations 2013

Keane, M. 2006. Container plants and mechanised planting – The way forward? In: Plant quality. A key to success in forest establishment. Eds: MacLennan, L., & Fennessy, J.

Kerruish, C. M. 1976. Thinning techniques applicable to *Pinus radiata* plantations. New Zealand Journal of Forestry Science 6(2): 200-213

Larson, J., & Hall, R. 1980. Equipment for reforestation and timber stand improvement. Forest Service Equipment Development Center. Fort Missoula. Missoula, Montana.

Ledgard, N., & Davis, M. 1994. Rangeland tree establishment – machine planting and direct seeding. N.Z. Forestry.

Levack, H. 1973. The Kaingaroa air sowing era 1960-71. New Zealand Journal of Forestry 18(1): 104-108

LogInFor, 2018. 'Equipos'. Accessed 5 September 2018. http://loginfor.cl/index.php/equipos

Maggard, A., and Barlow, B. 2018. Costs and trends of Southern forestry practices, 2016. The Alabama Cooperative Extension System.

Manktelow, E. 1967. Machine planting in Tarawera forest. New Zealand Journal of Forestry 12(2): 182-188

Metsateho 2018. Vision: Efficient wood supply 2025. Accessed 20 July 2018. http://www.metsateho.fi/briefly-in-english/

MPI. 2017. Situation and outlook for primary industries. December 2017. Ministry of Primary Industries.

MPI. 2018. Provisional estimates of treestock sales and forest planting in 2017. Ministry of Primary Industries.

Novelquip. 2017. Proplant1. Mechanical single planting head. Accessed 8 October 2018. http://www.forestry.co.za/uploads/File/Industry%20News/2018/PropPlant%201%20Brochure%20-%2020170818.pdf

Parker, R., Bayne, K., and Clinton, P. W. 2016. Robotics in forestry. New Zealand Journal of Forestry 60 (4): 8-14

Poyry 2014. Reinventing plantation forestry. Poyry point of view – November 2014.

Rantala, J., and Laine, T. 2010. Productivity of the M-Planter tree-planting device in practice. Silva Fennica 44(5): 859–869.

Raymond, K. 2010. 'Innovative harvesting solutions'. A step change harvesting research programme. New Zealand Journal of Forestry 55(3): 4-9

Restall, A. A. 1964. Sand dune reclamation on Woodhill forest. New Zealand Journal of Forestry 9 (2): 154-161

Rigby, B. 1999. A history of the Aupouri State forest. A report commissioned by the Waitangi Tribunal.

Roothman, D. 2014. Integrated mechanisation. Focus on forest engineering conference. November 2014.

Scott, J.D. 1975. Recent developments in mechanised planting and the future for Ontario, pp 70-85. In: Mechanisation of silviculture in Northern Ontario. Canadian Forestry Service.

Smaille, S. 2018. Review of needs and opportunities for automation in tree nurseries. Forest Growers Research.

Steenkamp, J. 2018. Forestry in Brazil. SA Forestry Online. Accessed 3 September 2018. https://saforestryonline.co.za/articles/forestry-in-brazil/

Stjernberg, E. 2004. The Bracke Planter: a Brief Study in Western Canada. Advantage 5, No 18, FERIC. *In:* Clark, G. 2009. Cost analysis of a forest seedling planting machine: A case study for BC. University of Northern British Columbia.

Strandstrom, M. 2016. Mechanised young stand management in Finland. In Proceedings of the OSCAR Workshop: Mechanised and efficient silviculture November 25-26, 2015 Natural Resources Institute Finland, Suonenjoki Research Unit, Finland Timo Saksa (Ed.): 7-9

Te Uru Rakau. 2018. One billion trees – Reclaiming our forest heritage together. March 2018. Accessed 21 October 2018. https://www.mpi.govt.nz/funding-and-programmes/forestry/planting-one-billion-trees/

Tustin, J. R., Terlesk, C. J., & Fraser, T. 1976. Thinning in New Zealand radiata pine plantations. Future practices and research needs. New Zealand Journal of Forestry Science 6(2): 333-349

Uebergang, C. 2010. SAMUEL. Accessed 8 October 2018. https://www.youtube.com/watch?v=oMuV129rb_o

United States Patent. 1988. Tree Pruner. Patent Number: 4,781,228

University of Canterbury. 2016. UC researchers awarded $5 million for smart ideas. Accessed 15 September 2018. https://www.canterbury.ac.nz/news/2016/uc-researchers-awarded-5-million-for-smart-ideas.html

Van Horlick, T. C. 2016. Van Horlick's cultivator planter (VHCP). Accessed 20 August 2018. http://www.vhmulcher.com/wp-content/uploads/2016/11/brochure.pdf

Van Horlick, T. C. 2018. New cultivation and planting forest machine, "VHCP". Accessed 20 August 2018. https://www.linkedin.com/pulse/new-cultivation-planting-forest-machine-vhcp-tim-c-van-horlick?articleId=6399318226895011840#comments-6399318226895011840&trk=prof-post

Wilkes, P. & Bren, L. J. 1986. Radiata pine pruning technology. Australian Forestry 49(3): 172-180

Young, M. 2002. Clouston's tree shaver. Blachly-Lane: 4-5

Photos

Figure 1.
- Double unit Lowther planters hauled by a crawler tractor, Tarawera forest, 1960s (Manktelow 1967).
- Rear view of similar planting machine in USA (author)

Figure 2.
- The FRI intermittent tree planter (FRIIP) developed in the late 1970s (Coates 1980).

Figure 3.
- Modern planting heads on excavators.
  - The Bracke tree planter from Sweden (www.brackeforest.com - Accessed 10 October 2018)
  - M-Planter from Finland (www.m-planter.fi/en/Company.html - Accessed 10 October 2018)

Figure 4.
- The Novelquip 'Proplant 1' from South Africa and the 'Van Horlick's Cultivator Planter' from Canada.
  - Novelquip Proplant 1 (Novelquip 2017)
  - 'Van Horlick's Cultivator Planter' (Van Horlick 2016)

Figure 5.
- Mechanised waste thinning machines
  - Developed in Australia in early 1970s (Kerruish 1976).
  - Currently in use in New Zealand (Hancock Forest Management (NZ) Ltd)

Figure 6.
- Mechanised pruning machines.
  - The 'YAMABIKO' (Campbell *et al.* 2013)
  - The 'Patas' (Advaligno 2018).
  - The 'Paterson Pruner' (Wilkes and Bren 1986).

Figure 15.
- Examples of significant investment in technology that either was never, or is no longer, operationalised.
  - The Silva Nova (Ersson 2010)
  - ReForester prototype automatic injection planting machine (Ersson 2010 (originally from Walters and Silversides 1979)).
  - The PlusJack (walking harvester) (Accessed 19 October 2018 www.theoldrobots.com/Walking-Robot2.html)

12 Appendices

Appendix 1 – Survey questions

Question 1. Do you have mechanisation occurring in the following silviculture operations? If so, what % of the operation's annual programme is mechanised?

	0%	1-25%	25-50%	50-75%	75-100%	N/A
Spot (rip) mounding						
Windrowing/Slash raking						
Planting						
Releasing						
Thinning						
Pruning						
Other (please specify)						

Question 2. Is obtaining and retaining suitable contractors/labour a current issue for your silviculture operations?

	No Issues	Some Issues	Significant Issues	N/A
Spot (rip) mounding				
Windrowing/Slash raking				
Planting				
Releasing				
Thinning				
Pruning				
Other (please specify)				

Question 3. Is the (further) development and/or implementation of mechanised silviculture important for your organisation?

	Yes, within 2 years	Yes, in 2-5 years	Likely, in 5-10 years	Maybe, 10 years+	Not Important
Spot (rip) mounding					
Windrowing/Slash raking					
Planting					
Releasing					
Thinning					
Pruning					
Other (please specify)					

Question 4. Is the development and/or implementation of automation/robotics for silviculture important for your organisation?

	Yes, within 2 years	Yes, in 2-5 years	Likely, in 5-10 years	Maybe, 10 years+	Not Important
Spot (rip) mounding					
Windrowing/Slash raking					
Planting					
Releasing					
Thinning					
Pruning					
Other (please specify)					

Question 5. Should the NZ forest industry develop a significant research and/or development programme for mechanisation of silviculture?

	Yes, within 2 years	Yes, in 2-5 years	Yes, in 5-10 years	Maybe, in 10+ years	No
Spot (rip) mounding					
Windrowing/Slash raking					
Planting					
Releasing					
Thinning					
Pruning					
Other (please specify)					

Question 6. Should the NZ forest industry develop a significant research and/or development programme for automation/robotics for silviculture?

	Yes, within 2 years	Yes, in 2-5 years	Yes, in 5-10 years	Maybe, in 10+ years	No
Spot (rip) mounding					
Windrowing/Slash raking					
Planting					
Releasing					
Thinning					
Pruning					
Other (please specify)					

Question 7. How should any research and development programme be funded and managed (tick one)?

Individual forest company	
A group of interested forest companies	
All industry (e.g. Forest Grower's Levy Trust)	
Industry and government	
Research and development programme not required	
Other (please specify)	

Question 8. What are some of the key opportunities and benefits of developing and/or implementing mechanisation/automation/robotics? (Select one option: No opportunity/benefit; Slight opportunity/benefit; Significant opportunity/benefit)

- Health and safety (e.g. less exposure to significant hazards)
- Provides a more attractive and skilled work environment to attract labour (mechanisation)?
- Enabling multiple operations to occur with the one machine (e.g. planting and slash raking or spot mounding; planting and fertilising/insecticide/herbicide application; thinning and pruning).
- Improved quality and consistency (e.g. regular planting spacing using GPS) and/or tree growth
- Opportunity to adopt or adapt what has been already produced overseas (e.g. mechanised planters from Scandinavia) or in other industries.
- Integration with other operations (e.g. GPS record of all planting spots – can utilise for future operations) or with other technologies (e.g. UAVs – e.g. spot/band spraying based off planting GPS records).
- Implementation of different silviculture regimes by utilising the benefits of mechanisation/automation/robotics
- Less operational supervision required (e.g. real-time data updates, GPS locations of planting).
- Multi-shift mechanised operations (e.g. 2 shifts per day)
- Use of containerised planting systems with mechanised planting (e.g. longer planting season)
- 24 hour operations (automation/robotics)
- Other (1) (please specify)
- Other (2) (please specify)
- Other (3) (please specify)

Question 9. What do you see as some of the key challenges and risks of developing and/or implementing mechanisation/automation/robotics for silviculture in NZ?

- Operating in steep areas
- Operating in areas with high incidence of physical impediments e.g. slash, stumps, vegetation
- Machine cannot operate economically on a per hectare basis compared with the manual alternative
- Sourcing funding for research and development
- Machine/s cannot operate across enough area to make them economic (e.g. having enough scale to provide continuous work throughout the year)
- Ensuring that the quality of the operation is as good if not better than the manual alternative
- Ensuring that any investment in R&D is focused on producing practical outcomes.
- Getting skilled and quality labour to operate mechanised machines
- Labour shortage for manual silviculture operations does not become a significant issue
- Ensuring that there is additional benefits from mechanisation e.g. an improvement in quality and/or tree growth
- Environmental effects (e.g. compaction from machines)
- Ensuring that R&D does not replicate what has been done overseas
- Use of containerised planting systems with mechanised planting
- Other (1) (please specify)
- Other (2) (please specify)
- Other (3) (please specify)

Question 10. Do you know about any significant recent research into, or the adoption of, mechanisation/automation/robotics for forest silviculture in other countries (that you are willing to share)? And/or - Do you have any other views on the role that mechanisation or automation/robotics of silviculture has in the NZ forest industry?