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Optimizing herbicide-use for the killing of eucalypt stumps

by

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Declaration

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DECLARATION:

In accordance with Rule G5.6.3, I hereby declare that the above-mentioned treatise/ dissertation/thesis is my own work and that it has not previously been submitted for assessment to another University or for another qualification.

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DATE : 14 September 2021

Abstract

The South Africa (SA) forest industry relies on plantations of exotic forestry trees (*Pinus, Acacia and Eucalyptus*) to fulfil its timber requirements. With 52.0% of the afforested land in South Africa planted to various eucalypts and their hybrid combinations. Of the total area planted to eucalypts in SA, 75 000 ha is re-established annually by means of silvicultural regimes and operations matched to site productivity, desired end-product and method of regeneration.

Unlike other commercially grown tree species, eucalypt species have the ability to coppice after felling. Coppicing is a common form of regeneration in South African forestry as it allows the plantation owner the option of a second timber rotation without replanting. However, if any factors affecting coppicing are compromised, and the site is to be replanted, then it is important to kill the stumps before replanting as rapid initial growth of the coppice shoots will require earlier control than that associated with normal weeding operations. Over time, various methods of woody plant control have been proposed and tested, with most of these making use of herbicides as opposed to the repeated manual removal of coppice regrowth.

Globally, most industries subscribe to standards associated with sustainable production (economic, environmental and social) against which they are measured. Within SA, 80% of the forests are certified though either the Forest Stewardship Council (FSC) or International Standards Organisation (ISO) which recommend the identification and avoidance of ‘highly hazardous’ chemicals; the promotion of ‘non-chemical’ methods for pest management as an element of an integrated pest and vegetation management strategy; and the appropriate use of chemicals that are used.

To test the current recommendations for killing eucalypt stumps to include other species, the potential of reducing herbicides used, and the influence of time after application on the survival of eucalypt stumps, two trials were initiated at Entabeni plantation (Venda, Limpopo) and one at Wilgeboom plantation (Bushbuckridge, Mpumalanga) between 2018 and 2020.

Extending eucalypt cut-stump control practices: Most of the trial work on killing of eucalypts in SA has been conducted on *Eucalyptus grandis*, *Eucalyptus camaldulensis* or *Eucalyptus macarthurii*, with all grown on shorter pulpwood rotations. To extend current recommendation to include *Eucalyptus cloeziana* (grown on a

longer rotation for poles), a trial was established in 2018 at Entabeni plantation (Limpopo Province) to quantify the interaction between Application method (basal-frill; cut-surface; foliar) and Herbicide (no herbicide applied; Roundup; Garlon; Roundup + Garlon) for the killing of 12 year-old stumps following harvesting. Assessments were carried out at 1, 3 and 6 months following application and included Stump survival, Stump quarter with coppice and Coppice heath.

Relative to the control plots (100% survival), all herbicides tested were equally effective, 70–90% of the stumps killed. This study confirms previous research regarding the killing of eucalypt stumps. Roundup, Garlon or a combination of two, when applied according to label recommendations to a stump as a basal-frill or cut-surface application (within 30 minutes of felling) resulted in 70-90% of the stumps killed.

Testing of natural/synthetic surfactants-herbicide combinations for enhanced cut-stump control: All certified organizations require the development and use of integrated pest management (IPM) to avoid/eliminate/reduce the use of chemical pesticides, and to minimize risks to human health and the environment while maintaining economically viable management.

The use of natural, or synthetic surfactants (Breakthru, Orosorb or Nu-Film) in combination with herbicides (glyphosate or triclopyr), if effective would be advantageous in terms of improved efficacy, and/or a reduction in the amount of herbicide applied. A trial was implemented in 2018 (Venda, South Africa) on a felled stand of *Eucalyptus cloeziana* to determine if the addition of natural/synthetic surfactants (with different modes of action) would allow for reduced rates of herbicide application without compromising efficacy.

Overall stump survival for the whole trial at 6 months was 20.7%, although there was a wide range in terms of the individual treatments tested (0-70%). Roundup (16.1%) and Garlon + Roundup (16.7%) were not significantly different from each other, but both were significantly better than Garlon (29.4%). Breakthru (16.7%) and Orosorb (16.1%) were not significantly different from each other, but both had significantly lower stump survival when compared to Nu-Film (29.4%). The recommended herbicide + surfactant rate was significantly better at killing stumps than where half the recommended herbicide + double surfactant rate were tested (stump survival: 1x_1x = 7.8%; 0.5x_2x = 33.7%).

Influence of time after herbicide/surfactant application on the ability to kill cut-stumps: There is a need to determine the best method for the killing of eucalypt stumps post-felling, taking into consideration the combined constraints around labourer safety in terms of the delayed time after felling that herbicides can be applied, and the judicious use of any herbicides. A trial was implemented at Wilgeboom Plantation (Mpumalanga, South Africa) in 2019 to test the efficacy of two herbicide/surfactant combinations for the killing of 24 year-old *E. grandis* cut-stumps at four time-intervals (0.5, 6, 24 and 48 hours) following felling.

Treatment efficacy in terms of stump survival (%) was assessed at 6 months, with the vigour of any coppice regrowth assessed in terms of coppice health and stump quarter with coppice present. Irrespective of treatment, mean stump survival for the whole trial was 34.4% at 6 months. Of the three factors tested, only Application time was significant, with 0.5 hrs significantly ($\bar{x}$ = 10%) better than the rest of the treatments, and 6 hrs also significantly better than 24 and 48 hrs (32% versus 45 and 51% respectively). For those stumps that were not killed, all herbicide and surfactant combinations (regardless of treatment, or application time) resulted in reduced coppice regrowth (reduced stump quarters) that was also regarded as unhealthy (lowered coppice health). This study therefore confirmed previous results in terms of the timeous application of herbicides to eucalypt cut-stumps for effective kill (within 0.5 hrs).

Although different methods for the management of competing vegetation (including coppice) can be used, integrated management practices are preferred and considered more holistic and sustainable as they reduce reliance on a single control method. Previous research on the killing of eucalypt stumps in South Africa has found herbicide application to be more effective compared to the untreated and manual/cultural removal of coppice regrowth. If two or more methods for the management of competing vegetation are combined with the use of herbicides, it is possible that the quantities applied may be reduced.

Dissertation at a glance

Optimizing herbicide-use for the killing of eucalypt stumps

CHAPTER 1

General introduction to silvicultural practices during establishment.

CHAPTER 2

Objective:

Extending eucalypt cut-stump control practices to include *Eucalyptus cloeziana.*

Method:

The treatments consisted of a 3 x 4 factorial arrangement of 12 treatments, replicated 3 times and laid out in a randomised complete blocks design (RCBD).

Main findings:

Relative to the control plots (100% survival), all herbicides tested were equally effective with 70–90% of the stumps killed.

CHAPTER 3

Objective:

Testing of herbicide/surfactant combinations at two rates for the killing of *Eucalyptus cloeziana* stumps, South Africa.

Method:

The 18 treatments were arranged as a 3 x 3 x 2 factorial, replicated three times and laid out in a randomised complete blocks design (RCBD).

Main findings:

The recommended herbicide + surfactant rate was significantly better at killing stumps than where half the recommended herbicide + double surfactant rate were tested (stump survival: 1x_1x = 7.8%; 0.5x_2x = 33.7%).

CHAPTER 4

Objective:

Influence of time after herbicide/surfactant application on eucalypt cut-stump survival.

Method:

The 2 x 2 x 4 factorial arrangement of 16 treatments were replicated 3 times, and laid out in a randomised complete block design (RCBD).

Main findings:

The mean stump survival for the whole trial was 34.4% at 6 months. The study confirmed previous results in terms of the timeous application of herbicides to eucalypt cut-stumps for effective kill (within 0.5 hrs).

CHAPTER 5

Summary of major findings and overall conclusions.

Table of Contents

List of figures

List of tables

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CHAPTER 1

General introduction to silvicultural practices during establishment

1.1 Background of the South African forestry industry

Before the implementation of plantation forestry in the Cape, forest products (fuelwood, railway sleepers and structural timber) were obtained from natural forests (Pirie 1982, DAFF 2020). Due to the lack of legislation or policies to control access during this period, over-exploitation of these natural forest occurred (Scott and Gush 2017). As these natural forest species had slow growth rates, with some species restricted to specific environmental conditions, their use as a commercial resource was limited (DAFF 2020). Exotic trees such as *Pinus, Acacia* and *Eucayptus* were introduced and grown in plantations to meet the increasing demand for timber products, (Britton 2006, DAFF 2020), with plantation forestry first recorded in 1876 (Louw 2006).

Over time, plantation forestry has been influenced by many internal and external factors such as World Wars' I and II, periodic global and economic recessions, introduced and indigenous pests and disease, abiotic risk (for example fire and drought), availability of land suitable for forestry and lack of skilled labour (Louw 2006). Despite these challenges, the forest industry in South Africa remains commercially viable (±140 years), with ca. 1 212 383 hectares planted in 2018 (FSA 2018). Prior to 1994, although forestry laws and policies existed that regulated forest practices, these were under the governance of the SA Directorate of Forestry, which acted as the link between the SA Government and private forestry sector. From 1998, a new act which was aimed at conserving water resources was approved, with the government's role strengthened in terms of monitoring, controlling and evaluating sustainable forest development practices (Louw 2006).

1.1.1 Eucalypts in South Africa

Currently the forest industry in South Africa relies on plantations of exotic forestry trees (*Pinus, Acacia and Eucalyptus*) to fulfil its timber requirements (Albaugh et al. 2013). Of these three, the *Eucalyptus* genus covers more than 19 million hectares of the world's land surface (Stape et al. 2001), mostly for the production of pulp and paper, solid wood products such as poles, furniture and construction timber, and fuel wood (amongst other uses) (Albaugh et al. 2013; Pereira and Alves 2015). Eucalypts were first grown in small trial blocks within South Africa in 1667 (Poyton 1979), with various species introduced as a source of mining timber from the late 19th century onwards. By the late 1980's eucalypts were the most commonly planted species for pulp and paper production in SA (Darrow 1984; Komakech 2007), with 52.0% of the afforested land (1 191 638 ha) in South Africa planted to various eucalypts and their hybrid combinations in 2018 (FSA 2018). This is due to a combination of their high rates of productivity over relatively short rotations, the ability to select from a range of eucalypts to match diverse sites and climatic regions, desirable pulping properties, and their ability to coppice (Little and Gardner 2003; Smith at el. 2005a; Smith at el. 2005b; Reed 2009; Albaugh et al. 2013).

1.1.2 Eucalypt management

Globally, the silvicultural system of clear-felling with subsequent replanting is a common practice (Hjelm et al. 2019). The South African commercial forestry industry practices an even-aged stand management system, where regeneration, tending and felling are separated in time and occur sequentially to each other (du Toit and Norris 2012). According to Evans and Turnbull (2004), this sequence can be divided into three stages: between harvesting and planting; between planting and canopy closure; and between canopy closure and harvesting. The stage between clear-fell and canopy closure is referred to as re-establishment.

Of the total area planted to eucalypts in SA, 75 000 ha is re-established annually, with silvicultural regimes and operations matched to site productivity, desired end-product and method of regeneration (Smith et al. 2001). Within South Africa, intensive silviculture is practised during re-establishment to maximise tree survival and accelerate the time taken to reach canopy closure (Smith 2006).

Intensive silvicultural management includes the following main components, land clearing, land preparation, fertilising, vegetation management, and other continuous activities which add value to the timber yield harvested at rotation age (Evans 1976; Coetzee 1985; Morris 1995; Little 2003; Rietz et al. 2006; du Toit and Norris 2012). Little et al (1997) described these practices during re-establishment as been critical, due to their influence on the quality and quantity of the product at rotation-end. In terms of short rotation pulpwood stands, intensive silviculture management is vital, since any impact (whether negative or positive) is likely to be carried through to rotation end due to a lack of thinning (du Toit and Norris 2012).

Of the silvicultural practices, the management of vegetation is considered important and includes the management of weeds that may occur on the site, as well as the killing of eucalypt stumps if the site is to be replanted so as to prevent competition from coppice sprouts (Little and van den Berg 2007). Trial work has been conducted to test and/or find an industry wide solution to killing eucalypt stumps (for example: Little et al. 1998; Little 2000; Little and Eccles 2000; Little and van den Berg 2007; Roberts et al. 2018). However, more work is still required, to investigate the effectiveness of current practices on other commercially grown eucalypts (for example *E. cloeziana* F. Muell).

1.1.3 Eucalypt coppice management

Unlike other commercially grown tree species such as pine and wattle, eucalypt species have the ability to coppice (produce new shoots from stumps) after felling (Farmer 1962; Florence 1996). The survival mechanism and ability to produce new growth following adverse environmental conditions of eucalypts depends mainly on the function of the bud system found in the tree stumps. Of the four bud types that may occur in eucalypts (species dependent), lignotubers and epicormic buds situated in the live bark or cambium at the base of the stumps are responsible for coppice regrowth following removal of the main stem (Leyser 2005).

The sprouting of these buds is usually prevented by the presence of auxin, a growth hormone produced by apical and axillary buds (Burrow 1990). New coppice shoots are produced when the inhibiting effect (also known as apical dominance) of auxin on the growth of these buds is removed. This may occur through damage or loss of the crown (for example, insect defoliation, drought stress and stem breakage), as well as during harvesting where the whole stem is removed (Leyser 2005).

Coppicing is a common form of regeneration in South African forestry as it allows the plantation owner the option of a second timber rotation without replanting, and thus reduces the temporary unplanted period and re-establishment costs (Zbonak et al. 2007). In South Africa the coppice shoots are thinned in a step-wise manner: the first at 3-4 m in height to 2-3 stems stump^{-1}; and the second to the original planting density (1-2 stems stump^{-1} depending on survival of adjacent stumps) at 7-8 m.

1.1.3.1 Factors to be considered before coppicing

Although coppicing is more cost-effective than replanting, a number of factors should be taken into consideration, as if any of these factors are compromised there will be a loss of productivity. Some of these factors include:

- Site-species matching/improved genetics: Is the correct species and best genetic material matched and planted on that site? The introduction of new pure species and their hybrid combinations into South Africa, together with improved site-species matching and genetic material (through tree breeding) has meant that higher productivity could be expected through replanting rather than coppicing.
- Planting density and stocking: Was the parent crop planted at the correct planting density, and is the final stocking adequate for coppicing? Due to changes in timber dimensions and/or end-product requirements, the original planting density may no longer be correct. In addition, mortality may have occurred during the rotation resulting in too few stems for that stand to be coppiced. Additional mortality following harvesting/extraction would also need to be taken into consideration.
- Ability of the eucalypt to coppice: Although stand age (reduced copping ability with age), time of year felled (reduced coppice production in drier seasons) and stand productivity (higher productivity results in improved coppicing) can influence the ability of eucalypts to coppice, some the eucalypts grown commercially in South Africa coppice better than others. Knowing the coppicing ability of the eucalypt to be felled is important as it will influence the decision of whether to replant or coppice. For example: *E. dunnii*, *E. grandis*, *E. grandis* x *E.*

camaldulensis, *E. grandis* x *E. urophylla*, *E. macarthurii*, and *E. smithii* show good potential for coppicing, whereas *E. nitens* and *E. fraxinoides* do not (Little 2003).

- Appropriate harvesting and extraction: To establish a coppice compartment, proper integration between harvesting and silviculture operations is required. For example, during harvesting/extraction care should be taken not to damage the bark on the stump such that it remains firmly attached to the stump following felling (Little 2003; Schwegman at el. 2018). High stumps (cut too high) produce too many coppice shoots which have a tendency to break off the stump, whereas stumps cut too low tend to produce fewer shoots. A stump of between 10 and 15 cm is regarded to be the optimum stump height for coppicing (Little 2003). In addition the management of slash following harvesting may also influence stump survival and the early growth of coppice shoots. If the slash is burned, the intensity of the fire may delay coppice growth and/or kill the stumps (if severe). In addition, it is important that harvesting slash is removed off the stumps as coppice shoot growing through brush generally has poor stem form and a weak attachment to the stump.

1.1.3.2 Management of eucalypt stumps if the site is to be replanted

If any of the above factors are compromised, and the site planted to eucalypts is to be replanted, then it is important to kill the stumps before replanting as rapid initial growth of the coppice shoots will require earlier control than that associated with normal weeding operations. Furthermore, if eucalypt stumps are not killed before replanting, the newly planted seedlings (or plants of clonal material – hereafter referred to collectively as seedlings) will be suppressed by the adjacent coppice regrowth, resulting in significant growth reduction as well as variable tree growth (Little and van den Berg 2007).

Over time, various methods of woody plant control have been proposed and tested, with most of these making use of herbicides as opposed to the repeated manual removal of coppice regrowth. In general these methods fall into two main groups: those aimed at killing standing trees; and those aimed at killing the stumps once the tree has been felled (Little and Eccles 2000; Little 2003). The latter option is the most applicable in a clear-fell situation where environmentally approved products (such as glyphosate, triclopyr, imazapyr or metsulfuron-methyl) that are registered in SA for use in plantations can be used. Currently the most common methods for the killing of eucalypt cut-stumps include:

- **Manual cutting** (bashing): This method involves the manual removal of coppice shoots from a stump using an axe or bush knife (when knee/hip height in South Africa). Not only is this method labour-intensive and costly, the regrowth requires repeated operations due to the rapid regrowth of the coppice shoots (Little and van den Berg 2006).
- **Basal bark:** Herbicides are applied as a band around the circumference of the trunk of the stem (including the root collar area) with a low-pressure backpack sprayer, or painted with a brush (Forrest and Richardson 1965; Pereira and Alves 2015). Even though the herbicide band should cover the trunk around tree, the width of the band depends on the size of the tree (trunk/stem) and the tree's susceptibility to the herbicide applied (Tu et al. 2001). This method is more effective on younger trees, as older trees develop a thicker bark which inhibits uptake. For smaller diameter trees with thin bark, the Basal bark method is considered an effective alternate to the cut-surface method (Forrest and Richardson 1965) due to no cutting required (for example axes), there is little spray drift which can cause off-target damage, and it can be applied any time of the year (Kochenderfer et al. 2012).
- **Basal frill**: This method involves the use of a hatchet or similar device (for example a sharp knife, saw, axe) to make a cut at a downward angle in order to give herbicides access to the growing cells in the trunk (Jackson and Finley 2016). The frill cut should be made as low as possible with the herbicide applied using a backpack sprayer, squirt bottle, syringe, or similar equipment within 30 minutes after the cuts have been made (Forrester and Jackson 1965). Although highly effective, since the herbicide is placed directly onto the thin layer of growing tissue in the trunk, this is not a preferred method of control in commercial forestry due to being labour intensive (Tu et al. 2001).
- **Cut-surface:** Herbicides are applied onto the cambium of a freshly (within 30 minutes) and horizontally cut-stump after harvesting (Little and van den Berg 2006). The thickness of the stem or trunk will determine the tool used to make

the cut and can include a chainsaw, axe, brush cutter, slasher or a bush knife. This method is often used on hardwoods and shrub (woody species) that re-sprout after felling (Tu et al. 2001). To prevent the cut-stump from sprouting herbicide should be applied to the entire inner bark (cambium) using backpack sprayers with hand wands, or handheld spray bottles within 1-2 hours (30 minutes recommended in SA) (Newman and Stringer 2016). The cut-surface method requires a relatively small amount of herbicide to be effective, which also allows for a higher degree of herbicide control (low probability of affecting non-target species or contaminating the environment) (Tu et al. 2001).

- **Stem injection:** A hatchet or lance-type tree injector is used to deliver the appropriate amount of herbicide with each blow to the stem (CRC 2004). With this method it is important that the injection (or drill hole) penetrates through the bark into the living tissue or sapwood at properly spaced intervals. Benefits of this method include no spray drift, and the ability to target individual plants for treatment. However this method makes use of specialized tool such as the EZ-Ject Lance and pellets (capsules), which are expensive, and depending on species, it may be difficult to thrust with enough power to drive the capsules far enough into thick barked trees to be effective (Tu et al. 2001).
- **Foliar spray:** Herbicides are sprayed under pressure directly onto the leaves and stems of the coppicing shoots (Jackson and Finley 2016) at relatively high volumes using either aerial or ground spray application equipment (such as a helicopter, skidder, or backpack sprayer) (Tu et al. 2001). To increase herbicide absorption, surfactants are added to the spray solution (Monaco et al. 2002). To be effective, the foliar spray needs: uniform coverage; the development of sufficient foliage for increased uptake of herbicide; and thorough wetting of the foliage. Although the effectiveness of this technique depends on a combination of herbicide used, species type and size (age), the roots of some species remain active following spraying resulting in the re-application of herbicides due to re-sprouting (Monaco et al. 2002).

Previous research on the killing of eucalypt stumps in SA found that herbicide application (regardless of method of application) to be more effective compared to the untreated and manual removal of coppice regrowth (Little and Eccles 2000; Little 2003;

Little and van den Berg 2006, 2007). In a series of trials comparing various herbicides and/or methods of herbicide application for the killing of single stem cut-stumps, either the once-off application of herbicides to a basal frill or to the cut surface resulted in approximately 90% stump kill (Little et al. 1998; Little and Eccles 2000; Little and van den Berg 2006). However, for multiple rotation coppice, herbicide application into a basal frill was the most suitable method of killing these larger stumps (Little 2003). For smaller stumps, such as those from first rotation *E. grandis* or *E. macarthurii*, herbicides applied to the cut surface of the stump or the coppice regrowth foliage are generally effective (Little et al. 1996; Little and Eccles 2000; Little and van den Berg 2007). As no major differences were found between the herbicides tested (Little et al 1998; Little 2003), financial (costs) and environmental (herbicide/mixture registration) aspects would contribute to the choice of product used. The most suitable method of killing stumps, would be that method which is cost-effective, where the stump is killed in a once off application, and where the newly planted seedlings are not damaged.

Although research on the killing of eucalypts to facilitate re-establishment has highlighted suitable herbicides, rates and methods of application, this research has focused on:

- commonly planted eucalypts in South Africa (for example *E. grandis*, *E. macarthurii* and *E. grandis* x *E. urophylla*), as well as
- the optimization of the timing of the application of herbicides (for example within 30 - 60 minutes of felling if applied to the cut-surface), and at rates at which they are most effective.

With safety and reduced and/or more effective chemical use being of importance to the forest industry, limited research could be found related to:

- the effectiveness of current practices on other commercially grown eucalypts (for example *E. cloeziana*);
- the possibility for the use of surfactants to either improve efficacy and/or reduce the amounts of herbicide applied; or
- the potential to extend the time after felling eucalypts for the application of herbicides to cut-surfaces (to facilitate delayed access to stumps following mechanized harvesting), yet still remain effective.

1.2 Vegetation (weed) management

Many definitions of weeds occur, for example Aldrich (1984) defined a weed as "*a plant that originated in a natural environment and, in response to imposed or natural environments, evolved, and continues to do so, as an interfering associate with our crops and activities*". Monaco et al. (2002) provided a simpler definition of a weed as "a *plant growing where it is not desired, or a plant out of place".* Regardless of the definition, weeds compete with trees for resources and may also harbour pests that are harmful to the planted trees. However, some weeds can reduce soil erosion, and provide shelter for birds and insects that may support crop production (for example pollination, or predation of crop pests) (Mishra et al. 2016; Gaba 2017; Sharma et al. 2019; Forestry Focus 2020).

The appropriate management of competing vegetation in eucalypt stands in SA has been shown to reduce mortality, reduce variability and ensure that the predicted yield at rotation end is obtained (Ashton and Monaco 1991; Little et al. 1999; Wagner et al. 2001; Little and van den Berg 2007). The management of weeds comprises three main objectives (prevention; eradication; and/or control) (Ashton and Monaco 1991), typically with a combination of two (or more) of these techniques used within any management regime (Zimdahl 2007, Harker and O'Donovan 2013), whereby:

- Weed prevention involves the prevention of weed species from contaminating an area through: a guarding process ensuring that no new weed seeds are introduced into a farm/plantation; restricting weeds in the plantation from flowering/seeding; and the prevention of the spread of those weeds that reproduce vegetatively (Monaco et al. 2002).
- Weed eradication is the complete elimination of all living plants and their seeds after they have become established in an area. Weed eradication is labour- and time-intensive and expensive to execute when compared to prevention and/or control (Tu et al. 2001, Monaco et al. 2002). In addition the area vacated by the weed will most likely be occupied by another (and sometimes less desirable) weed species.
- Weed control (or vegetation management) refers to the process of limiting a weed from multiplication or invasion. It also includes minimizing competition from

weeds through the use of techniques/methods of weed (vegetation) management, such that there are no negative effects on financial returns (Zimdahl 2007).

Weeds share several ecological attributes, such as a fast growth rate, high seed production and fast vegetative spread (amongst other attributes) (Gaba 2017). Despite this, there are hundreds of species, each with different ecological properties growing within varying environmental and management conditions, thus making them difficult to control (Tu et al 2001). To partially overcome this issue, any successful weed management regime will consist of a combination, or sequential use of, different weed management techniques (called Integrated Weed Management) (Tu et al. 2001; Pereira and Alves 2015; Mishra et al. 2016). Integrated Weed Management helps prevent production loss while reducing negative environmental impacts due to combining various management practices, for example: biological; mechanical/manual; chemical; cultural (Pereira and Alves 2015; Gaba 2017). A brief description of each method is provided.

1.2.1 Biological control

Biological weed control is the use of parasites, predators and/or pathogens to feed upon or otherwise interfere with a targeted pest species in order to maintain another organism’s population at a lower average density than would occur in their absence (Tu et al. 2001, Zimdahl 2007). Biological control is considered more environmentally acceptable at it does not leave chemical/herbicides residues, and if successful it provides extensive and permanent control that is cost-effective (Tu et al. 2001). A successful biological introduction will initially result in a high reduction of the target weed, provided there are no negative impacts on desirable plant species or to any ecological processes (Mishra et al. 2016).

Biological control is seldom used during the re-establishment phase in South Africa as:

- it is normally associated with the control of target weed species and not for the control of diverse weed species as found in eucalypt plantations;
- if a potentially competitive species is controlled then the vacated niche will be occupied by other weed species;

- once released, biological agents take a while to become established to such a level that they may have a negative impact on the development of weeds,
- as weed growth in plantations is only of a short duration, it is possible but unlikely that any biological agent will have a significant impact on weed development within one season; and
- weed control normally targets all competitive vegetation, some of which may also include host plants that are required to act as a reservoir for the biological control agent.

1.2.2 Mechanical/manual weed control

Mechanical weed control makes use of machine-drawn implements (for example discing, ploughing, slashing, rotovating, copper-rolling), but may be limited due to the terrain (steep, rocky, uneven) and presence of stumps and slash (if the area is not burned). If used, and the site conditions are conducive, mechanical weeding is confined to the inter-rows (areas between the tree rows). Manual weeding makes use of labourers hoeing (with an agricultural hoe) or slashing weeds with hand-held implements. Although manual weed control is easy to implement, it is labour intensive, costly, physically demanding (low ergonomic acceptance). As such manual weeding is combined with other methods of weed control and is normally confined to a ring-weeding around the trees when small.

1.2.3 Cultural control

Cultural weed control makes use of good practices concerning establishment and tending that contribute to a high standard of health and vigour in the plantation (Tu et al. 2001, Rolando 2008). These practices are often included by default, rather than by design and include:

- Species choice, whereby certain eucalypts (for example *E. grandis* x *E. urophylla* compared to *E. grandis* x *E. camaldulensis*) or pines (for example *P. patula* compared to *P. elliottii*) have a crown that is more dense and hence able to shade out competitive weeds sooner than trees with a crown that is more sparse;
- Crop-row spacing, whereby the crowns of trees planted at a closer spacing within the tree rows will shade out weeds sooner than if planted at a wider spacing;
- Site preparation methods, whereby the retention of slash, or ripping for the preparation of a planting position results in lowered weed growth, compared to the practices of burning the slash or complete site preparation;
- Timing of planting at the beginning of the planting season when weed germination and growth are generally lower.

1.2.4 Chemical control

Chemical weed control makes use of herbicides applied to prevent germination (pre-emergents), or to suppress and/or kill competing vegetation. Chemical weed control is considered the most effective method of weed management and consequently the most widely used technique (Forestry Focus 2020). This is due to the lowered dependency on labour, and lower cost when compared to manual weeding, inter-row slashing, the planting and management of cover-crops or mulching (Pereira and Alves 2015; Mishra et al. 2016). Even though, a large range of herbicides are considered safe and are effective for use in forests globally, no single herbicide type (with a fixed rate and application method) works for all the weed problems. Rather each situation requires a detailed assessment of the weed problem in terms of risk, together with the efficacy and cost-effectiveness of the method for control. In South Africa, most herbicide applications are applied manually through the use of knapsack sprayers.

Over the years, many herbicides with different modes of action have been formulated so as to provide greater efficacy and diversity to match the weed situation and desired outcome (Travos et al. 2017). Regardless of herbicide, the chosen method of application needs to ensure adequate contact is made with the target plant such that it can be absorbed and translocated within the tree without losing its toxic ability (Pacanoski 2015). Surfactants are chemicals that may be added to herbicides to improve efficacy, and to modify the spray droplets formation and retention on the leaf surface. Pacanoski (2015) defined an adjuvant as "*a material added to a tank mix to aid or modify the action of an agrichemical, or the physical characteristics of the mixture*". Adjuvants may decrease the amount of herbicide applied and lower total costs for weed control, in addition to reducing the leaching of herbicide through the soil profile (reduced environmental risk). Adjuvants can be broadly grouped according to purpose as:

- Wetting agents, which increase the ability of water to displace air or liquids from the leaf surface, allowing it to be wet by the herbicide;
- Mineral oils, which increase the retention time of a solution on leaves, allowing for an increase in herbicide uptake; and
- Surfactants, which influence the ability of herbicides to penetrate the leaf's waxy cuticle through improving the dispersing/emulsifying, absorbing, spreading, wetting, sticking, and/or penetrating properties of the spray mixture.

Although mineral oil is recommended for triclopyr (product label), limited research could be found where surfactants with different modes of action (for example penetrants and stickers) have been tested to either improve efficacy and/or reduce the amount of herbicide required to be effective for the killing of eucalypt stumps.

1.3 Forest certification and the use of herbicides

Globally, most industries (forestry included) subscribe to standards associated with sustainable production (economic, environmental and social) against which they are measured (Brink 2012). Within SA, 80% of the forests are certified though either the Forest Stewardship Council (FSC) or International Standards Organisation (ISO) (Norris 2020). The Forest Stewardship Council (FSC) Group recommends that where pesticides (herbicides included) are used in forestry, an Integrated Chemical Management protocol be adopted by forest managers with three main objectives, namely: the identification and avoidance of 'highly hazardous' chemicals; the promotion of ‘non-chemical’ methods for pest management as an element of an integrated pest and vegetation management strategy; and the appropriate use of chemicals that are used (FSC 2007).

1.4 Research questions and objectives

The objectives of the research proposal have been based upon a combination of the needs of the South African eucalypt growers and information from currently available literature. Three trials were implemented as part of a series, each with an objective that will contribute to determining the best method of killing eucalypt stumps. With safety and reduced and/or more effective chemical use being of importance, the following questions arose:

i) Will the current recommendations based on killing eucalypt stumps work on a eucalypt for which herbicides have not been tested before, namely *Eucalyptus cloeziana*?;

ii) Can one reduce the amounts of herbicides applied (possibly through the use of surfactants), and still achieve the desired results?; and

iii) With the move towards safety associated with felling operations, and hence the inability to apply herbicides within 30 minutes following harvesting, are there suitable herbicide and surfactant combinations that can be applied once the timber has been extracted (up to 24 hours after felling?).

Overall objective: Optimizing herbicide-use for the killing of eucalypt stumps

Sub-objective 1: Extending eucalypt cut-stump control practices to include *Eucalyptus cloeziana*, South Africa.

Null Hypothesis: Current recommendation for the killing of eucalypts post-felling will have no effect on killing *Eucalyptus cloeziana* stumps.

Sub-objective 2: Testing of herbicide/surfactant combinations at two rates for the killing of *Eucalyptus cloeziana* stumps, South Africa

Null Hypothesis: The addition of surfactants (with different modes of action) to herbicides will not allow for a reduction in the rates of herbicide application, nor prove to be more effective than current recommendations for the killing of eucalypt stumps.

Sub-objective 3: Influence of time after herbicide/surfactant application on eucalypt cut-stump survival.

Null Hypothesis: Extending the time after felling that herbicides can be applied will not be effective for the killing of eucalypt cut-stumps post-harvest.

NOTE: The research chapters (chapters 2, 3 and 4) included within this dissertation were prepared as separate research outputs (papers/technical notes). As the content within each of these chapters deals with subject matter around a common theme (improved control of eucalypt cut-stumps), some duplication is unavoidable, particularly in terms of the literature review sections.

CHAPTER 2

Extending eucalypt cut-stump control practices to include *Eucalyptus cloeziana,* South Africa.

Abstract

Background: Wood and wood-related products are important to the South African forest industry, with eucalypt species constituting ca. 52% of the timber grown for pulpwood in South Africa. Unlike other commercially grown tree species (such as pine and wattle), eucalypt species have the ability to coppice after being felled. If the stumps are not killed following felling, the rapid initial growth of coppice shoots relative to planted seedlings will result in competition and growth suppression.

Although recommendations for the killing of eucalypt stumps exist in SA, this work is based on research conducted on shorter (6-10 years), pulpwood rotations. *Eucalyptus cloeziana* is grown over longer rotations (12-15 years) for poles resulting is larger diameter stumps, with no information found in terms of the efficacy of current recommendations on the killing if stumps for this species.

Methods: To extend current recommendation to include this species, a trial was established in 2018 at Entabeni plantation (Limpopo Province) to quantify the interaction between Application method (basal-frill; cut-surface; foliar) and Herbicide (no herbicide applied; Roundup; Garlon; Roundup + Garlon) for the killing of 12 year-old stumps following harvesting. The 12 treatment combinations were arranged as a 3 x 4 factorial, replicated 3 times and laid out in a randomised complete blocks design (RCBD). Assessments were carried out at 1, 3 and 6 months following application and included Stump survival, Stump quarter with coppice and Coppice health.

Results: Relative to the control plots (100% survival), all herbicides tested were equally effective (70–90% of the stumps killed), with the cut-surface and basal-frill application providing significantly better control than the foliar application. These findings support results obtained in trials comparing similar application methods for the killing of eucalypt stumps. However, in contrast to previous research, the use of Roundup alone (when applied at 5%) was equally effective as Garlon (2%), or Roundup + Garlon (1% + 3%), possibly due to the higher rates of application as applied

in this trial (in comparison to Roundup applied at 3% in previous research conducted in South Africa).

Conclusions: This study confirms previous research regarding the killing of eucalypt stumps. Roundup, Garlon or a combination of two, when applied according to label recommendations to a stump as a basal-frill or cut-surface application (within 30 minutes of felling) resulted in 70-90% of the stumps killed. Future studies on *Eucalyptus cloeziana* stump killing should focus on the costs per treatment to understand, and choose the best herbicide/application method combination.

2.1 Introduction

South African commercial forestry occupies 1 191 638 ha (1.0%) of the total national land surface area and contributes 0.82% to the GDP, with 5% of the South African population dependent on the forest industry for their livelihood (FSA 2019). Wood and wood-related products are important to the South African forest industry (Smith 2004; FSA 2018), with eucalypt species constituting ca. 52% of the timber grown for pulpwood in South Africa. According to Smith (2006), the ability of the South African timber industry to supply consistent and sustainable raw material for pulp and sawtimber is often quoted as its competitive advantage (Smith et al. 2004). However, there is a risk of resource depletion in terms of timber production due to land, economic and labour constraints (resource depletion in terms of land used for forestry and hence the ability to grow trees) (Dovey et al. 2007). For example land claimants may convert land out of timber production, loss of timber may occur due to abiotic and biotic factors (fire, drought, pests and diseases), global production of timber may become cheaper than in SA due to increasing labour costs. Thus, the maximisation of cost-effective, yet sustainable timber yield of exisiting areas under production is important to ensure continued profitability, and that SA remains globally competitive (Dovey et al. 2007).

The *Eucalyptus* genus consists of over 800 species which are indigenous to Australia and the bordering islands of Polynesia, with >500 of these planted globally for timber productio (Kellison et al. 2013; Bayle 2019). When planted in non-native countries, eucalypts usually exhibit superior performance compared to their native country, most likely due to a combination of favourable climatic condition and the general lack of pests and disease in the new environment (Kellison et al. 2013). Due to the lack of a sustainable natural timber resource, South Africa relies on these fast-growing exotic plantations to meet its timber needs. Compared to other exotic species, most of the *Eucalyptus* species planted are known for their high rates of growth over short-rotations (Albaugh et al. 2013; Bayle 2019).

Of the various eucalypts grown in South Africa, *E. cloeziana* is grown by SAFCOL in Limpopo Province on an 8-15 year rotation-length, mainly for the production of poles. The climate in this region is warm temperate with a mean annual temperature and rainfall of 19ºC and 1 050-1 300 mm and at an altitudinal range of 729 m a.s.l. *Eucalyptus cloeziana* was first described in Australia 1878 by Ferdinand von Mueller from a specimen collected near Rockingham Bay (Dickson and Huth 2003). It is a fast growing hardwood which is easily propagated by seed to produce a

“Class 1” durable timber of cylindrical shape (low dimensional change from stem base to top), and with few, to no knots, on the stem (Brink 2020). *Eucalyptus cloeziana* is able to withstand adverse environmental conditions (for example drought), and is resistant to biological pests such as the *Eucalyptus* snout beetle (*Gonipterus cutellatus*) (Brink 2020). Like most eucalypt spp., *E. cloeziana* is also able to regenerate via coppice.

Generally, the volume of timber produced per hectare is positively correlated to matching the correct species to site, use of genetically improved seed, linking stand density to site and end-product, and silvicultural management regime. In SA, eucalypts are intensively managed, especially during the establishment phase so as to maximise yield on a sustainable basis. Management practices during establishment include site preparation (slash and soil management), preparation of a planting position, planting practices (use of water and/or hydrogels, insecticides), and post-planting management (fertilizing, vegetation management, pruning) (Evans 1976; Coetzee 1985; Morris 1995; Little 2003; Rietz et al. 2006).

Of the various establishment practices, the management of competing vegetation is considered essential so as to reduce mortality, reduce time taken to canopy closure and ensure optimum volume is obtained at rotation-end (Smith 2006). Little (2003) described vegetation management as the control of any plant species, either exotic or indigenous, which negatively affects plantation yield. The removal of weeds from the growing site reduces competition and thus ensures optimum availability of required resources (including water, nutrients, light and physical growing space) thereby promoting tree growth (Little 2000). In general, when felled, eucalypts have the ability to resprout via coppice from the cut-stumps (Schönau 1980; Schönau 1984; Little and Eccles 2000), which if uncontrolled will compete with the newly planted seedlings (Little and van den Berg 2007). If not killed, the rapid initial growth of the coppice shoots relative to planted seedlings will also require earlier control than that for normal weeding operations (weed developing from seeds) (Little 2008; Little and van den Berg 2009). Little and van den Berg (2009), state that it is therefore critical to kill eucalypt stumps, if the compartment is to be replanted.

Of the various methods of weed management, chemical weed control is the most cost-effective, and consequently the most widely used technique (Forestry Focus 2020). This is due to it being less labour intensive when compared to manual weeding with hoes or slashes, or where cover crops and mulches are used to smother crops

(Pereira and Alves 2015). Over time, various methods of woody plant control (eucalypts included) have been proposed and tested. Most of these methods make use of herbicides and fall into two main groups, namely those aimed at killing standing trees, and those aimed at killing the stump once the tree has been felled (Little and Eccles 2000; Little 2003).

In South Africa, the killing of the *Eucalyptus* stumps is mostly carried out by applying herbicide as a basal-frill, cut-surface and/or foliar application (Little 2007). A basal-frill involves the use of a hatchet or similar device (sharp knife, saw, axe) to make a cut at a downward angle to ensure the herbicides come into contact with the meristematic cells in the stem (cambium). In contrast, herbicides are applied onto the cambium of freshly cut stumps after harvesting (cut-surface), and onto the foliage and stems of coppice sprouts at some stage after felling (foliar) (Tu et al. 2001).

The foliar application is the least effective method of herbicide application in terms of efficacy, with the coppice regrowth requiring repeat follow-up applications resulting in increased herbicide use, increased cost of application and a high risk of herbicide damage to planted seedlings (Roberts et al. 2018). Although a basal-frill is effective, especially on large multi-stemmed stumps that have been coppiced many times, is not the preferred method of control in commercial forestry due to it being labour intensive and costly (Letaoana 2018). The application of herbicide onto the cut-surface is the most effective and most commonly method for killing stumps of a single stem origin, with research showing improved efficacy associated with the application of herbicide soon after the stem is felled for improved uptake and thus translocation (Tu et al. 2001).

All herbicides used in forestry in SA (referred to agricultural remedies) need to be registered with the Department of Agriculture Forestry and Fisheries (DAFF) in accordance with the REMEDIES ACT 36 OF 1947 (DEFF 2020). In addition, the SA forest industry subscribes to the principles of sustainable forest management, with most forestry companies belonging to, and making use of the principles of the Forest Stewardship Council in terms of pesticide-use (Roberts 2018). Of the herbicides tested that are registered for use in forestry in SA (and endorsed by FSC), those containing the active ingredients (a.i.) of glyphosate, triclopyr, imazapyr or metsulfuron-methyl have proved to be the most effective (Little and Eccles 2000; Little 2003; Little and van den Berg 2007). As imazapyr and metsulfuron-methyl remain active in the soil post-application they can have negative phytotoxic impacts on replanted hardwood seedlings (such as eucalypts) (Vizantinopoulos and Lolos 1994; Tu et al. 2001; Wang et al. 2005). This soil residuality translates into delayed planting (waiting period between 4-12 months) until the a.i. is at a low enough level that phytotoxic symptoms are negligible. Due to their rapid breakdown, triclopyr (median half-life value of 30 days in soil) (NPIC 2002), or glyphosate (median half-life value of 47 days in soil) (NPIC 2019) are the preferred herbicides, especially where treated stands are to be replanted to eucalypts. In addition Little et al. (2000) and Little and van den Berg (2007) showed that triclopyr (at a lowered rate of 1% in solution as opposed to 2%) applied as a tank-mix with glyphosate (at 3%) was equally as effective as applying triclopyr at 2% in solution, but with the advantage of reduced costs and overall rates of triclopyr applied. However, the combination of these two herbicides can only be used commercially following registration as a tank-mix with DAFF, as currently the use of an agricultural remedy for a purpose or in a manner other than that specified on the herbicide label is prohibited by law (Vermeulen et al., 1993).

Most of the trial work on killing of eucalypts in SA has been conducted on *Eucalyptus grandis* Hill ex Maiden, *Eucalyptus camaldulensis* Dehnh or *Eucalyptus macarthurii* H. Deane & Maiden, all grown on shorter pulpwood rotations. *Eucalyptus cloeziana* is grown in Limpopo province over longer rotations (12-15 years) for poles resulting is larger diameter stumps, with no information found in terms of the efficacy of current recommendations on stumps of this species and diameters.

To extend current recommendation to include *E. cloeziana*, a trial was established in 2018 at Entabeni plantation (Limpopo Province) to quantify the interaction between method of stump treatment and herbicides for the killing of 12 year-old stumps following harvesting.

2.2 Materials and Methods

2.2.1 Study site.

A site was selected at Entabeni plantation (Limpopo Province) which was considered typical for the growth of *E. cloeziana* for the production of transmission poles (**Table 2.1**). The trial was implemented when felled at rotation age (12 years), on single stems of seedling origin (not previously coppiced).

Table 2.1: Site characteristics and information in a trial to test various herbicides and application methods for the killing of *Eucalyptus cloeziana* cut stumps when felled at 12 years, Entabeni plantation (Limpopo, South Africa).

Plantation	**Entabeni plantation (Limpopo Province)**
Co-ordinates (Lat; Long)	24° 12' S; 28° 38' E
Altitude (m a.s.l.)	752
MAT (°C)	19
MAP (mm yr^{-1})	1 050 – 1 300
Climatic Region	Sub-tropical
Species	*E. cloeziana*
Age when felled (years)	12 (planted 12 March 2006)
Soil form	Red apedal dystrophic soil
Parent material	Basalt
Effective rooting depth (m)	1.5
Texture (0-15 cm)	clay-loam
Organic carbon (%) (0-15 cm)	7.2
Treatments assessed (months + days)	1 (31 days), 3 (87 days), 6 (185 days)
Trial size (Ha)	0.1080

2.2.2 Treatments

The trial consisted of a 3 x 4 factorial arrangement of 12 treatments, replicated 3 times and laid out in a randomised complete blocks design (RCBD). The main factors were **Application method** (basal-frill; cut-surface; foliar) and **Herbicide** (no herbicide applied; Roundup; Garlon; Roundup + Garlon) (**Table 2.2**). The treatments (Application methods and Herbicides) were selected based on past research in terms of known treatment efficacy. The Herbicides were selected due to their low environmental toxicity according to the criteria and indicators utilized by the forest certification systems (FSC 2019). For each Application method, an untreated control (no herbicide applied) was included, against which all the other treatments were compared.

The three Application methods included:

Basal-frill: An axe was used to prepare the basal-frill treatments where herbicide were applied into overlapping, downward angled cuts made into the cambium around the base of the stem. The basal-frill was made prior to the felling of the trees to facilitate treatment implementation due to the high slash loads and felled trees preventing access to stumps post-felling Herbicides for this treatment were applied to the cuts within 30 minutes after felling.

Cut-surface: For the cut-surface treatments, herbicides were applied to the cambium of the cut surface within 30 minutes after felling.

Foliar: Following felling, the coppice regrowth was allowed to grow and was sprayed once at 30 days, when between 15-50 cm in height. A full-cover spray was applied to foliage.

Each treatment plot consisted of 3 rows of 12 trees (36 tree plot^{-1}). Although all trees within each plot were treated, only the centre row of 10 trees were used for assessments (two buffer rows of trees between adjacent plots). Prior to spraying, all plots were laid out and marked with white paint on the base of the trees to allow for identification once the trees were felled.

All basal-frill plots were treated prior to felling to ensure that access to the stumps were not obstructed by harvesting debris (**Figure 2.1**).

Herbicide for all the treatments were applied to just prior to runoff, to ensure full cover of the herbicide over the entire cambium layer or leaf area. A Solo®435 backpack sprayer regulated to 1.5 KPa was used for all spraying, with a Delavan® CE 1 solid cone nozzle used for the cut-surface and foliar treatments and a solid stream spray nozzle for the basal frill treatments.

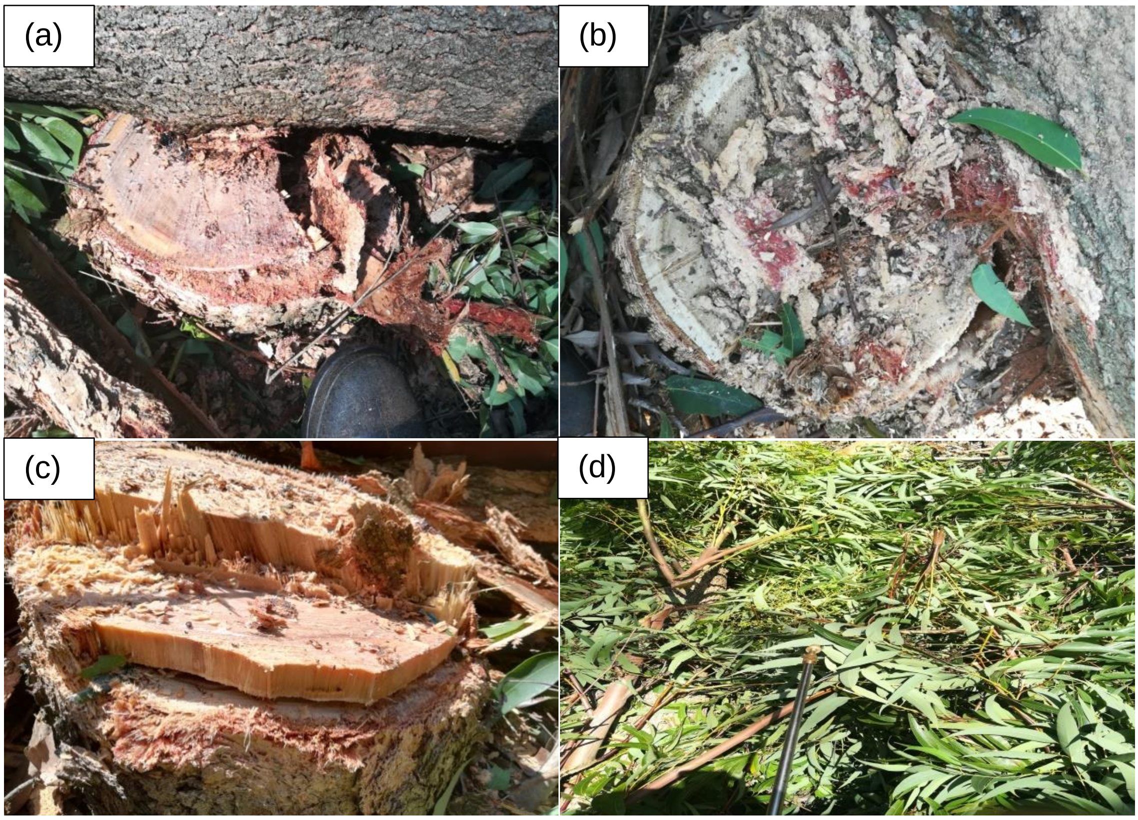

Figure 2.1: Images of different types of harvesting residues occuring on stumps following felling in an *Eucalyptus cloeziana* trial situated at Entabeni plantation (Limpopo, South Africa): (a) tree felled on top of a stump, (b) bark residue on top of a stump, (c) stump under-cut, (d) tree top covering stump.

Table 2.2: Herbicides and rates tested in combination with three methods of application for the killing of *Eucalyptus cloeziana* when felled at 12 years, Entabeni plantation (Limpopo, South Africa).

Herbicide (+ surfactant)		**Rates of herbicide application (%) for different three Application methods**		
Treatment/Trade name	**Active ingredient**	**Basal-frill**	**Cut-surface**	**Foliar**
Control	-	-	-	-
Garlon® +	triclopyr EC (480 g a.i. L^{-1})	2	2	1
Actipron Super®	emulsifiable mineral oil (820 g a.i. L^{-1})	0.5	0.5	0.5
Roundup® +	glyphosate (isopropylamine salt) SL (360 g a.i. L^{-1})	5	5	1.8
Actipron Super®	emulsifiable mineral oil (820 g a.i. L^{-1})	0.5	0.5	0.5
Garlon® +	triclopyr EC (480 g a.i. L^{-1})	1	1	1
Roundup® +	glyphosate (isopropylamine salt) SL (360 g a.i. L^{-1})	3	3	3
Actipron Super®	emulsifiable mineral oil (820 g a.i. L^{-1})	0.5	0.5	0.5

The use of trade names does not indicate endorsement of the product by Nelson Mandela University, and are included for the reader's benefit only

2.2.3 Measurements

Following felling, the height above-ground of each stump (cm) and the diameter of the cut surfaces (cm) were measured. To account for variable stump dimensions, the diameter was calculated as the mean of two readings, the first taken through the widest part of the stump and the second perpendicular to the first reading. This would allow for the determination of stump size (including volume), which could also be used as a co-variate if within-treatment differences were detected.

Treatment efficacy was quantified at 1, 3 and 6 months in three ways:

- **Stump survival**: The presence or absence of coppice regrowth was assessed for each stump. This would give an indication of treatment efficacy in terms of stump-kill. Where the treatments did not result in complete stump-kill, the Stump quarter and Coppice heath would provide an indication of coppicing vigour following treatment.
- **Stump quarter**: Coppice regrowth was assessed by dividing the stump into quarters (when viewed from above) and determining the presence or absence of coppice regrowth in each quarter.

- **Coppice health**: The foliage was assessed in terms of necrosis and discolouration with the use of a scoring method (0 = healthy; 1 = moderate; 2 = acute).

As the foliar treatment was implemented 1 month (31 days) after felling (once the coppice regrowth was 15-50 cm in height), only the Basal-frill and Cut-surface treatments would have been 6 months (185 days) at the final measurement, with the Foliar treatments 154 days after initial treatment.

2.2.4 Data analysis

Stump survival, Stump quarter and Coppice health were analysed to determine the effectiveness of the treatments. For all data, the assumptions were first checked prior to analysis (Shapiro-Wilk's test for normality and Levene's test for homogeneity of variance). An analysis of variance (ANOVA) appropriate for 3 x 4 Factorial arranged in a RCBD was then used to test treatment effects. Only where a *F*-value was significant ($p<0.05$), were treatment differences further investigated using the Student's *t*-test statistic (least significant differences). All analyses were carried on plot mean data using GenStat® for Windows™ (VSN International 2019). To ensure differences in stump diameter and heights (as a function of felling) did not influence the coppicing potential, they were included as co-variates. As they were not significant, they were excluded from further analyses.

2.3 Results and discussion

2.3.1 Stump measures.

Prior to the felling of the stand, the stocking was 816 stems ha^{-1}, which was a 26% reduction from the original planting density of 1 111 stems ha^{-1} (one thinning carried out at 18 months). The average stump diameters for the 12-year-old *E. cloeziana* trees were 26.50 cm (s.e. = 2.7; range = 23.0-28.7 cm). No significant treatment differences were detected for stump diameter following felling, indicating a degree of uniformity of the standing trees prior to felling. The mean stump diameters were used as co-variates during analysis to account for differences (if any) between the size of the stump and coppice regrowth, that is, the bigger the stump diameter the larger the stump volume, yet with a corresponding increase in the quantity of herbicide applied. As stump diameter was not significant when used as a co-variate (diameter did not influence treatment efficacy), the range of stump diameters tested in this trial were equally impacted by the treatments.

The stump heights ($\bar{x}$ = 11.4 cm; s.e. = 1.9; range = 8.80-20.05 cm) following harvesting were within the accepted range of 10-15 cm for manually felled stands in South Africa (Little 2000). Although no significant treatment differences were detected for stump height, there was high variability, with this variation indicating some inconsistency over the whole trial in terms of the height at which felling occurred. As no weeds were present on the site which would hinder access to the stems, slash was removed from around the base of each tree prior to felling, and only one chainsaw operator was used for the felling of all trees in the trial, this variability is most likely associated with either the underlying ground conditions or gradient of the slope.

Table 2.3: Summary of analysis of variance showing the mean squares for stump survival (%) at the final measurement (6 months after treatment) in a trial to test various herbicides and application methods for the killing of *Eucalyptus cloeziana* cut stumps when felled at 12 years, Entabeni plantation (Limpopo, South Africa).

Source of variation	**df**	**Stump survival (%)**
Rep	2	8.33
Herbicides	3	13633.33**
Application method	2	175.00^{ns}
Herbicide.Application method	6	275.00***
Residual	22	71.97
Total	35	
Grand mean		31.7
Standard error of differences of means (units)		6.9
Coefficient of variation (units) (%)		26.8
Levene's test for homogeneity (treatments)		22.12^{ns}
Shapiro-Wilk test for normality		0.785^{ns}

Note: **, *** indicates significance at $p<0.01$ and <0.001, and ^{ns} non-significance

2.3.2 Stump survival (presence or absence of coppice regrowth).

Stump survival at 6 months was significant for the main factor of Herbicides (F_{prob} = 0.001), and the interaction between Herbicide and Application method (F_{prob} = 0.009) (**Table 2.3**; **Figure 2.2**). Where no herbicide was applied, coppice regrowth was high (88.9%), with no significant differences between the various application methods. The 6 month survival equated to a further 11.1% decline in stump survival following felling (from 816 to 725 sph), and indicates that *E. cloeziana* coppices as well as other commercially grown eucalypts in SA, for example: *E. dunni* = 89.1% (Little 2004); *E. macarthurii = 97.5%* (Little and van den Berg, 2007)*; E. grandis* = 74.7 % (Little and du Toit 2003); and *E. grandis* x *E. urophylla* = 92.7% (Crous and Burger 2015).

Compared to the untreated controls, all herbicides and application methods tested resulted in a significant reduction in stump survival (**Table 2.3**). There were no significant difference between the Garlon, Roundup, or Garlon + Roundup treatments in terms of application method, with both herbicides (and herbicide combination) successful for killing stumps, irrespective of the application method used. All three herbicide treatments killed 75–90% of the stumps, when compared with the control (**Figure 2.2**). Similar results were achieved in trials comparing similar methods and herbicides to kill eucalypt stumps (Little et al. 1998; Little and van den Berg, 2007), where between 88 and 95 % of the stumps were killed.

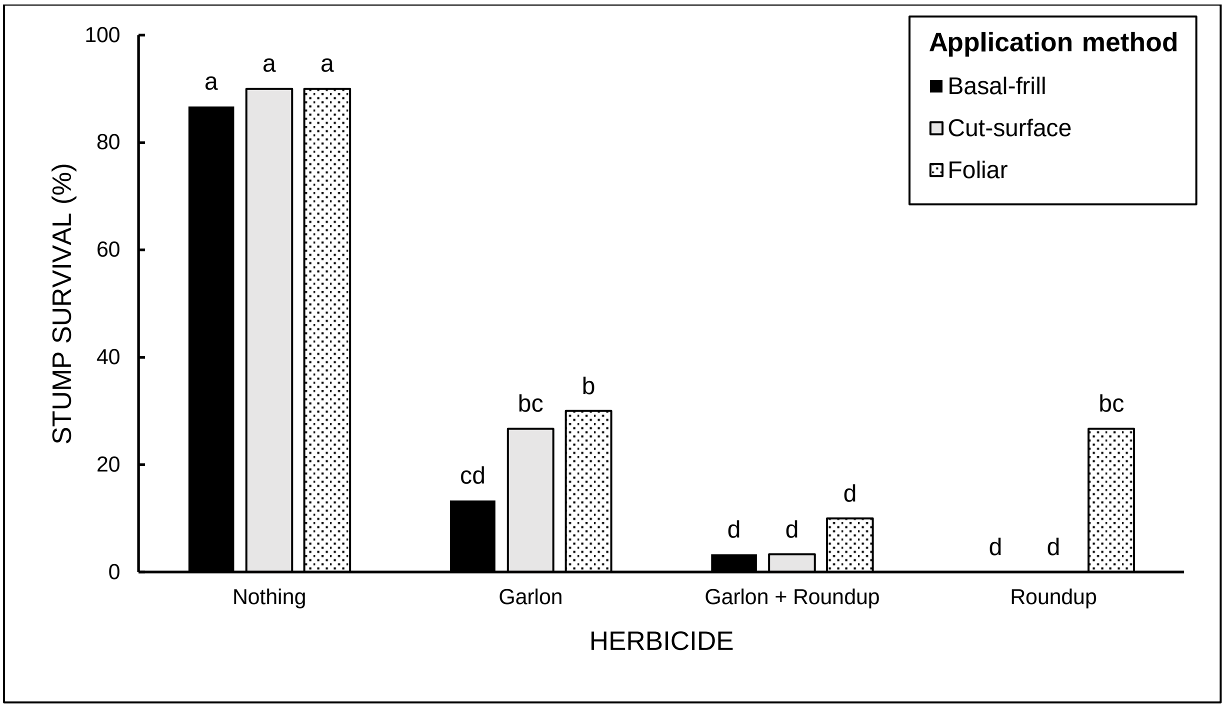

Figure 2.2: Stump survival (%) at 6 months in a trial to test various herbicides and application methods for the killing of *Eucalyptus cloeziana* cut stumps when felled at 12 years, Entabeni plantation (Limpopo, South Africa). Within treatment, different letters on bars indicate significant differences at $p<0.05$.

The application of herbicides as a Foliar spray was the least effective of the three application methods, with the Garlon or Roundup basal frill significantly better than the Foliar spray. In terms of application method, the Basal-frill was generally the best treatment in terms of killing stumps, with no significant differences between the 3 herbicides tested. In contrast to other studies where Garlon and/or Garlon + Roundup outperformed Roundup (Little et al. 1998; Little 2000; Little and Eccles 2000; Little and van den Berg 2007; Roberts et al. 2016), Roundup applied as a basal-frill in this trial was as effective as Garlon or Garlon + Roundup. This may in part be explained by the higher rates of Roundup application used in this study (5%) when compared to the 3% that was used in the other studies.

In this trial, the application of Garlon to the cut-surface was not as effective as the application of Roundup or Garlon + Roundup (26.7 % compared to 3.3% and 0% respectively). Reasons for this are unclear as studies comparing the application of Roundup, Garlon, or Roundup + Garlon by Sealander and Chomba (1989), Little et al. (2000) and Roberts et al. (2018) have shown Garlon to be as effective as, or better than Garlon + Roundup, or Roundup alone.

Of interest, in a study conducted at two sites in Sri Lanka, Reed et al. (2009) concluded that Roundup applied to the cut-surfaces of 75 x *E. camaldulensis* stumps was ineffective at the rates applied (4%), with no stumps killed. In contrast, Dickinson and Huth (2003) conducted a trial to determine the influence of Roundup applied at a high rate (15% a.i.) to *E. grandis*, *E. cloeziana* and *Corymbia citriodora* subsp. *variegata* cut-stumps during a thinning operation on the remaining stems (also termed “flashback”). They found that although flashback did occur (remaining trees negatively impacted), all the thinned stumps were killed. It is also possible that the effectiveness of Roundup in this trial could also be due to shading/competition from remaining trees in stand, in addition to the high rates applied.

2.3.3 Coppice health (abundance and phytotoxicity).

In addition to the overall presence or absence of coppice growth on a stump following felling and/or treatment, the vigour (coppice health) or abundance of any coppice that does regrow is also important. Limited phytotoxic symptoms and/or regrowth may mean that although there is coppice regrowth, it remains at a sub-competitive level during stand re-establishment, and will easily be controlled during routine weeding operations. Herbicide phytotoxicity may result in either mortality, reduced and/or abnormal growth, foliar necrosis and/or discolouration (European and Mediterranean Plant Organization 2014). Based on these categories, the three controls showed no signs of phytotoxicity, with no negative visual impacts on growth recorded and with new sprouts and/or healthy leaves occurring on all the coppice (100%). This was expected as no herbicides were applied in these treatments. In contrast discolouration (chlorosis and necrosis) and reduced growth (smaller in size) occurred in all the nine herbicide application method treatments. Coppice growth was also assessed by dividing the stumps cut-surface into quarters and scoring the presence of coppice regrowth in each quarter (maximum score of 4). Coppice abundance for the untreated controls was the highest with 86.7%, 90% and 90% recorded for the Basal-Frill, Cut-Surface and Foliar treatments at 6 months. For all other treatments there was a decrease over time in the number of stump quarters with coppice (**Figure 2.3**). This indicates that:

- although coppice regrowth did occur on the treated stumps (albeit significantly less than for the untreated controls), this regrowth was not vigorous;
- coppice health should be taken into consideration, together with the scoring for presence of coppice regrowth, to provide a more comprehensive understanding of treatment effectiveness; and
- future studies should consider the impact of this suppressed regrowth on newly planted trees (if any), as well as the ability to kill this remaining coppice regrowth during routine weeding operations (where weeds are sprayed with glyphosate at ca. 4 L ha^{-1})

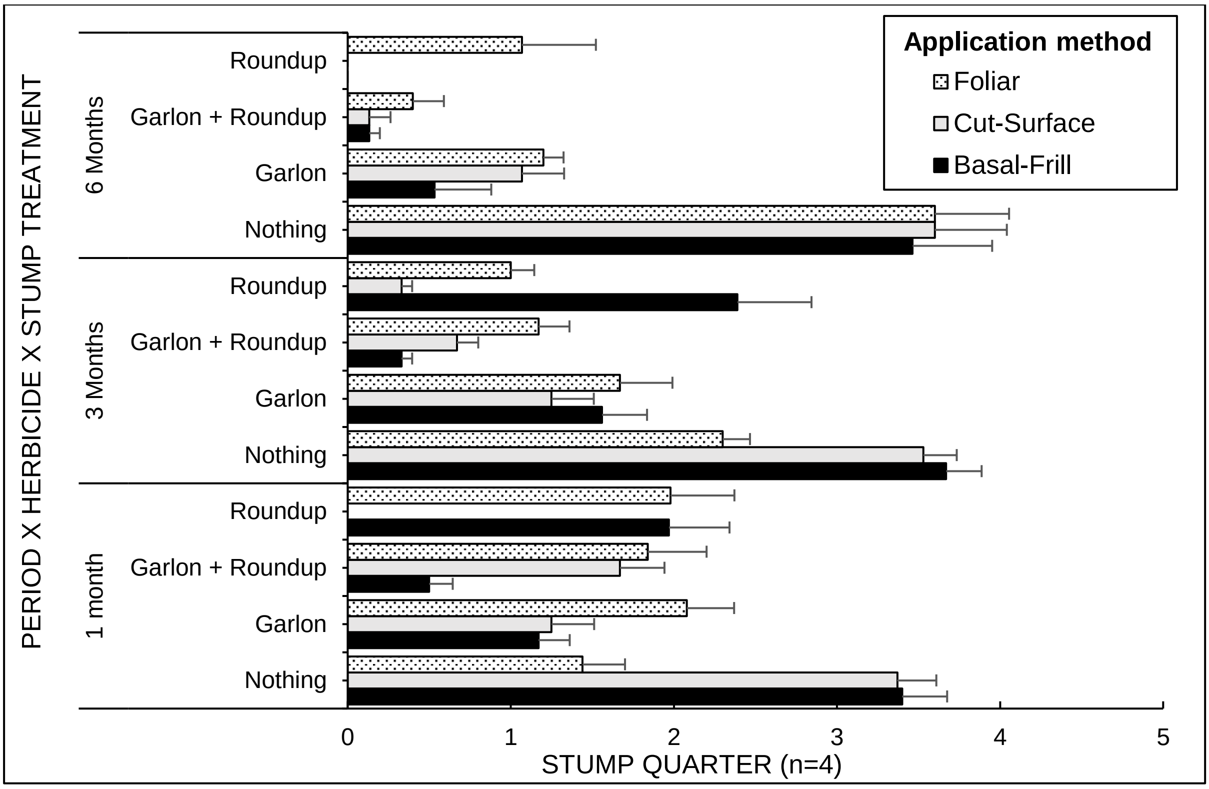

Figure 2.3: Stump quarters (n = 4) with coppice growth when assessed 1, 3 and 6 months after felling in a trial to test various herbicides and application methods for the killing of *Eucalyptus cloeziana* cut stumps when felled at 12 years, Entabeni plantation (Limpopo, South Africa). Bars on the graph indicate confidence interval values (p<0.05) for each measurement date.

2.4 Conclusion

A trial was established in 2018 at Entabeni plantation (Limpopo Province) to quantify the interaction between Application method (basal-frill; cut-surface; foliar) and Herbicide (no herbicide applied; Roundup; Garlon; Roundup + Garlon) for the killing of *Eucalyptus cloeziana* 12 year-old stumps following harvesting.

Relative to the control plots (100% survival), all herbicides tested were equally effective (70-90% of the stumps killed), with the cut-surface and basal-frill application providing significantly better control than the foliar application. These results are encouraging as they confirm previous research comparing similar application methods for the killing of eucalypt stumps, indicating that current recommendations can be extended to include *Eucalyptus cloeziana*, even if the stumps are larger as a consequence of the longer rotation (12 years).

In contrast to previous research, the use of Roundup alone was equally effective as Garlon, or Roundup + Garlon, possibly due to the higher rates of application as applied in this trial. In this trial Roundup was applied at 5%, whereas in previous research conducted in South Africa it was applied at 3%. This result is encouraging as it provides the forester with more options in terms of potential treatments.

Any treatment where the stump is killed with a once-off herbicide application, and is the most cost-effective would be the preferred method for killing *Eucalyptus cloeziana* stumps. As such, future studies should focus on the costs per treatment to understand, and choose the best herbicide/application method combination.

CHAPTER 3

Testing of herbicide/surfactant combinations at two rates for the killing of *Eucalyptus cloeziana* stumps, South Africa.

Abstract

Background: In South Africa, various *Eucalyptus* spp. make up 52.0% of the plantation area, and are grown mainly due to their desirable pulping and paper properties. When felled, eucalypts are able to regenerate though the production of new coppice shoots, which if not killed prior to replanting the stand, will likely compete with the newly planted seedlings. Although herbicides are considered the most effective means for the killing of eucalypt stumps, there is also the need to find ways in which the amounts of any herbicides used can be reduced, without compromising their efficacy. One way in which this may be possible is through the use of surfactants, which can be either used to improve efficacy (enhance or modify the performance of the solution), and/or reduce the amount of herbicide applied. A trial was implemented in 2018 (Venda, South Africa) on a recently felled stand of 12 year-old *Eucalyptus cloeziana* to determine if the addition of natural/synthetic surfactants (with different modes of action) would allow for reduced rates of herbicide application without compromising efficacy.

Methods: The main factors and treatments were **Herbicide** (Roundup, Garlon, or Garlon + Roundup), **Surfactant** (Nu-film, Orosorb and Breakthru) and **Rate** of application (recommended herbicide rate + recommended surfactant rate: 1x_1x; half recommended herbicide rate + double surfactant rate: 0.5x_2x). The 18 treatments were arranged as a 3 x 3 x 2 factorial, replicated three times and laid out in a randomised complete blocks design (RCBD). Treatment efficacy in terms of stump survival (%) was assessed at 6 months, with the vigour of any coppice regrowth assessed in terms of coppice health (0 = healthy; 1 = moderate; 2 = acute) and stump quarter with coppice present (n = 4).

Results*:* Overall stump survival for the whole trial at 6 months was 20.7%, although there was a wide range in terms of the individual treatments tested (0-70%). Stump

survival at 6 months was significant for the main factor of **Herbicide**, **Surfactant** and **Rate** (all $F_{prob}<0.001$), with no significant interactions between the main factors detected. Roundup (16.1%) and Garlon + Roundup (16.7%) were not significantly different from each other, but both were significantly better than Garlon (29.4%). Breakthru (16.7%) and Orosorb (16.1%) were not significantly different from each other, but both had significantly lower stump survival when compared to Nu-Film (29.4%). The recommended herbicide + surfactant rate was significantly better at killing stumps than where half the recommended herbicide + double surfactant rate were tested (stump survival: 1x_1x = 7.8%; 0.5x_2x = 33.7%). For those stumps that were not killed, all herbicide and surfactant combinations (regardless of treatment) resulted in reduced coppice regrowth (reduced stump quarters) that was also regarded as unhealthy (lowered coppice health). This is of benefit to the forestry industry in that even if the compartment were to be re-planted at 4-6 months, the coppice regrowth occurring on any surviving stumps could still be more easily managed than if the stumps were not treated.

Conclusions: Whilst the results (in terms of killing of eucalypt stumps) obtained from this trial in terms of the herbicides and surfactants tested support previous research, the significantly reduced efficacy of the herbicides when applied at half the recommended rate (with double the surfactant rate) was disappointing.

3.1 Introduction

The forest industry in South Africa relies on plantations of exotic forestry species (pines, eucalypts and wattle) to fulfil its timber demands (Albaugh et al. 2013; Godsmark 2017). The area under plantations cover more than 1.19 million hectares, (representing only 1% of the land area), with 360 000 trees planted every working day (more than 90 million trees planted anually). Furthermore, the forest industry produces ca. 8.7% of the gross value of the agricultural product (which includes forestry) (DAFF 2020).

Eucalyptus spp. are considered an important component of the South African forestry industry due to their desirable pulping and excellent paper properties. Of the 1.19 million ha of plantation forests in the country, about 52.0% of the area is planted to various eucalypt species and their hybrid combinations (Adam et al. 2013).

Compared to other commercially grown species (pines and wattle), eucalypt species are able to produce new shoots from their stumps after being felled (Farmer 1962; Florence 1996). Although these shoots may develop from four recognized bud types, only the lignotubers and epicormic buds situated in the live bark or cambium at the base of the stumps are responsible for coppice regrowth after felling (Leyser 2005). On healthy trees, the growth of these buds is prevented by the production of the growth hormone (auxin). When the tree is under stress (for example from loss of foliage due to drought or insect feeding), or during harvesting, the production of auxin is removed/reduced, resulting in the development of the remaining buds (Leyser 2005).

Eucalyptus cloeziana was first noted in Australia in 1878 by Ferdinand von Mueller from a specimen collected near Rockingham Bay (Dickson and Huth 2003). It was described as a fast growing hardwood which could be easily propagated by seed to produce a “Class 1” durable timber of cylindrical shape (limited dimensional difference from top to bottom), and with few to no knots on the stem (Brink 2020).

Eucalyptus cloeziana is able to withstand adverse environmental conditions (for example drought), and is resistant to biological pests such as the *Eucalyptus* snout beetle (*Gonipterus cutellatus*) (Brink 2020). Like most eucalypt spp., *E. cloeziana* is also able to regenerate via coppice. *E. cloeziana* is grown by SAFCOL in Limpopo Province on an 8-15 year rotation-length, mainly for the production of poles. The climate in this region is warm temperate with a mean annual temperature and mean annual rainfall of 19°C and 1 050-1 300 mm (respectively), and at an altitudinal range around 729 m a.s.l.

As the rapid initial growth of coppice shoots requires prompt, intensive control (relative to normal weeding), site preparation (which includes the management of stumps and/or killing of coppice regrowth) is important in compartments previously planted with eucalypts (Little and van den Berg 2007). Due to the repeated application of chemical weed control during, and following site preparation is expensive, one of the major challenges associated with re-establishment is to find/develop more efficient and cost-effective methods for site preparation (including that of killing stumps) (Hjelm et al. 2019). The primary goal in terms of killing stumps would be to reduce the costs associated with the number of compartment visits (preferably once) (Hjelm et al. 2019), with herbicides forming an important component of any management strategy. However care needs to be taken when selecting and using herbicides so as to reduce any environmental impacts, and any misapplication or overspray onto young seedlings (Bai et al. 2014).

The South African forestry industry adheres to the principles of sustainable forest management, which are endorsed through certification bodies such as the programme for Endorsement of Forest Certification (PEFC), International Organization for Standardization (ISO), and Forest Stewardship Council (FSC). These certification bodies have three main objectives associated with pesticide use: (i) the elimination of the use of any hazardous chemical pesticides; (ii) a reduction in the overall volume and number of chemical pesticides used; and (iii) the promotion of the best practices to minimize associated risks to human health and the environment when using chemical pesticides (FSC 2019).

All certified organizations require the development and use of integrated pest management (IPM) to avoid/eliminate/reduce the use of chemical pesticides, and to minimize risks to human health and the environment while maintaining economically viable management (FSC 2019). Therefore, any research conducted on the use of pesticides for application in certified forests should take into consideration these objectives, with the main aim of reducing the amounts of those pesticides which are considered environmentally acceptable (Roberts et al. 2016). Surfactants are products that can be used to improve efficacy (enhance or modify the performance of the solution), and/or reduce the amount of herbicide applied, and are grouped depending on their mode of action (stickers, penetrants, wetting agents, spreaders) (Hess 1999;

Hazen 2000; Hao et al. 2019). According to Hess (1999): surfactants promote absorption by bringing herbicides into a more direct contact with the leaf surface, while keeping it in a soluble form for longer; spray modifiers alter the wetting, spreading or sticking characteristics of the spray solution; and activators/surfactants influence the absorption of the herbicide by direct interaction with the plant cuticle. Surfactants may form part of the formulation (Blanco et al. 2009), or need to be mixed with the pesticide (tank-mix) prior to application (Hazen 2000; Dzardanov et al. 2015; Hao et al. 2019). If effective, surfactants can be used to fulfil some of the objectives (as required by certification organisations) regarding pesticide use through a reduction in herbicide quantities and/or improved herbicide efficacy.

Currently in South Africa, the application of registered herbicides as foliar, cut-surface and/or as basal-bark application on *Eucalyptus* are the most effective methods of control. Herbicide applied to the cut-surface are the preferred and most commonly used method, as compared to a basal-frill and foliar, it is as (or more) effective, less labour intensive, and requires a smaller quantity of herbicide. These aspects in combination allow for greater herbicide control in terms of affecting non-target species or the environment through soil/water contamination (Tu et al. 2001). A cut-surface application requires herbicide to be applied onto the cambium onto a horizontally cut-stump after harvesting (Little and van den Berg 2006). The diameter of the stem will determine the implement used to make the cut, and can include a chainsaw, axe, brush cutter, slasher or a bush knife. To prevent the cut-stump from sprouting, herbicide should be applied to the entire inner bark (cambium) using a backpack sprayer with hand wand, or handheld spray bottles within 1-2 hours (Newman and Stringer 2016).

Previous research conducted on the killing of *Eucalyptus cloeziana* stumps using herbicides, showed that 70-90% stump were killed through the once-off application of glyphosate or triclopyr when applied within 30 minutes after felling (see Chapter 2 – this thesis). The use of natural, or synthetic surfactants in combination with herbicides (glyphosate or triclopyr), if effective would be advantageous in terms of improved efficacy, and/or a reduction in the amount of herbicide applied (Hazen 2000). A trial was implemented in 2018 (Venda, South Africa) on a recently felled stand of *Eucalyptus cloeziana* to determine if the addition of natural/synthetic surfactants (with different modes of action) would allow for reduced rates of herbicide application without compromising efficacy.

3.2 Materials and Methods

3.2.1 Study site

A site was selected at Entabeni plantation (Limpopo Province) which was considered typical for the growth of *E. cloeziana* for the production of transmission poles (**Table 3.1**). The trial was implemented when felled at rotation age (13 years), on single stems of seedling origin (previously not coppiced).

Table 3.1: Site characteristics and information in a trial testing herbicide/surfactant combinations at two rates for the killing of *Eucalyptus cloeziana* stumps, Entabeni plantation (Limpopo, South Africa).

Plantation	**Entabeni Plantation (Limpopo Province)**
Co-ordinates (Lat; Long)	23° 12' S; 28° 38' E
Altitude (m a.s.l.)	887
MAT (°C)	19
MAP (mm yr^{-1})	1 050-1 300 mm
Climatic Region	Sub-tropical
Species	*E. cloeziana*
Age when felled (years)	13 (planted 12 June 2005)
Soil form	Red apedal dystrophic soil
Parent material	Granite
Effective rooting depth (m)	1.5
Texture (0.15 cm)	Clay (35%)
Organic carbon (%) (0-15 cm)	7.2
Treatments assessed (months)	1 (31 days), 3 (94 days), 6 (180 days)
Trial size (Ha)	0.437

3.2.2 Treatments

The treatments consisted of a 3 x 3 x 2 arrangement of 18 treatments. The main factors and treatments were **(Table 3.2)**:

Herbicide (Roundup, Garlon, or Garlon + Roundup):

These three herbicides were selected based on previous research that showed their effectiveness for the killing of eucalypts when applied to the cut-surface (see Chapter

2 – this thesis). In addition, only those herbicides with low environmental toxicity and that are registered for use in SA forestry were tested.

Surfactant (Nu-film, Orosorb and Breakthru):

These surfactants were selected due to differing modes of action. Nu-film and Orosorb are natural products, which enhance the sticking and wetting (respectively) of the herbicide. Although Breakthru is a synthetic product, it was selected as it is a spreader/penetrant which facilitates the transport of active ingredients through the protective layers and barriers in a plant/leaf.

Rate (recommended herbicide rate + recommended surfactant rate: **1x_1x**; half recommended herbicide rate + double surfactant rate: **0.5x_2x**):

The recommended herbicide and surfactant rates were based on previous research and/or label recommendations. Double the recommended surfactant rate (200%) was combined with half the recommended herbicide rate (50%), which if effective would serve as a guide/baseline for future research investigating the use of surfactants for reducing the amount of herbicide-use, without the loss of efficacy.

The 18 treatments were replicated three times and laid out in a randomised complete blocks design (RCBD).

Each treatment plot consisted of 3 rows of 12 trees (36 tree plot^{-1}). Although all trees within each plot were treated, only the centre row of 10 trees were used for assessments (two buffer rows of trees between adjacent plots). Prior to spraying, all plots were laid out and marked with white paint on the base of the trees to allow for identification once the trees were felled.

Herbicides for all the treatments were applied to just prior to runoff to ensure full cover of the herbicide over the entire cambium layer. A Solo®435 backpack sprayer regulated to 1.5 kPa was used for all spraying, with a Delavan® CE 1 solid cone nozzle used.

Table 3.2: Herbicides, surfactants and rates tested for the killing of *Eucalyptus cloeziana* stumps, Entabeni plantation (Limpopo, South Africa)

Herbicide + Surfactant[1]	**Active ingredient**		**Rate of application**			
	Herbicide	**Surfactant**	**1x_1x**		**0.5x_2x**	
			Herbicide	**Surfactant**	**Herbicide**	**Surfactant**
Actipron Super®[2]		mineral oil (820 g a.i. L^{-1})		0.5%		0.25%
Garlon® + Break-Thru®	triclopyr EC (480 g a.i. L^{-1})	polyether-polymethylsiloxane-copolymer (1 000 g a.i. L^{-1})	2%	0.3%	1%	0.6%
Garlon® + Nu-Film P®	triclopyr EC (480 g a.i. L^{-1})	poly-1-menthene (975 g a.i. L^{-1})	2%	0.3%	1%	0.6%
Garlon® + Orosorb®	triclopyr EC (480 g a.i. L^{-1})	orange oil (50 g a.i. L^{-1})	2%	0.3%	1%	0.6%
Garlon® + Roundup® + Break-Thru®	triclopyr EC (480 g a.i. L^{-1}) glyphosate isopropylamine salt (360 g a.i. L^{-1})	polyether-polymethylsiloxane-copolymer (1 000 g a.i. L^{-1})	1% 3%	0.3%	0.5% 1.5%	0.6%
Garlon® + Roundup® + Nu-Film P®	triclopyr EC (480 g a.i. L^{-1}) glyphosate isopropylamine salt (360 g a.i. L^{-1})	poly-1-menthene (975 g a.i. L^{-1})	1% 3%	0.3%	0.5% 1.5%	0.6%
Garlon® + Roundup® + Orosorb®	triclopyr EC (480 g a.i. L^{-1}) glyphosate isopropylamine salt (360 g a.i. L^{-1})	orange oil (50 g a.i. L^{-1})	1% 3%	0.3%	0.5% 1.5%	0.6%
Roundup® + Break-Thru®	glyphosate isopropylamine salt (360 g a.i. L^{-1})	polyether-polymethylsiloxane-copolymer (1 000 g a.i. L^{-1})	5%	0.3%	2.5%	0.6%
Roundup® + Nu-Film P®	glyphosate isopropylamine salt (360 g a.i. L^{-1})	poly-1-menthene (975 g a.i. L^{-1})	5%	0.3%	2.5%	0.6%
Roundup® + Orosorb®	glyphosate isopropylamine salt (360 g a.i. L^{-1})	orange oil (50 g a.i. L^{-1})	5%	0.3%	2.5%	0.6%

[1] The use of trade names does not indicate endorsement of the product by Nelson Mandela University, and are included for the reader's benefit only;

[2] Actipron Super® was added to all herbicides and herbicides mixture

3.2.3 Measurements

Following felling, the height above-ground of each stump (Stump_ht in cm) and the diameter of the cut-surfaces (Stump_diam in cm) were measured. To account for variable stump shapes, the diameter was calculated as the mean of two readings, the first taken through the widest part of the stump and the second perpendicular to the first reading. This would allow for the determination of stump size (including volume), which could also be used as a co-variate if within-treatment differences were detected.

Treatment efficacy was quantified at 1, 3 and 6 months in three ways:

- **Stump survival**: The presence or absence of coppice regrowth was assessed for each stump, with the presence recorded as a plot mean. This would give an indication of treatment efficacy in terms of stump-kill. Where the treatments did not result in complete stump-kill, Stump quarter and Coppice health would provide an indication of coppicing vigour following treatment.
- **Stump quarter**: Coppice regrowth/abundance was assessed by dividing the stump into quarters and determining the presence or absence of coppice regrowth in each quarter.
- **Coppice health**: The foliage was assessed in terms of necrosis and discolouration with the use of a scoring method (0 = healthy; 1 = moderate; 2 = acute)

3.2.4 Data analysis

Stump survival data were analysed to determine the effectiveness of the treatments. As the assumptions for a valid analysis of variance were violated (Shapiro-Wilk's test for normality and Levene's test for homogeneity of variance) the data received a square root transformation ($y = (x+10)^{0.5}$) prior to carrying out an analysis of variance (ANOVA) appropriate for 3 x 3 x 2 Factorial arranged in a RCBD **(Table 3.3)**. Only where the *F*-value was significant ($p<0.05$), were treatment differences further investigated using the Student's *t*-test statistic (least significant differences). As the significance between factors and treatments were the same for the untransformed and transformed data, the data was displayed **(Figure 3.1)** using untransformed data (for the readers benefit). All analyses were carried on plot mean data using GenStat® for Windows™ (VSN International 2019). To ensure differences in stump diameter and heights (as a function of felling) did not influence the coppicing potential, they were included as co-variates. As they were not significant, they were excluded from further analyses. Stump quarter and Coppice health were displayed graphically using descriptive statistics (means and 95% confidence intervals) **(Figures 3.2 and 3.3)**.

Table 3.3: Summary of analysis of variance showing the mean squares for stump survival (%) at the final measurement (6 months after treatment) in a trial testing herbicide/surfactant combinations at two rates for the killing of *Eucalyptus cloeziana* stumps, Entabeni plantation (Limpopo, South Africa).

Source of variation	**df**	**Stump survival (sqrt transformed)**
Rep	2	1.16^{ns}
Herbicide	2	8.75***
Surfactant	2	6.24***
Rate	1	75.66***
Herbicide.Surfactant	4	0.72^{ns}
Herbicide.Rate	2	1.31^{ns}
Surfactant.Rate	2	0.37^{ns}
Herbicide.Surfactant.Rate	4	1.12^{ns}
Residual	34	0.77^{ns}
Total	53	
Grand mean		5.3 (20.7%)
Standard error of differences of means (units)		0.716
Coefficient of variation (units) (%)		16.6
Bartlett’s test for homogeneity (treatments) (17 df)		1.62^{ns}

Note: ***signifies significance at *p*<0.001 and ^{ns} non-significance

3.3 Results and discussion

Stump height ($\bar{x}$ = 10.8 cm; s.e. = 0.16; range = 8.5-13.7 cm) and stump cut-surface diameter ($\bar{x}$ = 26.8 cm; s.e. = 0.21; range = 23.0-30.0 cm) measures were taken to provide an indication of stump size, as well as to be used as co-variates to describe the relationship between the shape, form and size of the stumps and coppice. Although more herbicide could be applied to the cut-surface of stumps with larger than smaller diameters, the amount of herbicide relative to the size (volume) may be less. If significant differences were detected, this information would have been useful for determining the minimum/maximum stump diameter, above/below which the treatment was no longer effective. Stump height and diameter were not significant when analysed as individual variates, or when used as co-variates, indicating a degree of uniformity of the standing trees prior to felling, the heights at which they were felled, and that for this trial, stump size did not have a significant impact on the outcomes of the various treatments tested.

The trees were planted at a density of 1 111 stems ha^{-1} (3 x 3 m spacing), with only 816 stems ha^{-1} (after thinning) remaining prior to felling. Overall stump survival for the whole trial at 6 months was 20.7%, although there was a wide range in terms of the individual treatments tested (0-70%). Stump survival at 6 months was significant for the main factor of **Herbicide** (F_{prob}<0.001), **Surfactant** (F_{prob}<0.001) and **Rate** (F_{prob}<0.001), with no significant interactions between the main factors detected (F_{prob} = 0.05) (**Table 3.3**; **Figure 3.1**).

3.3.1 Herbicide as a main effect:

For **Herbicide** as a main factor, significant differences (F_{prob}<0.001) occurred in terms of stump survival, with Roundup (16.1%) and Garlon + Roundup (16.7%) not significantly different from each other, but both significantly better than Garlon (29.4%). Similar results were achieved by Little et al. (2000), where triclopyr (Garlon) and triclopyr + glyphosate (Garlon + Roundup) resulted in 26% and 10% stump survival. However, based on previous trial results where Garlon was tested for the killing of eucalypt stumps (Little et al. 1998; Little and Eccles 2000; Little and van den Berg

2007; Roberts et al. 2016), lower levels of survival were achieved than obtained in this trial.

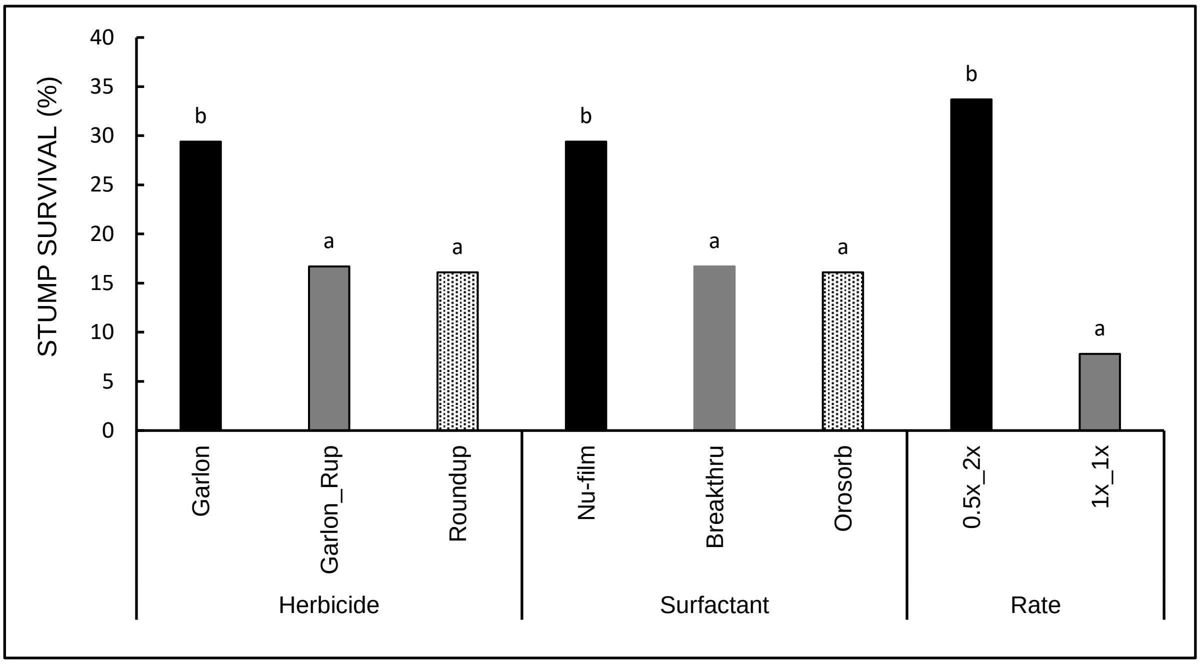

Figure 3.1: Six-month Stump survival (%) for the main factors of Herbicide, Surfactant and Rate in a trial testing herbicide/surfactant combinations at two rates for the killing of *Eucalyptus cloeziana* stumps, Entabeni plantation (Limpopo, South Africa). Within each factor, letters on bars indicate significant difference (*p*<0.05).

3.3.2 Surfactants as a main effect:

There was a significant difference (F_{prob}<0.001) between the surfactants tested in terms of stump survival. Breakthru (16.7%) and Orosorb (16.1%) were not significantly different from each other, but both had significantly lower stump survival when compared to Nu-Film (29.4%). This could be due to the nature of the surfactants tested which would have enhanced uptake and thus efficacy. Break-thru is a penetrant which would have enhanced herbicide uptake, and Orosorb is a spreader, which would have resulted in the uniform coverage of the herbicide over the cut-surface. In contrast, Nu-Film is a sticker that forms an elastic film on the sprayed surface, and as such this may have prevented herbicide penetration and uptake.

Herbicides are efficient when applied at the correct rates of application and in the appropriate manner (Self et al. 2019), with research indicating improved efficacy from the herbicide-surfactant combinations through improved spray deposition, penetration and retention on the target species (Gaskin and Murray 1997; Hess 1999; Rolando et al. 2014; Letaoana 2018). However within this trial, although Nu-Film was not as effective as Breakthru or Orosorb, the rates of application tested did not result in improved efficacy.

3.3.3 Rate as a main effect:

The rate of herbicide plus surfactant applied had a significant ($F_{\text{prob}}<0.001$) impact on stump survival. The recommended herbicide + surfactant rate was more successful than where half the recommended herbicide + double surfactant rate were tested (stump survival: 1x_1x = 7.8%; 0.5x_2x = 33.7%). Although this result is disappointing, it does support herbicide label recommendations, and previous research in terms of optimum rates of application.

Although not significant, Roundup + Orosorb and Garlon + Roundup + Breakthru were the best of the treatments that were applied at half the recommended herbicide + double surfactant rate (both resulting in 76.7% mortality) indicating the potential for further testing of these herbicide + surfactant combinations.

3.3.4 Coppice health and abundance

In addition to the overall presence or absence of coppice growth on a stump following felling and/or treatment, the vigour (coppice health) or abundance of any coppice that does regrow is also important (**Figures 3.2 and 3.3**). Higher phytotoxic symptoms and/or regrowth may mean that although there is coppice regrowth, it remains at a sub-competitive level during stand re-establishment, and will easily be controlled during routine weeding operations.

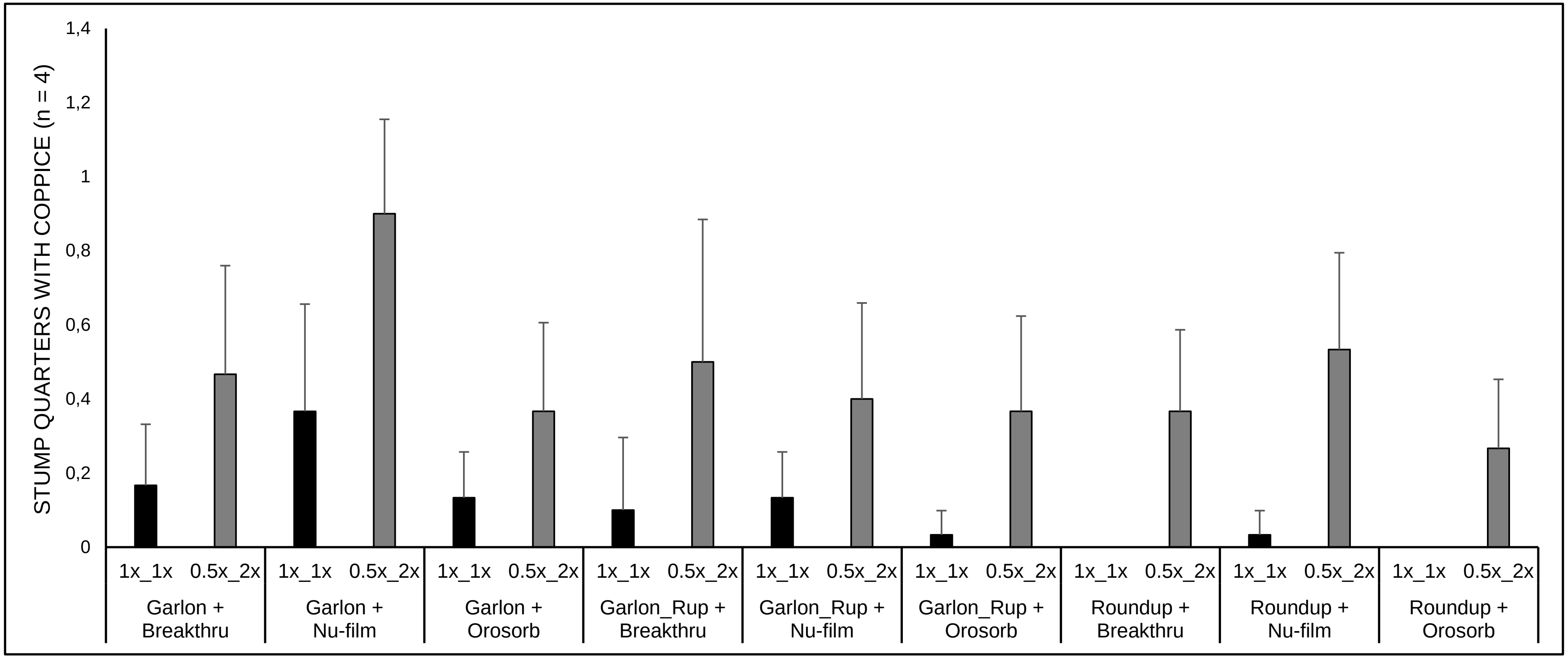

Figure 3.2: Six-month Stump quarters with coppice (n = 4) in a trial testing herbicide/surfactant combinations at two rates for the killing of *Eucalyptus cloeziana* stumps, Entabeni plantation (Limpopo, South Africa). Bars on means indicate 95% confidence intervals.

If coppice regrowth is present on stumps following treatment, its occurrence can be expressed in terms of the number of stump quarters within which it occurs (maximum score of 4). Although the overall score was low ($\bar{x} = 0.28$), in general those treatments which were least effective in terms of stump kill **(Figure 3.1)** also had a higher score in terms of stump quarters with coppice regrowth: Herbcide: Garlon ($\bar{x} = 0.4$) > Garlon + Roundup ($\bar{x} = 0.26$) > Roundup ($\bar{x} = 0.20$); Surfactant: Nu-film ($\bar{x} = 0.39$) > Breakthru ($\bar{x} = 0.27$) > Orosorb ($\bar{x} = 0.19$); Rate: 0.5x_2x ($\bar{x} = 0.46$) > 1x_1x ($\bar{x} = 0.11$) **(Figure 3.2)**. In addition, the coppice regrowth that did occur also received a higher score in terms coppice health (higher score = unhealthy), with the 1x_1x ($\bar{x} = 0.06$) resulting in higher scores for most treatments than the 0.5x_2x ($\bar{x} = 0.02$) rates of application **(Figure 3.3)**. This is due to the higher levels of active ingredients applied in the 1x_1x treatments.

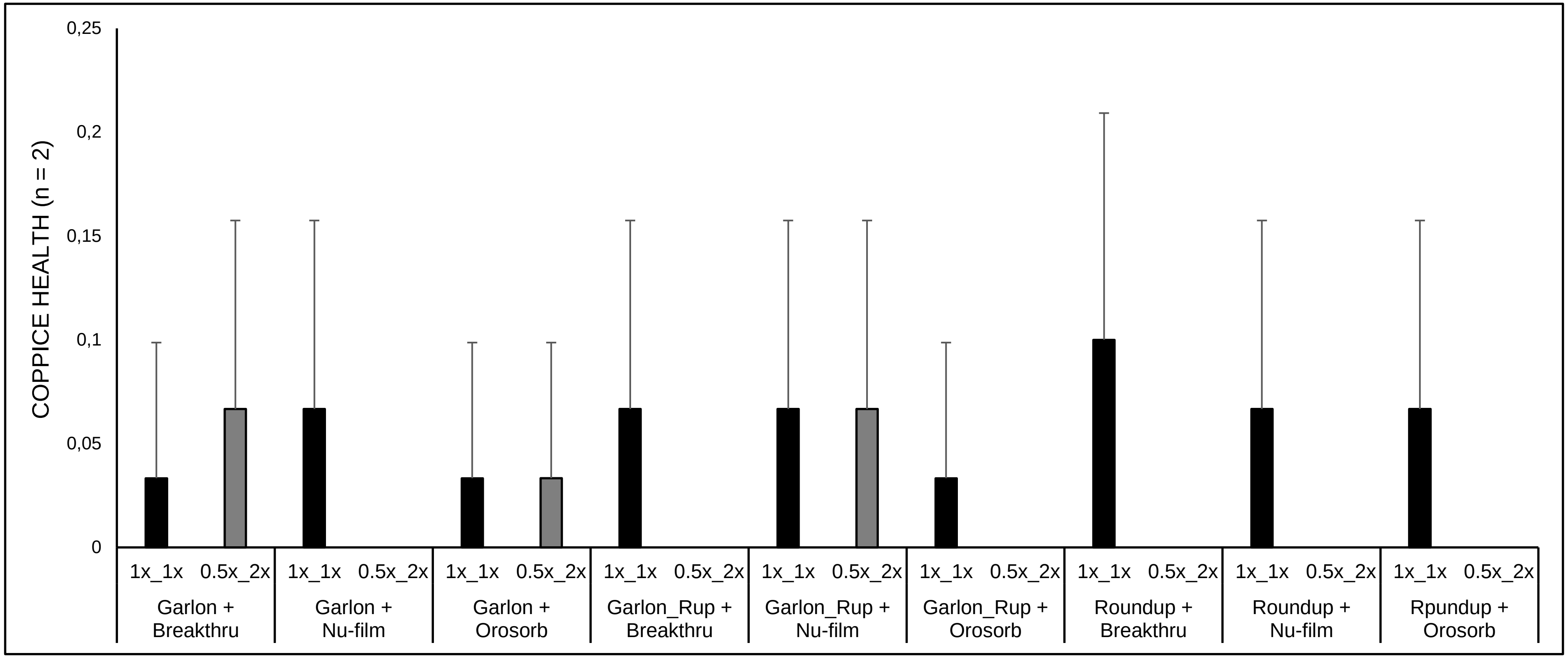

Figure 3.3: Six-month Coppice health (0 = healthy; 1 = moderate; 2 = acute) in a trial testing herbicide/surfactant combinations at two rates for the killing of *Eucalyptus cloeziana* stumps, Entabeni plantation (Limpopo, South Africa). Bars on means indicate 95% confidence intervals.

3.4 Conclusions

A trial was implemented in 2018 (Venda, South Africa) on a recently felled stand of *Eucalyptus cloeziana* to determine if the addition of natural/synthetic surfactants (with different modes of action) would allow for reduced rates of herbicide application without compromising efficacy.

Although stump survival at 6 months was significant for the main factors of **Herbicide**, **Surfactant** and **Rate**, there were no significant interactions between the three factors tested. Of the herbicides tested, Roundup (16.1%) and Garlon + Roundup (16.7%) were not significantly different from each other, but both were significantly better than Garlon (29.4%). Of the surfactants tested, Breakthru (16.7%) and Orosorb (16.1%) were not significantly different from each other, but both had significantly lower stump survival when compared to Nu-Film (29.4%). In addition, the recommended herbicide + surfactant rate was significantly better at killing stumps than where half the recommended herbicide + double surfactant rate were tested (stump survival: 1x_1x = 7.8%; 0.5x_2x = 33.7%).

Whilst the results (in terms of killing of eucalypt stumps) obtained from this trial in terms of the herbicides and surfactants tested support previous research, the significantly reduced efficacy of the herbicides when applied at half the recommended rate (with double the surfactant rate) was disappointing. If not significantly different from the recommended herbicide + surfactant rate, this would have enabled a reduction in herbicide-use, without loss of efficacy. Nevertheless, these results do confirm current label recommendations in terms of rates of application.

For those stumps that were not killed, all herbicide and surfactant combinations (regardless of treatment) resulted in reduced coppice regrowth (fewer stump quarters with coppice) that was regarded as unhealthy (lowered coppice health score). This is of benefit to the forestry industry in that even if the compartment were to be re-planted at 4-6 months, the coppice regrowth occurring on any surviving stumps could still be more easily managed than if the stumps were not treated.

CHAPTER 4

Influence of time after herbicide/surfactant application on eucalypt cut-stump survival

Abstract

Background: Plantation management practices have recently come under scrutiny with respect to their social (including health and safety) and environmental impacts. In response, there has been accelerated development of mechanised systems in the South African forest industry over the past decade so as to improve the ergonomics amongst forestry workers, and reduce their exposure to safety risks.

In a compartment previously planted to *Eucalyptus* spp., it is critical to kill stumps before replanting due to the rapid growth of coppice sprouts outcompeting newly planted seedlings. Previous research has shown that the application of registered herbicides to a stump within 0.5 hrs of felling will provide 70-90% control. In stands that are mechanically harvested, access to the site/stump is restricted (including the manual application of herbicides) until the timber has been extracted (up to 48 hrs). With the move towards safety associated with felling operations, and hence the inability to apply herbicides within 0.5 hrs following harvesting, questions were raised as to the testing of potential herbicide and surfactant combinations that could be applied once the timber has been extracted (up to 48 hrs after felling) without compromising efficacy.

Methods: A trial was implemented at Wilgeboom Plantation (Mpumalanga, South Africa) on 24 year-old *E. grandis* cut-stumps when felled in 2018. The main factors tested were **Herbicide** (Roundup and Garlon), **Surfactant** (Breakthru and Orosorb) and **Application time** (0.5, 6, 24, 48 hrs). The herbicides and surfactants were selected based on past research in terms of known treatment efficacy. The 2 x 2 x 4 factorial arrangement of 16 treatments were replicated 3 times, and laid out in a randomised complete block design (RCBD). Treatment efficacy in terms of stump survival (%) was assessed at 6 months, with the vigour of any coppice regrowth

assessed in terms of coppice health (0 = healthy; 1 = moderate; 2 = acute) and stump quarter with coppice present (n = 4).

Results: Irrespective of treatment, mean stump survival for the whole trial was 34.4% at 6 months. Of the three factors tested, only **Application time** was significant (F_{prob}<0.001), with 0.5 hrs significantly ($\bar{x}$ = 10%) better than the rest of the treatments, and 6 hrs also significantly better than 24 and 48 hrs (32% versus 45 and 51% respectively). There were no significant differences between the two **Herbicides** (Roundup or Garlon) or **Surfactants** (Breakthru or Orosorb) tested in terms of stump kill, irrespective of the application timing. For those stumps that were not killed, all herbicide and surfactant combinations (regardless of treatment, or application time) resulted in reduced coppice regrowth (reduced stump quarters) that was also regarded as unhealthy (lowered coppice health).

Conclusions*:* This study confirmed previous results in terms of the timeous application of herbicides to eucalypt cut-stumps for effective kill (within 0.5 hrs). Although the addition of surfactants did not enhance herbicide efficacy, there was reduced coppice regrowth and vigour for the delayed application treatments (6/24/48 hrs). These treatments should be explored further as viable alternatives to no control, especially if the reduced coppice regrowth is easily controlled, together with reduced labour risk during application.

4.1 Introduction

South African commercial forestry occupies 1 191 638 ha (1.0%) of the total national land surface area and contributes 0.82% to the GDP, with 5% of the South African (SA) population dependent on the forest industry for their livelihood (FSA 2019). Due to constraints associated with timber production in terms of increased abiotic and biotic stress factors, limited land available for forestry, increased global competition, and reduced availability of labour, the maximisation of sustainable timber yield from a static plantation base is regarded as critical for remaining globally competitive (Dovey et al. 2007).

Of the various practices that ensure sustainable timber production, practical silvicultural research has demonstrated the benefits of early intensive silviculture, with significant improvements in site productivity recorded for the management of the competing vegetation (amongst other practices) (du Toit et al. 2001). Little (2003) described vegetation management as the control of any plant species, either exotic or indigenous, which negatively affects plantation yield. Benefits of controlling competing vegetation include reduced mortality, need for blanking operations (replanting of dead seedlings), variability and time to canopy closure, and increased production (Smith 2006). Vegetation management in SA plantations is divided into three distinct phases: establishment phase (between planting and canopy closure), with vegetation intensively managed to reduce competition; post-establishment phase (between canopy closure and felling), where vegetation is controlled for reasons other than competition; and the pre-establishment phase, with any vegetation that develops between post-felling needing to be managed prior to re-planting (Smith 2006).

If the site to be re-planted was previously planted to eucalypts, the killing of stumps (as part of the pre-establishment phase) is considered important, as if not killed, the rapid development of coppice sprouts will likely out-compete any newly planted seedlings (Schönau 1980; Schönau 1984; Little and Eccles 2000; Little and van den Berg 2007).

Various methods of woody plant control have been tested for the killing of eucalypt stumps post-felling. In 2007, Little and van den Berg (2009) initiated a cut-stump trial on first rotation *Eucalyptus macarthurii* H. Deane & Maiden and concluded that all herbicides tested (triclopyr, metsulfuron-methyl and glyphosate) killed ca. 83-90% of the stumps treated. Little and van den Berg (2007) further showed that if triclopyr is applied at a 3% concentration within 15 minutes of felling, 88 – 95% stump mortality is achieved. In a trial conducted on larger diameter *Eucalyptus cloeziana* cut-stumps at Entabeni Plantation (Limpopo Province), (Chapter 2 – this thesis) obtained similar results, whereby triclopyr, glyphosate (or a tank-mixture of the two) applied to a stump within 30 minutes of felling resulted in ca. 70-90% mortality.

Globally, as an industry, forestry is regarded as hazardous, with a high incidence of accident and occupational injuries (ILO 1998). According to the International Labour Organisation (ILO), managers should take necessary measures to ensure that their work personnel are competent and have necessary authority and resources to perform their duties effectively.

Although occupational safety has always been an important component of any forest management operations, the increase in global trade over the past two decades has also seen an increased emphasis placed on practices associated with “fair trade” (organisations certified to provide fair wages and safe working conditions). In response, plantation management practices have come under increased scrutiny in terms of their impact on people and the environment (Smith 2006), with the development of mechanised systems in the domestic forest industry aimed at improving ergonomics amongst forestry workers and reducing their exposure to safety risks. This move towards mechanisation has a dual function, that of meeting the increased demand in timber production and fibre yield, whilst ensuring improved safety around manual or motor-manual operations (Hogg et al. 2009).

One of the areas within which there has been increased use of mechanisation in SA is that of harvesting (Hogg et al. 2009). Motor-manual felling, de-branching and cross-cutting, and manual de-barking and stacking have been replaced by semi-mechanised, or fully-mechanised operations (Schwegman et al. 2018). As part of this process, all companies have Operational Harvesting Plans (OHP’s) which actively promote safety management in addition to operational productivity through adhering to guidelines set forth by the ILO.

In terms of harvesting, this requires that no two workers operate within closer proximity than twice the length of the tallest tree to be felled (ILO 1998). In addition, the presence of labourers in-field during the extraction of timber is restricted, which means that any silvicultural operations (such as the removal of slash from stumps, or the treating of cut-stumps) cannot occur until the trees have been felled, and timber extracted (up to 48 hrs after felling). Whilst most research conducted on the killing of cut-stumps has focussed on efficacy in terms of methods of application, testing of different products and optimizing herbicide rates, all treatments tested have been applied as soon after felling as is possible (within 30 minutes as per label recommendations). Limited research could be found linking delayed herbicide application in combination with that of increased rates of application (with, or without surfactants to aid efficacy) to ensure an acceptable level of control is achieved.

Globally, most industries (forestry included) subscribe to standards associated with sustainable production (economic, environmental and social) against which they are measured (Brink 2012). Within SA, 80% of the forests are certified through either the Forest Stewardship Council (FSC) or International Standards Organisation (ISO) (Norris 2020).

The Forest Stewardship Council (FSC) Group recommends that where pesticides (herbicides included) are used in forestry, forest managers adopt an Integrated Chemical Management protocol. Although these protocols may differ between companies, they all have three main objectives: the identification and avoidance of ‘highly hazardous’ chemicals; the promotion of ‘non-chemical’ methods of pest management as an element of an integrated pest and vegetation management strategy; and the appropriate use of chemicals that are used (FSC 2007).

Whilst the use of highly hazardous pesticides is prohibited, the FSC standards focus on developing strategies for the reduction in use of pesticides, and to ensure that, when their use is necessary, pesticides are applied correctly/safely (Willoughby et al. 2009; FSC 2007). These expectations and strategies include safety precautions for those workers applying the pesticides, as well as measures put in place to ensure the pesticides do not enter waterways or other sensitive areas (FSC 2007).

There is a need to determine the best method for the killing of eucalypt stumps post-felling, taking into consideration the combined constraints around labourer safety in terms of the delayed time after felling that herbicides can be applied, and that of the judicious use of any herbicides that are applied. A trial was implemented at Wilgeboom Plantation (Mpumalanga, South Africa) in 2018 to test the efficacy of two herbicide/surfactant combinations for the killing of 24 year-old *E. grandis* cut-stumps at four time-intervals (up to 48 hours) following felling.

4.2 Materials and Methods

4.2.1 Study site

A site was selected at Wilgeboom plantation (Mpumalanga Province) which was considered typical for the growth of *E. grandis* for the production of sawtimber and transmission poles (**Table 4.1**). The trial was implemented when felled at rotation age (24 years), on single stems of seedling origin (not previously coppiced).

Table 4.1: Site characteristics for a trial testing the influence of time after herbicide/surfactant application on *Eucalyptus grandis* cut-stump survival, Wilgeboom Plantation (Mpumalanga, South Africa).

Plantation	**Wilgeboom Plantation (Mpumalanga Province) Compartments E25 + E28**
Co-ordinates (Lat; Long)	24° 58' S; 31° 1' E
Altitude (m a.s.l.)	863 (E25); 847 (E28)
MAT (°C)	18.8
MAP (mm yr^{-1})	1 050-1 300 mm
Climatic Region	Warm temperate
Species	*E. grandis*
Age when felled (years)	24 (planted 1995)
Soil form	Red apedal dystrophic soil
Parent material	Granite
Effective rooting depth (m)	1.2-1.5
Texture (0 - 15 cm)	Clay-loam
Organic carbon (%) (0-15 cm)	25-35
Treatments assessed (months)	1 (34 days), 3 (90 days), 6 (183 days)
Trial size (Ha)	0.162 (E25); 0.054 (E28)

4.2.2 Treatment

The trial consisted of a 2 x 2 x 4 factorial arrangement of 16 treatments, replicated 3 times and laid out in a randomised complete block design (RCBD).

The main factors were **Herbicide** (Roundup and Garlon), **Surfactant** (Breakthru and Orosorb) and **Application time** (0.5, 6, 24, 48 hrs) (**Table 4.2**). The herbicides, surfactants and the time after application were selected based on past research in terms of known treatment efficacy (see Chapters 2 and 3 – this thesis). Although the recommendation is for the cut-surface application of a herbicide within 30 minutes following felling (0.5 hrs), the efficacy of the herbicide x surfactant treatments were also tested at 6, 24 and 48 hrs so as to reflect the time post-felling that the timber had been extracted from the site, thus allowing for the operator or herbicide applicator to safely enter the harvesting area.

Table 4.2: Treatments (herbicides and surfactants) in a trial testing the influence of time after herbicide/surfactant application on *Eucalyptus grandis* cut-stump survival, Wilgeboom Plantation (Mpumalanga, South Africa).

Herbicide/Surfactant		Rates of herbicide application (%) for different treatments Time after felling herbicides applied			
Treatment	**Active ingredient**	**0.5 hrs**	**6 hrs**	**24 hrs**	**48 hrs**
Garlon®	triclopyr EC (480 g a.i. L^{-1})	2	2	2	2
Actipron Super®	mineral oil (820 g a.i. L^{-1})	0.5	0.5	0.5	0.5
Orosorb®	orange oil (50 g a.i. L-1)	0.3	0.3	0.3	0.3
Garlon®	triclopyr EC (480 g a.i. L^{-1})	2	2	2	2
Actipron Super®	mineral oil (820 g a.i. L^{-1})	0.5	0.5	0.5	0.5
Break-thru®	polyether-polymethylsiloxane-copolymer (1000 g a.i. L^{-1})	0.3	0.3	0.3	0.3
Roundup®	glyphosate SL (360 g a.i. L^{-1})	5	5	5	5
Actipron Super®	mineral oil (820 g a.i. L^{-1})	0.5	0.5	0.5	0.5
Orosorb®	orange oil (50 g a.i. L-1)	0.3	0.3	0.3	0.3
Roundup®	glyphosate SL (360 g a.i. L^{-1})	5	5	5	5
Actipron Super®	mineral oil (820 g a.i. L^{-1})	0.5	0.5	0.5	0.5
Break-thru®	polyether-polymethylsiloxane-copolymer (1000 g a.i. L^{-1})	0.3	0.3	0.3	0.3

[1] The use of trade names does not indicate endorsement of the product by Nelson Mandela University, and are included for the reader's benefit only

Due to the treatments (in terms of the application of the herbicides) being linked to time after felling, the area within which the trial was located needed to be large (although the total size of the treatment plots within this area was small). Safety in terms of treatment application was also taken into consideration, which meant that although treatment plots within each Rep were within the same compartment, they could not be located directly adjacent to each other. For this reason a large area that was being felled was identified for the trial, and consisted of two adjacent compartments (**Table 4.1:** Compartments E25 and E28). Both compartments had similar site characteristics, and were managed in a similar manner in terms of species, timing of planting and any silvicultural inputs over the 24 years prior to felling. Each treatment plot consisted of 3 rows of 12 trees (36 tree plot^{-1}). Although all trees within each plot were treated, only the centre row of 10 trees were used for assessments (two buffer rows of trees between adjacent plots). Prior to spraying, all plots were laid out and marked with white paint on the base of the trees to allow for identification once the trees were felled. A motor-manual operation was used for the felling of the trees, with the slash removed from stumps, and the application of herbicides delayed to meet the treatment objectives.

Herbicide for all the treatments were applied to just prior to runoff, to ensure full cover of the herbicide over the entire cambium layer. A Solo®435 backpack sprayer regulated to 1.5 kPa was used for all spraying, with a Delavan® CE 1 solid cone nozzle used.

4.2.3 Measurements

Following felling, the height above-ground of each stump (Stump_Ht in cm) and the diameter of the cut-surfaces (Stump_Diam in cm) were measured. To account for variable stump dimensions, the diameter was calculated as the mean of two readings, the first taken through the widest part of the stump and the second perpendicular to the first reading. This would allow for the determination of stump size (including volume), which could also be used as a co-variate if within-treatment differences were detected.

Treatment efficacy was quantified at 1, 3 and 6 months in three ways:

- **Stump survival**: The presence or absence of coppice regrowth was assessed for each stump. This would give an indication of treatment efficacy in terms of stump-kill. Where the treatments did not result in complete stump-kill, the Stump quarter and Coppice health would provide an indication of coppicing vigour following treatment.

- **Stump quarter**: Coppice regrowth was assessed by dividing the stump into quarters (when viewed from above) and determining the presence or absence of coppice regrowth in each quarter (n = 4).
- **Coppice health**: The foliage was assessed in terms of necrosis and discolouration with the use of a scoring method (0 = healthy; 1 = moderate; 2 = acute)

4.2.4 Data analysis

Stump survival data were analysed to determine the effectiveness of the treatments. As the assumptions for a valid analysis of variance were violated (Shapiro-Wilk's test for normality and Levene's test for homogeneity of variance) the data received a square root transformation ($y = (x+10)^{0.5}$) prior to carrying out an analysis of variance (ANOVA) appropriate for 2 x 2 x 4 Factorial arranged in a RCBD **(Table 4.3)**. Only where the *F*-value was significant ($p<0.05$), were treatment differences further investigated using the Student's *t*-test statistic (least significant differences). As the significance between factors and treatments were the same for the untransformed and transformed data, the data is displayed **(Figure 4.3)** using untransformed data (for the readers benefit). All analyses were carried on plot mean data using GenStat® for Windows™ (VSN International 2019). To ensure differences in stump diameter and heights (as a function of felling) did not influence the coppicing potential, they were included as co-variates. As they were not significant, they were excluded from further analyses. Stump quarter and Coppice health were displayed graphically using descriptive statistics (means and 95% confidence intervals).

Table 4.3: Summary of analysis of variance showing the mean squares for six-month Stump survival (%) in a trial testing the influence of time after herbicide/surfactant application on *Eucalyptus grandis* cut-stump survival, Wilgeboom Plantation (Mpumalanga, South Africa).

Source of variation	df	Stump survival (sqrt transformed)
Rep	2	3.8298^{ns}
Herbicides	1	0.009^{ns}
Surfactants	1	0.065^{ns}
Application time	3	26.457**
Herbicide.Surfactant	1	0.002^{ns}
Herbicide.Application time	3	0.115^{ns}
Surfactant.Application time	3	0.599^{ns}
Herbicide.Surfactant.Application time	3	0.235^{ns}
Residual	30	0.989^{ns}
Total	47	
Grand mean		6.47 (34.4%)
Standard error of differences of means (units)		0.812
Coefficient of variation (units) (%)		15.2
Levene’s test for homogeneity (treatments)		0.948^{ns}
Shapiro-Wilk test for normality		0.592^{ns}

Note: **signifies significance at p<0.01 and ^{ns} non-significance

4.3 Results and discussion

Prior to the felling of the stand, the stocking was 816 stems ha^{-1} (original planting density of 1 111 stems ha^{-1}). The average stump diameter and stump height for the 24-year-old *E. grandis* trees post-felling was $\bar{x}$ = 39.1 cm (range = 32.9-43.3 cm), and $\bar{x}$ = 11.2 cm (range 10.2-13.0 cm) respectively. No significant treatment difference were detected for stump diameter and stump height following felling, indicating a degree of uniformity of the standing trees prior to felling (stump diameter), as well as the heights at which the stumps were felled (stump height). In addition, stump diameter and stump height were not significant when used as co-variates for the analysis of stump survival. This indicates that the size and shape of the stumps were uniform, which resulted in a similar cut-surface surface area onto which the herbicides were applied relative to the size of the stumps. If significant as co-variates, this would indicate that stump heights and/or stump diameters would have had an influence on treatment efficacy.

4.3.1 Stump survival

A mean stump survival of 34.4% was recorded for the whole trial (irrespective of treatment) at 6 months. Of the three factors tested, only **Application time** was significant (F_{prob}<0.001), accounting for 82% of the variation in the data set (**Table 4.3**). The blocking of the treatments (indicated by Reps) was the next highest at 12%, albeit not significant. In addition to **Herbicide** and **Surfactant** not being significant, none of the interactions between the three factors were significant. The higher variation accounted for by Reps could in part be explained by the use of two adjacent compartments, with two replicates situated in Compartment E25 (replicate means for stump survival: $\bar{x}$ = 29.4 and 31.9), and one in E28 ($\bar{x}$ = 41.9%). Although both compartments were established to *E. grandis* (same seedlot and time), were managed in a similar manner, and were similar in terms of site characteristics, there may have been factors that were not assessed that resulted in some treatment differences between the Reps.

There was no significant difference between the two herbicides (Roundup or Garlon) or surfactants (Breakthru or Orosorb) tested in terms of stump kill, irrespective of the application timing. Although the herbicides tested were selected as both were equally effective for killing eucalypt stumps when applied to the cut-surfaces (Little et al. 1998; Little 2000; Little and Eccles 2000; Little and van den Berg 2007; Roberts et al. 2018), it was hoped that the addition of a surfactant would have enhanced herbicide performance. That this did not happen was disappointing, as increasing the time interval between tree felling and applying the cut-stump treatment would provide labourers greater flexibility and reduce the need for them to work in close proximity to fellers. Studies examining the benefits of surfactant-herbicide combinations have shown improved efficacy (Turner 1980; Donald 1988; Balneaves et al. 1993; Gaskin et al. 1997; Sieverding et al. 2006; Gaskin et al. 2013; Letaoana 2018). Gaskin and Murray (1997) further explain that surfactants improve the retention of sprays, in the best instance by more than five-fold. Although there are many studies that have tested various herbicides for the control of hardwoods, few could be found which also compared herbicide + surfactant treatments applied to cut-stumps. Where surfactants have been included, the efficacy of treatments was generally higher than if not included (for example Ballard and Nowak 2006).

In terms of Application time, 0.5 hrs was significantly ($\bar{x}$ = 10%) better than the rest of the treatments, with 6 hrs also significantly better than 24 and 48 hrs (32% versus 45 and 51% respectively) **(Figure 4.1)**. Similar results for the 0.5 hrs application were obtained by Little and van den Berg (2006) for *Eucalyptus macarthurii* cut-stump control in Paulpietersburg in KwaZulu-Natal, where all herbicides (Garlon, Roundup and Garlon + Roundup) killed 83-90 % of the stumps (applied within 15 minutes after felling) when compared to the control. In a trial to test the effects of timing of application of different herbicide concentrations on killing a hardwood (Beech wood), Kochenderfer and Kochenderfer (2009) concluded that the application of the herbicides tested could still be effective at 120 hrs. This may have been due to high concentration herbicide used (100% concentration), or the season and weather condition (cold and rainy). The cool temperatures, high humidity and precipitation may have slowed the drying of the surfaces of the cut-stumps, making them able to effectively absorb the herbicide for a longer period of time compared to the relatively dry conditions experienced in this trial.

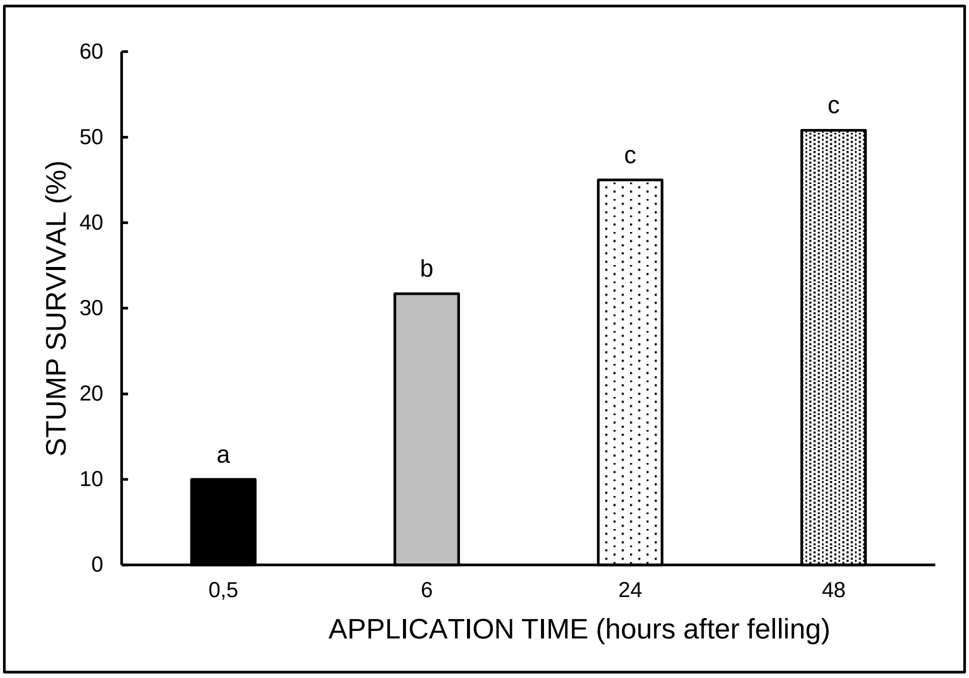

Figure 4.1: Six-month Stump survival (%) for the main factor of Application time in a trial testing the influence of time after herbicide/surfactant application on *Eucalyptus grandis* cut-stump survival, Wilgeboom Plantation (Mpumalanga, South Africa). Letters on bars indicate significant difference ($p<0.05$).

Kochenderfer and Kochenderfer (2009) indicated that in living trees, water (and dissolved nutrients/sap) taken up from the soil by the roots is translocated through the stem/branches to the leaves as part of photosynthesis. Although the loss of moisture during photosynthesis creates a negative tension in the soil-plant-atmosphere continuum, the water taken up by roots may also result in a positive pressure which facilitates the upward movement though the xylem (osmotic pressure: movement of water from high concentration to low concentration between cells). When the tree is felled sap flow is disrupted, however if the soil moisture content is high, sap may still flow out of the cells and onto the stumps, which may initially dilute any herbicide applied, or once the sap has dried, it may form a barrier reducing herbicide absorption. This exposure of the xylem cells (vessel elements and tracheids) at the cut-surface will also result in the drying out of the sap within these cells over time, further limiting the uptake of any herbicides that may be applied.

4.3.2 Coppice health and abundance

In addition to the overall presence or absence of coppice growth on a stump following felling and/or treatment (stump survival), the vigour (abundance) or coppice health of any coppice that does regrow is also important. Limited phytotoxic symptoms and/or regrowth may mean that although there is coppice regrowth, it remains at a sub-competitive level during stand re-establishment, and will easily be controlled during routine weeding operations. Herbicide phytotoxicity may result in either foliar necrosis and/or discolouration, reduced and/or abnormal growth, or mortality (European and Mediterranean Plant Organization 2014). Based on these categories, discolouration (chlorosis and necrosis) and reduced growth (smaller in size) occurred in all the herbicide application method treatments (**Figures 4.2 and 4.3**).

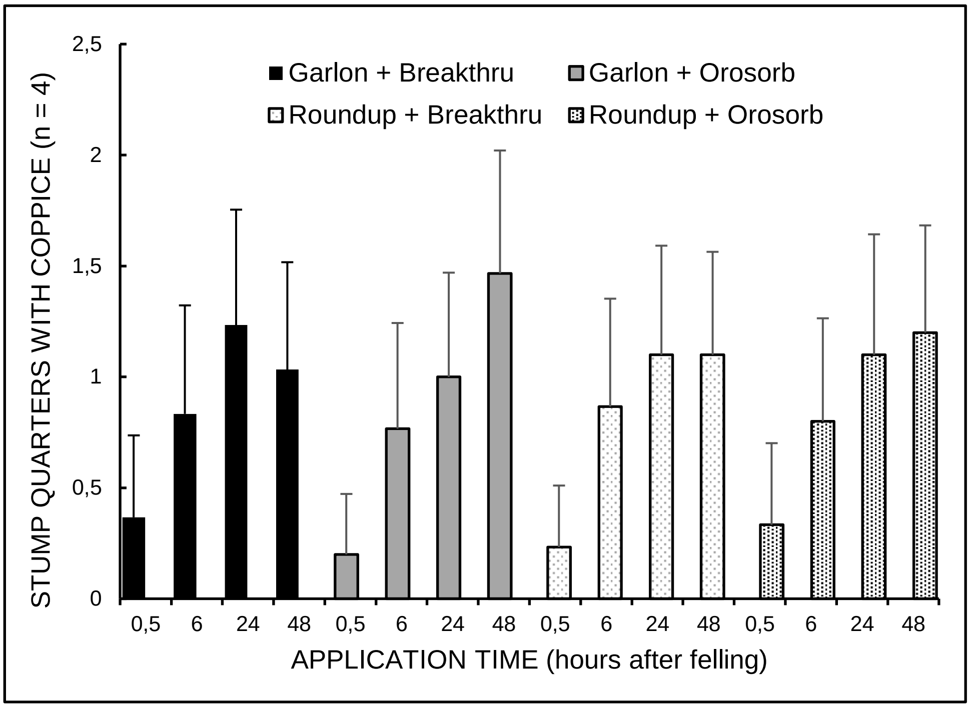

Figure 4.2: Six-month Stump quarters with coppice (n = 4) in a trial testing the influence of time after herbicide/surfactant application on *Eucalyptus grandis* cut-stump survival, Wilgeboom Plantation (Mpumalanga, South Africa). Bars on means indicate 95% confidence intervals.

Although there was a direct link between stump survival and stump quarters (those treatments with a higher number of dead stumps also recorded fewer stump quarters), all treatments recorded stump quarters of less than 1.5 (**Figure 4.2**). As for stump survival, there was a clear differentiation in terms of the **Application time** for the number of stump quarters (maximum of 4) that had coppice regrowth: 0.5 hrs ($\bar{x}$ = 0.28) < 6 hrs ($\bar{x}$ = 0.82) < 24/48 hrs ($\bar{x}$ = 1.11/1.20). In addition, of the coppice that did grow, most exhibited some visual symptoms of phytotoxicity (coppice health) (**Figure 4.3**). This is of benefit to the forestry industry in that even if the compartment were to be re-planted at 4-6 months, the coppice regrowth of the 6/24/48 hr treatments (although higher than the 0.5 hr treatment) could still be more easily managed than if the stumps were not treated.

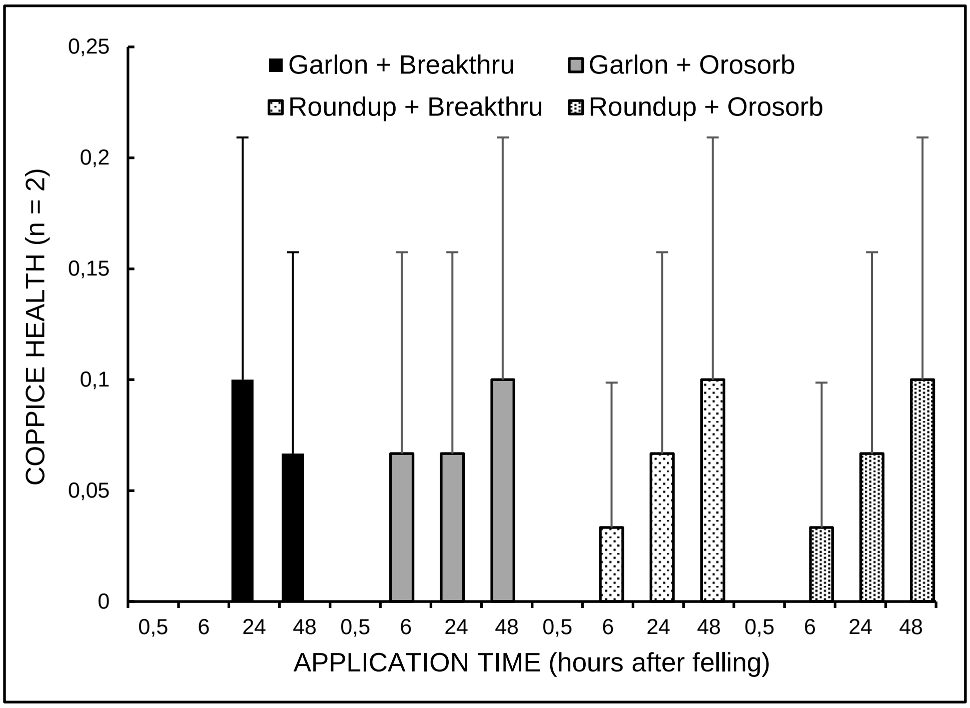

Figure 4.3: Six-month Coppice health (0 = healthy; 1 = moderate; 2 = acute) in a trial testing the influence of time after herbicide/surfactant application on *Eucalyptus grandis* cut-stump survival, Wilgeboom Plantation (Mpumalanga, South Africa). Bars on means indicate 95% confidence intervals.

4.4 Conclusions

A trial was implemented in 2019 at the SAFCOL Wilgeboom Plantation to quantify the interaction between **Herbicide** (no herbicide applied; Roundup; Garlon), **Surfactant** (Breakthru; Orosorb) and **Application time** (0.5, 6, 24, 48 hrs) for the killing of *Eucalyptus grandis* 24 year-old stumps following harvesting.

Mean stump survival of 34.4% was recorded for the whole trial (irrespective of treatment) at 6 months. Of the three factors tested, only **Application time** was significant (F_{prob}<0.001), accounting for 82% of the variation in the data set. The 0.5 hrs treatments were significantly ($\bar{x}$ = 10%) better than the rest of the treatments, with 6 hrs also significantly better than 24 and 48 hrs (32% versus 45 and 51% respectively). Irrespective of the application timing, there were no significant differences between the two herbicides (Roundup or Garlon) or surfactants (Breakthru or Orosorb) tested in terms of stump kill. Although the herbicides tested were selected as both were equally effective for killing eucalypt stumps when applied to the cut-surfaces it was hoped that the addition of a surfactant would have enhanced herbicide performance.

There was a clear differentiation in terms of the **Application time** for the number of stump quarters (maximum of 4) that had coppice regrowth (0.5 hrs < 6 hrs < 24/48 hrs. In addition, of the coppice that did grow, most exhibited some visual symptoms of phytotoxicity (coppice health). This is of benefit to the forestry industry in that even if the compartment were to be re-planted at 4-6 months, the coppice regrowth of the 6/24/48 hr treatments (although higher than the 0.5 hr treatment) could still be more easily managed than if the stumps were not treated.

CHAPTER 5

Synthesis and conclusions

Unlike other commercially grown tree species (such as pine and wattle), eucalypts have the ability regenerate through the production of new shoots from their stumps after felling. This form of regeneration is referred to as coppicing, whereby the coppice shoots are selectively thinned over time, allowing the plantation owner the option of a second timber rotation without replanting, thus reducing the temporary unplanted period together with establishment costs. If the site is to be replanted with seedlings and the eucalypt stumps are not killed following felling, the rapid initial growth of the coppice shoots supresses the newly planted seedlings resulting in significant growth reduction as well as variable tree growth. In addition, the application of herbicides to the foliage of the coppice requires repeated applications (at higher rates and volumes used), which may also result in spray-drift onto the adjacent seedlings. It is therefore important to kill the stumps before replanting, if the site to be re-established was previously planted to eucalypts.

Research on the killing of eucalypt stumps post-felling so as to facilitate re-establishment has highlighted suitable herbicides, rates, methods and timing of application. Within South Africa, this research has focused mostly on commonly planted eucalypts (for example *E. grandis*, *E. macarthurii* and *E. grandis* x *E. urophylla* grown on short, pulpwood rotations), as well as the testing of products according to label recommendations in terms of timing of application (within 30-60 minutes after felling) and rates of application (product-dependent).

In South Africa (and globally) there has also been an increased emphasis placed on silvicultural operations in terms of reducing any negative environmental impacts together with increased worker safety. As such, any silvicultural operations that are labour-intensive and/or make use of pesticides are being scrutinized so as to reduce any negative impacts. One example would be the increase in mechanized harvesting requiring the exclusion of labourers from the site until the timber has been extracted. This means that the effectiveness of current recommendations in terms of herbicide application to cut-stumps with 30-60 minutes is compromised.

Taking the above aspects into consideration, limited research could be found related to:

i. the effectiveness of current practices on other commercially grown eucalypts (for example *E. cloeziana* when grown over a longer rotation for the production of poles);
ii. the potential for the use of surfactants to either improve efficacy and/or reduce the amounts of herbicide applied; or
iii. the potential to extend the time after felling eucalypts for the application of herbicides to cut-surfaces (to facilitate delayed access to stumps by labourers following mechanized harvesting), yet still remain effective.

To address the above aspects, three trials were implemented between 2018 and 2020, with the outcomes summarized below.

Extending eucalypt cut-stump control practices to include Eucalyptus cloeziana*, South Africa.*

A trial was established in 2018 at Entabeni plantation (Limpopo Province) to quantify the interaction between Application method (basal-frill; cut-surface; foliar) and Herbicide (no herbicide applied; Roundup; Garlon; Roundup + Garlon) for the killing of *Eucalyptus cloeziana* 12 year-old stumps following harvesting.

Relative to the control plots (100% survival), all herbicides tested were equally effective (70–90% of the stumps killed), with the cut-surface and basal-frill application providing significantly better control than the foliar application. These results were encouraging as they confirmed previous research comparing similar application methods for the killing of eucalypt stumps, indicating that current recommendations can be extended to include *Eucalyptus cloeziana*, even if the stumps are larger as a consequence of the longer rotation (12 years).

In contrast to previous research, the use of Roundup alone was equally effective as Garlon, or Roundup + Garlon, possibly due to the higher rates of application as applied in this trial. In this trial Roundup was applied at 5%, whereas in previous research conducted in South Africa it was applied at 3%. This result is encouraging as it provides the forester with more options in terms of potential treatments.

Any treatment where the stump is killed with a once-off herbicide application, and is the most cost-effective would be the preferred method for killing *Eucalyptus* *cloeziana* stumps. As such, future studies should focus on the costs per treatment to understand, and choose the best herbicide/application method combination.

Testing of herbicide/surfactant combinations at two rates for the killing of Eucalyptus cloeziana *stumps, South Africa.*

A trial was implemented in 2018 (Venda, South Africa) on a recently felled stand of *Eucalyptus cloeziana* to determine if the addition of natural/synthetic surfactants (Nu-film, Orosorb and Breakthru) would allow for reduced rates of herbicide application without compromising efficacy (Roundup, Garlon, or Garlon + Roundup applied at either recommended herbicide rate + recommended surfactant rate: 1x_1x; or half recommended herbicide rate + double surfactant rate: 0.5x_2x).

Although stump survival at 6 months was significant for the main factors of Herbicide, Surfactant and Rate, there were no significant interactions between the three factors tested. Of the herbicides tested, Roundup (16.1%) and Garlon + Roundup (16.7%) were not significantly different from each other in terms of stump survival, but both were significantly better than Garlon (29.4%). Of the surfactants tested, Breakthru (16.7%) and Orosorb (16.1%) were not significantly different from each other, but both had significantly lower stump survival when compared to Nu-Film (29.4%). In addition, the recommended herbicide + surfactant rate was significantly better at killing stumps than where half the recommended herbicide + double surfactant rate were tested (stump survival: 1x_1x = 7.8%; 0.5x_2x = 33.7%).

Whilst the results (in terms of killing of eucalypt stumps) obtained from this trial in terms of the herbicides and surfactants tested support previous research, the significantly reduced efficacy of the herbicides when applied at half the recommended rate (with double the surfactant rate) was disappointing. If not significantly different from the recommended herbicide + surfactant rate, this would have enabled a reduction in herbicide-use, without loss of efficacy. Nevertheless, these results do confirm current label recommendations in terms of rates of application.

For those stumps that were not killed, all herbicide and surfactant combinations (regardless of treatment) resulted in reduced coppice regrowth (fewer stump quarters with coppice) that was regarded as unhealthy (lowered coppice health score). This is of benefit to the forestry industry in that even if the compartment were to be re-planted at 4 - 6 months, the coppice regrowth occurring on any surviving stumps could still be more easily managed than if the stumps were not treated.

Influence of time after herbicide/surfactant application on eucalypt cut-stump survival

A trial was implemented in 2019 at the SAFCOL Wilgeboom Plantation to quantify the interaction between Herbicide (no herbicide applied; Roundup; Garlon), Surfactant (Breakthru; Orosorb) and Application time (0.5; 6; 24; 48 hrs) for the killing of *Eucalyptus grandis* 24 year-old stumps following harvesting.

Mean stump survival of 34.4% was recorded for the whole trial (irrespective of treatment) at 6 months. Of the three factors tested, only Application time was significant, accounting for 82% of the variation in the data set. The 0.5 hrs treatments were significantly ($\bar{x}$ = 10%) better than the rest of the treatments, with 6 hrs also significantly better than 24 and 48 hrs (32% versus 45 and 51% respectively). Irrespective of the application timing, there were no significant differences between the two herbicides (Roundup or Garlon) or surfactants (Breakthru or Orosorb) tested in terms of stump kill. Although the herbicides tested were selected as both were equally effective for killing eucalypt stumps when applied to the cut-surfaces it was hoped that the addition of a surfactant would have enhanced herbicide performance.

There was a clear differentiation in terms of the Application time for the number of stump quarters (maximum of 4) that had coppice regrowth (0.5 hrs < 6 hrs < 24/48 hrs. In addition, of the coppice that did grow, most exhibited some visual symptoms of phytotoxicity (coppice health). This is of benefit to the forestry industry in that even if the compartment were to be re-planted at 4-6 months, the coppice regrowth of the 6/24/48 hr treatments (although higher than the 0.5 hr treatment) could still be more easily managed than if the stumps were not treated.

Limitations of these trials and future research opportunities

These trials were implemented as applied trials, with the treatments selected to answer specific questions related to the killing of eucalypt stumps, and that any outcomes would be of practical value that could easily be incorporated into future re-establishment plans. Being applied in nature meant that assessments were confined to easily measured, yet sound variables that would satisfy the needs of both the statistical procedures used and for recommendations to be made. Additional process-based measurements which would have assisted with the understanding of why certain treatments were more/less effective than others were not taken (time and cost). Future trials should possibly include more process-based measures (for example the assessment of carbohydrate reserves or measures of stress prior to felling and the linking of these to coppicing vigour).

As only three trials were implemented (one trial to test each research question), the selection of site, species, timing of felling was important. This would ensure that the conditions in the trial were similar to those that would be experienced operationally, and that any outcomes could be extrapolated more readily. In trying to control external variables, any "treatment x coppicing" differences associated with different site qualities, eucalypts, tree age, growth vigour of parent crop, season of felling, climatic conditions around treatment implementation could not be determined, and with that the robustness of the treatments. As all of the above aspects have been shown to have an influence on coppicing vigour, future trials should combine the above aspects together with the most promising treatments.

Regardless of the skill and care taken by the operators, there will always be some degree of damage to the stumps during felling and extraction operations. Despite the stumps to be treated being clearly marked before felling to facilitate the removal of slash/sawdust from the cut-surface before herbicide application, the actual practice of carrying this out was difficult. In addition, the timber had to remain on the site for six weeks before it was processed, with some areas also used as a landing area for log sorting, stacking and loading, and this may have delayed the initial development of coppice regrowth (if any). These aspects will need to be taken into consideration to reflect "operational reality" when recommending any specific treatment.

Although different methods for the management of competing vegetation (including coppice regrowth post-felling) can be used, integrated management practices are preferred and considered more holistic and sustainable as they reduce reliance on a single control method (such as relying on herbicides alone). Although previous research on the killing of eucalypt stumps in South Africa has found that herbicide application (regardless of method of application) to be more effective compared to the untreated and manual removal of coppice regrowth, site-preparation aspects (such as stump grinding, mulching or the burning of slash), or cultural practices (such as increased shading due to closer tree row spacing, or species choice) may delay and/or reduce coppice growth. If these are combined with the use of herbicides, it is possible that the quantities applied may be reduced.

Future research should also take into consideration the cost-benefit scenarios associated with combining the delayed application of herbicide to cut-stumps together with follow-up foliar spraying of any coppice regrowth. These trials have shown that although the delayed application of herbicide to cut-stumps is not as effective as when applied immediately after felling, the vigour of any coppice regrowth is reduced and delayed. Whether this level of control is cost-effective still needs to be determined.

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