# Resources

# *A review of current mechanical & robotic tree pruning equipment*

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Forest & Wood Products Australia

# A review of current mechanical & robotic tree pruning equipment

Prepared for

**Forest & Wood Products Australia**

by

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# Executive Summary

This review report provides an overview of current and emerging mechanical and robotic tree pruning equipment for use in plantation forest management. Recently, increased interest has been expressed by plantation forest managers in the potential economic use of mechanical or robotic tree pruning systems to do pruning either for bushfire risk management or improved resource value. The RD&E sector has expressed interest in both importing and testing specific commercial solutions, or the design and development of specific solutions for Australia. However, before committing an RD&E investment in this space, an independent international review of the state of the technology in use, or development for mechanical or robotic tree pruning is requested. The technical review is supported by a literature review on the development and application of mechanical and robotic tree pruning.

From the review it is apparent that improvements in technologies have been made since the initial robotic pruning equipment introduced in the '60s, however, the range of equipment is very limited. From the earliest robotic pruning systems such as the Sachs Tree Monkey, several issues have been identified, in particular, those relating to the weight of the equipment, agility and range of application, and the capacity to move along whorls or to cut large branches (>5 cm in diameter) on stems. Many of these issues are still present in more modern equipment such as the Patas.

However, this report notes a trend in upcoming improvements and investments such as those in the Patas, UAV-based pruning, and futuristic Stick Insect robots. Their capacity to be operated remotely increases work health and safety. UAV's and the Stick Insect need further development to become operational and commercial, however, their remote control and access to rugged terrain are attractive attributes.

# Table of Contents

# Introduction

On behalf of Forest & Wood Products Australia (FWPA) the forest operations group at the Forest Research Institute (FRI) carried out a desktop review and technology scan with its international research partners to get a view of what mechanical or robotic pruning technology is in use or under development within their country or region.

Where mechanical or robotic tree pruning systems were identified as either commercially used or under applied research, contact was made with commercial users, researchers and/or the manufacturers of the equipment, where possible. A standard set of information was collected on each identified system of interest around the machine technical description, capabilities (i.e. stem size, height, branch size, tree age, tree species, etc.), and performance (i.e. trees per hour, ha per day, the impact of gradient, etc.). Each piece of equipment was compared for technology readiness, capital costs, operating costs, range of application, and general strengths and weaknesses for potential application in Australia.

This review report is focused on current international state of the art mechanical and robotic tree pruning equipment used in plantation forest management and includes a review of the current academic literature (published in the last five years) and current industry journals (last two years). In particular, the review explored deployable automated pruning solutions for Australian forest management systems. Overlap between findings in the literature and technology review serves to improve the reporting detail on identified technologies. Where information is only available in the literature, technologies were noted as either emerging or failed options.

# Literature Review

The rationale behind tree pruning in Australian forest management systems is to reduce bushfire risk and improve resource value. Research shows that pruning treatments can significantly change the fuel structure in young plantations (Bartlett, 2012; Cruz et al., 2017). Ladder and canopy fuels are relocated to the surface layer, forming a disconnect for vertical fire spread. The vertical discontinuity effect is long-lasting and outweighs the short-lived effect of increased surface fuels. When applied in fuel management zones, the analysis also indicated a succession of treatments can transform a highly flammable zone into a low flammable zone early in the rotation (Cruz et al., 2017). The size and quantity of this pruning slash are of some importance for several years until they decay. Burning of heavier slash close to fire-sensitive species, especially, Radiata pine (*Pinus radiata*) trees, could cause significant damage to the lower trunk (Bartlett, 2012). Recently, a study in the Lower Eyre Peninsula found that 70% of residents, landowners and fire authorities have the perception that pruning trees as a mitigation strategy reduced the risk of fires (Weber et al., 2019).

The effect of pruning has been studied around the world on many plantation species. A study on Radiata and Maritime pine (*Pinus pinaster*) in western Spain found decreased diameter growth with increasing pruning intensity, measured 5 years after pruning (Hevia et al., 2016). In Australian studies, similar trends are found on *Eucalyptus globulus* sites with decreased diameter growth apparent one year after pruning, however, the authors noted that the effect was more apparent on low-quality sites (Alcorn et al., 2013; Forrester and Baker, 2012). Lift pruning to 6.5 m height on the sawlog retained at least 70% of the live crown and only removed shaded and inefficient foliage (Forrester and Baker, 2012). Other research on Eucalypt plantations suggested that pruning of high-quality plantations should start near 2-3 years of age to restrict knotty cores in logs and limit the development of large branches. The proportion of leaves removed at that stage is insufficient to reduce tree growth following pruning of the lower 5-6 m (West and Smith, 2020). Overall, the trade-off between high-quality reduced-diameter pruned butt logs and high-volume (diameter) higher-defects in unpruned systems needs to be considered, especially in Radiata pine (Burdon and Moore, 2018).

# Technology Review

In this report, little attention was given to mechanised hand tools and platforms or cherry pickers. Much of these have been described in a report prepared for FWPA by R. McWilliam (McWilliam, 2004). That report outlines techniques and tools for low pruning in Australian plantations and includes an overview of manual pruning equipment (secateurs, loppers and saws), handheld mechanised pruning equipment (chainsaw, circular saw and shears) and emphasises the handheld battery-powered pruning tool "Electrocoup" (McWilliam, 2004). More recently a new pruning and tending system for young stands of Douglas fir (*Pseudotsuga menziesii*) in Germany was described as a handheld mechanised pruning system (Schönauer et al., 2021). The system was found more productive compared to the manual chainsaw operation, the physical workload was reduced, and overall costs were reduced by 6%.

Sutton (1971) suggested that the objectives for mechanised pruning should be to perform a pruning operation comparable in quality, or an improvement on, current manual methods; to reduce physical work effort; to increase productivity above present manual methods; and to reduce costs. Lack of suitable labour has also been noted as a reason for ongoing interest in mechanised pruning (Baker, 2018).

Some of the semi-automated pruners and self-mobile mechanised pruning solutions are described by Baker (2018) and McWilliam (2004). This review report will reiterate some of the more automated solutions, however, it recognises that most of these solutions provide limited novelty and date back to the '70s such as the Paterson Pruner (Wilkes and Bren, 1986) or even the '60s such as the Sachs Tree Monkey (Cremer and De Vries, 1969).

## 1. Paterson Pruner

The Paterson Pruner (**Figure 1**) is described as full mechanisation with a mechanised pruner attached to a machine. It is the first known attempt of a self-mobilised mechanical pruning system that was developed by the CSIRO Division of Forest Research in Australia in the mid-1970s (Wilkes and Bren, 1986). Six chisel knives are clamped to the stem by hydraulics and a boom that aligns with the tree moves the knives up and down the stem. The major problem with the machine is excessive stem damage as the knives move up and down (Wilkes and Bren, 1986). It is suggested, however, that using low-pressure pneumatic tyres to align the boom with the tree would reduce the damage. The system is also regarded to be operator-safe, however, it was not developed beyond the prototype stage (McRobert, 2020).

**Figure 1: CSIRO Paterson Pruner (Wilkes and Bren, 1986).**

Another variant of the pruner is described as:

- The Systematic Augmented Mechanical Under-Excision Limb (SAMUEL) pruner, presented by the Aust-Pacific Forest Management Pty Ltd., and demonstrated on *Araucaria cunninghamii* (Uebergang, 2010).

## 2. Sachs Tree Monkey

The Sachs Tree Monkey was developed in Germany and was introduced to Australia in 1967 to test its performance. Even though the equipment was quite novel at the time, the performance was doubtful as a very optimistic trial scenario was used, the ergonomics of handling the machine were unfriendly and the reduced cost of machine pruning was rarely justified. Pruning performance was unsatisfactory for trees with a bent stem, stem cones, or thick (>5cm) or steeply angled branches. The bottom 1.5m of each stem also needed to be manually cleared before the pruner could be attached. A list of modifications was suggested as follows (Cremer and De Vries, 1969):

1. Automatic stopping of the engine when pruner returns to the ground;
2. Improved power to weight ratio to reduce stalling and increase speed;
3. Automated governor to vary power output as required;
4. Reduce weight so it can be handled by a single person;

5. A device to throw gear into neutral when stalling the engine;
6. Improved wheel grip and use of pneumatic tyres;
7. Mounting engine so that sawblade follows the contour of the trunk more closely;
8. Lengthening the wheelbase to reduce tilt of sawblade on curved stems;
9. Increase power to cope with large branches (>50 mm) and cones;
10. Modify the frame to embrace large butts and whorls.

Similar findings were described in a New Zealand trial, even after modifications to the original equipment (**Figure 2**) were performed by two Japanese companies, Sumitomo Corporation and Kioritz (Baker, 2018; Wilkes and Bren, 1986).

**Figure 2: Example of Sachs Tree Monkey or similar (http://www.chainsawcollectors.se/phpbb3/viewtopic.php?t=21220).**

## 3. Prototypes

Several machines are currently under a "prototype" or "no patent" label, all of which a similar to the Sachs Tree Monkey as described above.

- The Clouston Tree Shaver, developed by John Clouston is currently in its second prototype and has received a patent on the basic design. The first prototype was created in 1997. It is suggested it can prune trees up to 8 meters above the ground and return in 2 minutes to the ground. It is therefore considerably slower than most other automated equipment which makes it less suitable for densely planted plantations and more suitable for open silvopastoral stands for example. The current design can prune trees between 3.5 and 11.5 inches (8.9 – 29.2 cm), and one gas tank can prune up to 30 trees up to 8 m. Two people are required to lift and move the 45 kg piece of equipment. The system does not work well on curved stems, forks and trees with large whorls at branch nodes like Radiata pine (Merwin, 2014),

- WOODY, developed in the Sugano Lab at Waseda University in Japan in 2003, is now in its third-generation prototype. The robot has a tree-climbing and tree-pruning component to it. This robot has two sets of climbing arms that in an alternating way move vertically up the tree, similar to an inchworm. The highest pair of arms is equipped with a chainsaw to cut branches (Sugano Laboratory, 2012).

Other robots such as the Kawasaki, Fauroux and Morillon, Uncle Sam, RiSE, TREPA, DIGbot or Treebot are examples of tree-climbing robots, however, none have been described with any pruning capacity. Often these robots are used for surveillance, retrieval and inspection of trees, however, they are often not flexible or robust enough to do tree pruning work (Gui et al., 2018).

## 4. Yamabiko

Seirei Industry Co.'s AB232R Automatic Pruning Machine 'Yamabiko' (**Figure 3**) is described as the only commercial tree climbing robot that spirals up a tree with fixed angle mounted wheels (Gui et al., 2018). The gripping force is created from pre-loaded springs, which limits the diameter of the tree that it can operate on (7 - 23 cm) (Campbell et al., 2013). However, it was not used extensively because of its weight (32.8 kg) and branch bite (saw jamming during cutting) problems (Gui et al., 2015). Branch bite may require operators to climb the tree to free the saw (Ishigure et al. 2010). As such the issues arising are similar to those described in the Sachs Tree Monkey.

**Figure 3: Yamabiko pruning system (Campbell et al., 2013).**

## 5. Patas

The mechanical pruner 'Patas' was developed by advaligno from Germany in 2017 (advaligno GmbH, 2018). The machine (**Figure 4**) was developed for the careful delimbing of pines, firs, spruces and eucalypts. Pruning rates vary between 30 and 50 trees per hour in European native conifer stands and 80 to100 trees per hour in plantations. Pruning heights up to 15 m can be reached in about 8-10 seconds before the pruner comes rapidly coming back down and automatically stops at ground level (4 m/s). Rubber-driven belts are hydraulically rolled over the bark with minimum pressure and maximum grip, while five knives separate branches from the stem. Pneumatic pressure is applied to press the knives against the trunk with pressures between 3.0 and 8.0 bar (advaligno GmbH, 2018). The machine has been tested on *Pinus elliottii* and *Pinus taeda* stands in Brazil and suggests that the rougher the bark the better the Patas works.

Unlike most of the previously described pruners, the Patas consists of two separate modules (**Figure 5**); a drive unit that connects to standard small tractors or harvesters and the cutting unit as described above. The cutting unit is attached to the drive unit when moving over a longer distance. Both units are connected with a supply hose of 25 m with a rubberized exterior (longer hoses are available). Both units are patented (advaligno GmbH, 2018).

**Figure 4: Patas cutting unit (advaligno GmbH, 2018).**

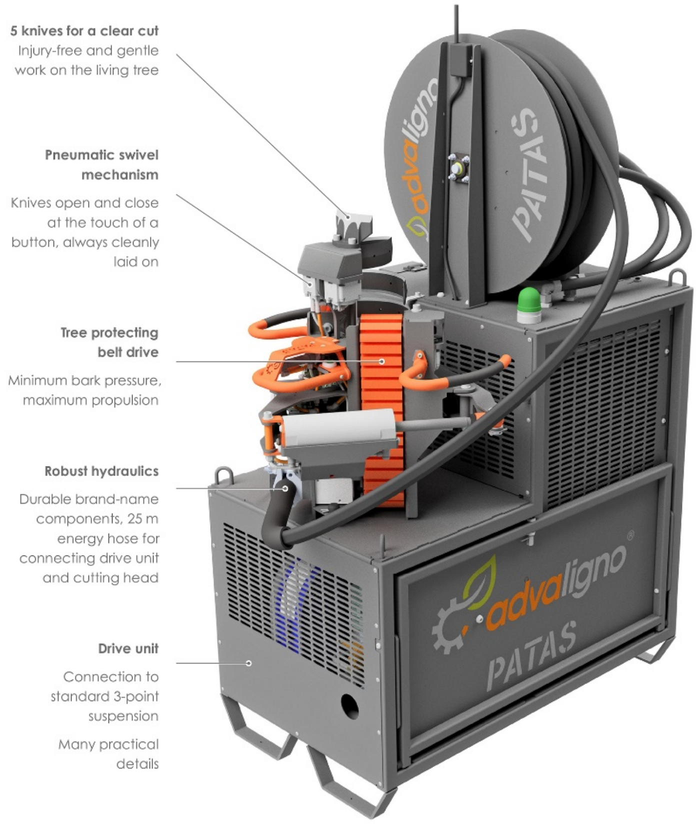


**Figure 5: Patas drive and cutting unit (advaligno GmbH, 2018).**

The 'Patas' is a recent development with original sales commenced in 2019. It has since been tested as a pilot study by the Department of Ergonomics and Process Technology at the University of Göttingen in 2020 (Hartsch et al., 2021). The study took place in a 40-year-old, 1.7 ha Larch (*Larix* spp.) stand, that had no understory or residues on-site that could hinder the process. A total of 188 trees (110 trees per ha), with a mean height of 20.3 m and a mean diameter at breast height (DBH) of 21.9 were pruned up to a 12 m height. The study found that diameters are desirably less than 25 cm to ease the attachment of equipment to the tree. The minimum diameter is 6-7 cm. The process is a two-person job and manual removal of branches at the trunk might be required before fixing the Patas. Radio remote control allows for a safe operating environment of 10 m from the tree. The pruning height of the machine can be read from a colour code on the hose. Roughly 11% of fine branches remain on the stem after pruning, 76% of those above 9 m height. A further 25% of branch stumps remain, of which 89% are above 9 m. Minor bark injuries occur in 8% of the trees (Hartsch et al., 2021).

The Patas costs AUD 31.50 per hour, with a system cost of AUD 166.90 per hour, and productivity of 28.45 trees per hour, which results in a cost of AUD 5.80 per tree (Hartsch et al., 2021). This is based on a European costing model with a wage of AUD 110.20 per hour of work for two workers and AUD 25.2 per hour for a 37 kW tractor. Study estimates indicate a cost saving of 75% compared to manual pruning. As a comparison, a heavier tractor set-up was also tested using a 110kW tractor with an associated cost of AUD 54.34 per hour (Hartsch et al., 2021). Thereby 188 trees were pruned in 527.69 minutes including both working and non-working time, with a resulting pruning performance of 21.38 trees per hour. This resulted in a higher system cost of AUD 197.66 per hour or AUD 9.14 per tree. The manufacturer indicated during the study that costs can be further reduced if more trees her hectare were pruned, labour costs were reduced, or a cheaper tractor set-up was used. In plantations with higher tree densities, higher productivity can be achieved, however, this is highly dependent on site conditions such as slope, accessibility, stems per ha, debris and understory, DBH/height ratios and others.

Ergonomic results for the 50 kg piece of equipment indicates that workers would operate below the individual performance limit of 186 heartbeats per minute, however, mostly above the continuous performance limit of 130 heartbeats per minute. To prune 188 trunks in an 8 hour day over an area of 1.7 ha, the tractor also has to be moved around 62 times with an average working radius of 10.9 m per tractor position, an average of three trees per position (Hartsch et al., 2021). This ergonomic study includes non-working times and is based on a German sylvicultural future-tree system, where future trees were selected (around 80-100 per hectare) and debranched, and a maximum of 1-2 competitor trees are felled.

As the most recent technology and the only active commercial solution available, the Patas has made some improvement over the original Sachs Tree Monkey, however, some limitations still occur, especially when operating in Radiata pine, e.g. it can only cut branches up to 3.5 cm (advaligno GmbH, 2018). The technology provider is continuously working on improvements on the system that could potentially increase its agility, range of application and ergonomics.

## 6. UAV

In New Zealand, a 2-year research project was initiated in 2016 as a proof of concept by the University of Canterbury looking at autonomous pruning using an unmanned aerial vehicle (UAV) (University of Canterbury, 2019). The rationale behind using drones is to access rugged, rocky and steep terrains.

The system setup (**Figure 6**) involves a gimbal-mounted on a drone that can operate in 1 degree of freedom to target branches in front of the drone. The combination of drone, gimbal and pruner weighs over 2 kg, and measures over 80 cm nose-to-tail, which makes it subject to more restricted UAV licencing. The blade is mounted on the front of the drone and is counterweighted by a battery in the back.

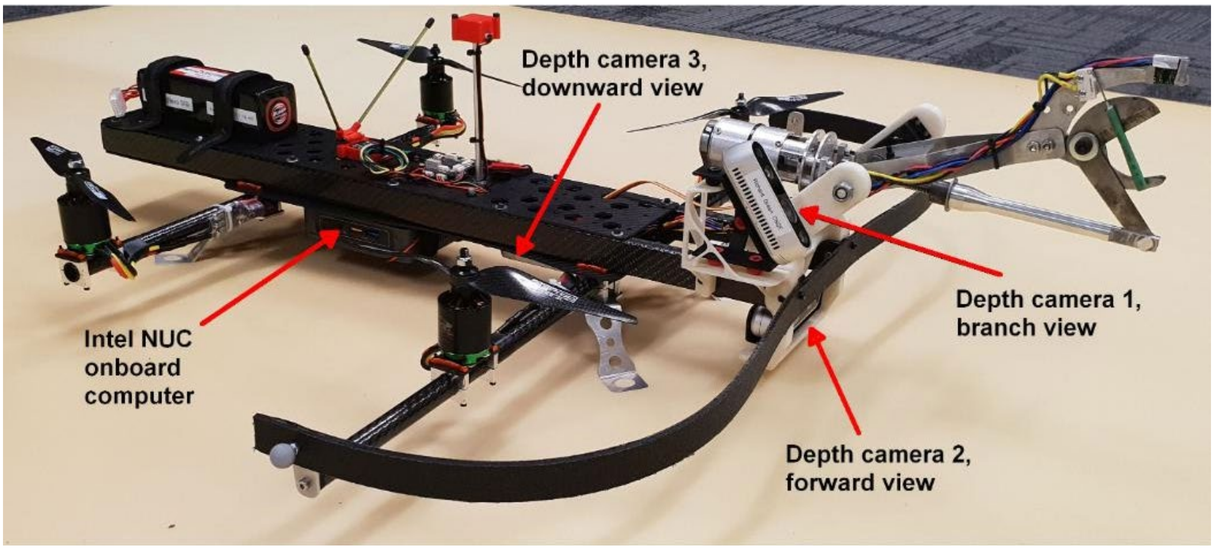


**Figure 6: UAV-based pruning prototype (University of Canterbury, 2019).**

The UAV system can carry out fully autonomous flights using visual odometry - no GPS is required. The UAV is equipped with a trunk detector in the front, able to recognise trees as vertical objects. The onboard neural network has up to 1 cm precision in branch detection and the cut point is determined in real-time. As the UAV moves to the branch, the blade cuts the branch automatically. Branches up to 15 mm can be pruned in the current prototype.

Due to its prototype status and current limitations, this system is not yet deployable in a commercial environment. Several conditions also limit the use, as UAV's are sensitive to weather (especially rain and wind) and struggle under dense forest structures. In current trials at the University of Canterbury, the lower half of the trunk is cleared prior to the UAV operation to reduce collision risk between UAV and surrounding branches or vegetation. The undisturbed access to trees, as well as the speed of operation, makes the system more appealing to urban environments. It should be noted that the use of drones and UAVs are emerging technologies and also become more important in the daily practices in forest management.

It should also be noted that the artificial intelligence (neural networks) used in this technology are used in the pruning of horticultural crops such as grapevines (Botterill et al., 2017; Saxton et al., 2014), incorporated in a ground-based fully autonomous robot.

## 7. The Stick Insect

A tree-to-tree forestry machine, based on a locomotive idea to move from one tree to the next without touching the ground, like a stick insect, was developed in New Zealand in 2002 (**Figure 7**). With funding from Scion, the Ministry for Primary Industries and the Forest Growers Levy Trust, the machine was built by four University of Canterbury students in 2013 (Parker et al., 2016).

As with the UAV in the previous section, this type of robot is considered useful for rocky and steep terrain. The machine would eventually be able to perform tasks autonomously such as tree measurements, pruning, thinning, felling and yarding. The idea would be to deploy a swarm of Stick Insects that co-operate in any of the abovementioned practices and are incorporated with gadgets such as sensors and saws (Russell Dale, 2016).

**Figure 7: Stick Insect prototype (Parker et al., 2016).**

The prototype Stick Insect has a 2.2 m reach and weighs about 50 kg. The device is fairly lightweight compared to some of the ground-based systems and is supported by grippers on the end of each arm which avoids soil compaction.

# Summary

Based on the literature and technology review, several overarching conclusions can be made. A summarizing table can be found on the following page (**Table 1**).

Since the introduction of the Sachs Tree Monkey, there have been several alterations made and new products launched. However, some of the issues identified in the '60s are still present. The heaviness of equipment is the main concern. This makes equipment unattractive for use on young trees (fuel reduction pruning), or to be carried by forest workers, particularly in steep or rough terrain. Often the equipment needs to be carried by 2 or more people and still results in physical strain on the body. It is noted that the mechanics of these inventions have improved (Patas), however, the agility and range of application are still limited. In particular, applied to Radiata pines, it is noted that the bulges/whorls around branches are of major concern. The Patas manufacturer, however, noted that rough bark increased the performance of the system, performance is dependant on the site conditions and potentially higher in plantations, and that further developments of the systems are underway. Branch size could be optimised, especially when considering pruning near the plantation edge for fuel reduction where it is expected that lateral branches are larger. It would therefore be preferred to prune at a younger age, to reduce branch size, and also decrease the accumulation of ground-based fuels, especially considering the potential fire risk and damage it could cause to Radiata pine.

Few of the mechanised pruners reviewed met the objectives suggested by (Sutton, 1971) (performing a pruning operation comparable in quality, or an improvement on, current manual methods; reducing physical work effort; increasing productivity above present manual methods; and reducing costs) and those that do, do so under limited operating conditions: straight stems with no bumps, small branches at right-angles to the stem and high pruning lifts where manual pruning is at a disadvantage due to the requirement for repositioning ladders.

Finally, more recent technologies such as UAV's and the Stick Insect show promise in pruning. However, they need to overcome several technical and operational challenges to become operational and commercial. Their biggest innovation stems from their remote control or autonomous function and access to rugged terrain, as well as some high-performance artificial intelligence in terms of branch detection and automated tree measurements.

**Table 1: Overview of existing mechanical and robotic pruning equipment.**

| | **Paterson Pruner ('70s)** | **Sachs Tree Monkey ('60s)** | **Clouston Tree Shaver** | **Woody** | **Yamabiko** | **Patas** | **UAV** | **Stick insect** |
|---|---|---|---|---|---|---|---|---|
| **Status** | Prototype | Commercial | Prototype | Prototype | Commercial | Commercial | Prototype | Prototype |
| **Stem size** | <10 cm | 10-25 cm | 9-29 cm | - | 7-23 cm | 7-25 cm | NA | |
| **Height** | 11 m | 9 m | 8 m | - | - | 15 m | NA | NA |
| **Branch size** | NA | 5.0 cm | NA | - | 4.5 cm | 3.5 cm | 1.5 cm | |
| **Tree age** | 9-12 | - | - | - | - | - | NA | NA |
| **Tree species** | Test on pine (AU) | Test on pine (AU) | Test on fir and poplar (USA) | - | - | Test on fir, larch and pine (EU and BR) | Test on Radiata pine (NZ) | Test on Radiata pine (NZ) |
| **Trees/h** | 180 | 14.3 | < 30 | - | - | 28.5 | - | - |
| **Ha/day** | - | - | - | - | - | 1.7 | - | - |
| **Gradient** | Flat terrain | Flat terrain | Flat terrain | Flat terrain | Flat terrain | Flat terrain | All-terrain | All-terrain |
| **Weight** | NA | 45.0 kg | 45.0 kg | - | 32.8 kg | 50.0 kg | >2.0 kg | 50.0 kg |
| **Capital cost** | - | - | - | - | - | AUD 54,000.00 | - | - |
| **Operating cost** | - | AUD 1.40/hour (1969) | - | - | - | AUD 31.50/hour<br>AUD 5.80/tree | - | - |
| **Application range** | Delimbing | Straight stem only | Straight stem only | Straight stem only | Straight stem only | 10.9 m radius from tractor | Any | 2.2 m reach |
| **Strength** | • Safe<br>• All branch size | • NA | • All branch size | • NA | • NA | • Safe<br>• Fast | • Autonomous<br>• Remote<br>• Safe<br>• No compaction | • Autonomous<br>• Remote<br>• Safe<br>• No compaction |
| **Weakness** | • Stem Damage | • 3-person job<br>• Heavy<br>• Stem damage | • 2-man job<br>• Heavy<br>• Slow<br>• Stem damage | • NA | • Heavy<br>• Branch bite<br>• Slow | • 2-man job<br>• Heavy<br>• Stem damage<br>• Compaction | • Slow<br>• No obstruction | • Limited range |

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