Understanding the system and supply chain effects of two residue management treatments in pine and eucalyptus plantations

By

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Declaration

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Summary

There is an increased interest in understanding the effect of different residue management practices on forestry in South Africa. In addition to clearly established environmental benefits of residue mulching, as opposed to burning residues in-situ, as mulching or mastication offers the alternative of comminuting these residues almost immediately after harvesting. The aim of this study was to investigate the cost of mulching and determine whether this cost is justified through potential savings from increased pitting and planting productivity in the forestry value chain. Relevant data was collected from sites in Zululand and Bulwer in KwaZulu-Natal and Jessievale on the Mpumalanga Highveld. The study was limited to *Eucalyptus grandis x urophylla* pulpwood and *Pinus patula* pulpwood and sawtimber regimes.

The study included estimating residual biomass and remaining stump volumes using a Zigzag and Line-Intercept methods respectively. Time studies quantified time consumption and the productivities of the various mulching machines, mechanised pitters, semi-mechanised planters, manual pitters, and manual planters, between treatments. An attempt to classify mulch quality was investigated. The costs of each operation per residue treatment were calculated to determine cost effectiveness. Initial plant growth response to mulched and burnt residues were evaluated.

Mulching results for pulpwood residues showed no significant difference between Eucalyptus sites (0.35 ha) and pine sites (0.36 ha PMH^{-1}) and were also not affected by residual biomass volume. Significant differences were found in Eucalyptus mechanised pitting productivity between mulched (0.26 ha PMH^{-1}) and burnt (0.25 ha PMH^{-1}) treatments. Mechanised pitting on sawtimber pine stands differed significantly with a 24% increase in productivity after mulching. Productivities of 0.57 ha PMH^{-1} and 0.46 ha PMH^{-1} on mulched and burnt pine sawtimber residues respectively were seen. Manual pitting was more productive for burnt sites (0.06 ha PPH^{-1}) than mulched sites (0.05 ha PMH^{-1}). Semi-mechanised planting was 27% faster on mulched sites (1.70 ha·PMH^{-1}) than on burnt sites (1.33 ha PMH^{-1}). Manual pine planting after mulching was 33% faster compared to planting on burnt sites. This resulted in a manual planting productivity on

mulched sites of 0.08 ha $PPTH^{-1}$ being greater than on sites where residues were burnt (0.06 ha $PPTH^{-1}$).

In both pine and eucalypts, increases in productivities in mechanised pitting, semi-mechanised planting, and manual planting (except manual pitting) after mulching were evident. The total cost of mulching was approximately R 5 450 ha^{-1} for eucalyptus sites and R 6 170 ha^{-1} in pine pulpwood sites. The increase in pitting and planting productivity after mulching approximately offsets the mulching cost by R 220 ha^{-1} on eucalyptus and R 290 ha^{-1} in pine pulpwood. These saving in increase productivity after mulching are however not enough to justify the expense of mulching generally.

When considering mulching foresters should holistic approach the undertaking by considering the biological advantages of mulching in general including soil nutrients benefit as well as long term growth and yield gains, in addition to the increase in productivity of pitting and planting after mulching.

Opsomming

Daar is tans groot belangstelling om die effek van verskillende reste bestuurspraktyke in die bosbedryf in Suid-Afrika te verstaan. Benewens duidelik bekende omgewingsvoordele van reste-deklaag bewerking, in teenstelling met die brand van reste in opstande, bied deklaag bewerking 'n geskikte alternatief deur hierdie reste feitlik onmiddellik na inoesting te behandel. Die doel van hierdie studie was om die koste van deklaag bewerking te ondersoek en te bepaal of hierdie koste geregverdig is in die bosbou-waardeketting deur potensiële verhogings in groei produktiwiteit. Die nodige data is ingesamel in Zoeloeland en ook Bulwer in KwaZulu-Natal asook Jessievale op die Mpumalanga Hoëveld. Die studie was beperk tot *Eucalyptus grandis x urophylla* (gom) pulphout en *Pinus patula* (denne) pulphout en saaghout bestuurspraktykke.

Die studie het die skatting van reste massa en oorblywende stomp volumes ingesluit deur gebruik te maak van onderskeidelik ’n Z-patroon en lyn afsnit opname metode. Tydstudie het tydverbruik en die produktiwiteit tussen behandelings van die verskillende deklaag masjiene, gemeganiseerde gat makers, semi-gemeganiseerde planters, gat maak met die hand en plant met die hand bepaal. Daar is ook gepoog om deklaag kwaliteit te klassifiseer. Die koste van elke operasie van reste behandeling is bereken om kostedoeltreffendheid te bepaal. Aanvanklike groei uitkomste op onderskeidelik deklaag en gebrande reste is gemeet.

Deklaag resultate vir pulphout reste het geen beduidende verskil tussen gom persele (0.35 ha PMH^{-1}) en denne persele (0.36 ha PMH^{-1}) getoon nie en is ook nie deur reste volume beïnvloed nie. Beduidende verskille is gevind in produktiwiteit van gemeganiseerde gate maak, tussen deklaag (0.26 ha PMH^{-1}) en gebrande (0.25 ha PMH^{-1}) behandelings in gomme. Gemeganiseerde gate maak by denne saaghout persele het aansienlik verskil, met 'n 24% toename in produktiwiteit na deklaag bewerking. Produktiwiteit van 0.57 ha PMH^{-1} en 0.46 ha PMH^{-1} op onderskeidelik deklaag- en gebrande reste in denne saaghout persele is opgemerk. Gate maak met die hand was

meer produktief vir gebrande persele (0.06 ha PPH^{-1}) as deklaag persele (0.05 ha PMH^{-1}). Semi-gemeganiseerde plant bewerking was 27% vinniger op deklaag persele (1.70 ha·PMH^{-1}) as op gebrande persele (1.33 ha PMH^{-1}). Plant van denne saailinge en gate maak met die hand na deklaag bewerking was 33% vinniger in vergelyking met plant op gebrande persele. Dit het daartoe gelei dat produktiwiteit op deklaag persele van 0.08 ha $PPTH^{-1}$ groter was as op gebrande persele (0.06 ha $PPTH^{-1}$) wanneer met die hand geplant is..

Met vestiging van beide denne- en gom saailinge was verhogings in produktiwiteit in gemeganiseerde gate maak, semi-gemeganiseerde plant en plant-met-hand, behalwe in die geval van gate maak met die hand, na deklaag bewerking duidelik sigbaar. Die totale koste van deklaag bewerking was ongeveer R5 450 ha^{-1} vir gom persele en R 6 170 ha^{-1} in denne pulphout persele. Die toename by handgemaakte gate en plant produktiwiteit na deklaag bewerking verminder die deklaag koste met ongeveer R 220 ha^{-1} in gom pulphout en R 290 ha^{-1} in denne pulphout. Die verhoogde produktiwiteit en besparing met deklaag bewerking is egter nie genoeg om die koste van deklaag bewerking oor die algemeen te regverdig nie.

By die oorweging van deklaag bewerking moet bosbouers die onderneming in geheel benader deur die biologiese voordele van deklaag bewerking, grondvrugbaarheid voordele sowel as langtermyn groei- en opbrengs winste, in konteks met die toename in produktiwiteit van gate maak en plant na deklaag bewerking oorweeg.

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List of Acronyms

BI	Biomass index
cm:	Centimetre
CTL:	Cut-to-length
cVol:	Conical volume
DBH:	Diameter at breast height
Dq:	Quadratic diameter
E.gxu:	Eucalyptus grandis X urophylla
GLD:	Ground line diameter
GNSS	Global navigation satellite system
Hr:	Hour
ha:	Hectare
Ht:	Height
Kg:	Kilogramme
l:	Litre
m^3:	Cubic- meters
m:	metre
mins:	Minutes
Min:	Minimum
Max:	Maximum
PMH:	Productive machine hour

PPH: Productive person hour

PPTH: Productive planting team hour

PH: Productive hour

P.pat: Pinus patula

r: Radius

R: Rands

S: Seconds

SPHA: Stems per hectare

SD: Standard deviation

S1P1: Speed 1 with 1 pass

S1P2: Speed 1 with 2 passes

S2P1: Speed 2 with 1 pass

S2P2: Speed 2 with 2 passes

1 Introduction

Recent research has shown an ongoing transition from manual harvesting operations to mechanical operations in the forestry industry in South Africa (McEwan & Steenkamp, 2014; Sibiya et al., 2021) This is partly due to the need for greater efficiency and the ergonomic inferiority of manual operations (McEwan & Steenkamp, 2014).

With the realisation that silvicultural processes and management should be viewed as a continuum of interdependent steps (Ackerman & Rietz, 2014), it is important that residue management be carried out in a manner that makes subsequent operations more efficient. Residue management is crucial as the type and quantity of residue is known to affect subsequent operations such as, soil preparation, planting operation and weed control (Gonçalves et al., 2007). Harvesting residues also poses a significant fire hazard if not properly managed. According to (Gonçalves et al., 2007), the choice of residue management practices can lead to significantly different impacts on tree growth.

In South Africa the most employed method of residue management is burning. Burning is preferred as it is relatively cheap, quick and more efficient in comparison to other mechanical alternatives (Dragotescu & Kneeshaw, 2012). However, burning is not ideal as it is constrained by amongst other burning windows and attaining permission from authorities to burn which may lead to delays in performing subsequent silvicultural activities (Oldeman, 1998). Furthermore, with burning there are both short- and long-term burning negative effects on soil properties, the atmosphere and the ecosystem amongst others. Several studies have shown that burning can cause significant loss of Soil Organic Carbon (SOC) and associated nutrients (Page-Dumroese et al., 2017; Titshall, 2011). Another particularly worrying effect of burning is the contribution to carbon dioxide emission, a gas that is associated with global warming (Titshall, 2011).

An alternative to burning, is mulching (or masticating) to manage the residual biomass. Mulching can reduce risks associated with burning. These can include a reduction in SOM, loss of soil nutrients and increase in soil erosion, while not impacting the environment or atmosphere. Some of the positive results of mulching according to Heath et al., (2000), are an increase in SOM, a reduction in erosion, the conservation of soil nutrients and the conservation of soil moisture. Moreover, mulching can facilitate the establishment of a new stand (Sinkevičienė et al., 2009). In felling to waste operations mulching may be considered a complete system, with felling and processing being completed in one step (Sinkevičienė et al., 2009). Moreover, a large piece of land can be cleared using a one-man-operated machine.

Although it is generally accepted that it is more beneficial to mulch than burn, the feasibility of mulching has not been widely studied. Most studies are interested in how mulching, when compared to burning, improves soil structure, nutrient availability and subsequently the success of tree establishment. For instance, a comparison made by Reichert et al., (2015) suggested that the use of double vertical and horizontal rotor mechanisms decreased residue particle size, which consequently improved particle decomposition, nutrient release and soil structure when compared to burning. It may therefore be necessary to conduct an economic assessment, to establish whether differences exist between the cost of mechanical mulching and burning and the effects on the efficiency of downstream operations. This may assist in developing cost and productivity models when these operations are implemented.

This study will assess the costs, risks, and benefits of mechanical mulching as a residue management option and will also consider operational benefits and drawbacks from the perspectives of site management, risk, productivity, financial feasibility and sustainability. Consequently, the study will then assess the effects of mulching versus burning on post-harvest re-establishment operations, including soil preparation, pitting and planting.

1.1 Research questions

- ❖ What productivity / cost levels can / are being achieved in mulching and which factors influence these most?
- ❖ What are the direct benefits / consequences of mulching on re-establishment efficiency?

1.2 Research aims and objectives

- ❖ Provide a better understanding of overall productivity and costs of mulching.
- ❖ Investigate the effect of mulched and burnt material on subsequent operations i.e., pitting and planting.
- ❖ Improve methods for assessing pre-treatment biomass quantities.
- ❖ Investigate whether the high cost of mulching is justified from an operational perspective.

2 Literature review

2.1 Overview

It has been noted that, in as much as plantation forestry is expanding globally, the growth pattern in South Africa remains stagnant (Madikizela, 2014). This in part is due to a decline in available forestry specific land (Madikizela, 2014). Global expansion is likely to be one of the drivers of the escalating global competition in accessing timber markets as noted by (Uys, 2018). Unfortunately, for the forestry industry in South Africa, recurring droughts have had serious consequences on the industries profitability and sustainability (Uys, 2018). Therefore, in the face of increasing global competition and negative climatic conditions, local forestry industries must direct operations and practices towards cost reduction and long-term sustainability. In this context residue management is an example of a silvicultural operation that must be carried out in a manner that is considerate of the challenges facing forestry industries in South African. The choice of management practice must consider both financial costs and environmental effects. This literature review focusses on the costs and benefits of mechanical mulching, with the desire to explore the economic viability of mechanical mulching as a residue management practice.

2.2 Overview of South African forestry modernisation

Over the past decade, South Africa has undergone a process of modernising re-establishment activities (Ramantswana, et al., 2021). A study by Ramantswana, et al., (2021) highlighted that re-establishment operations have evolved with regards to technology, however it was found that drivers were needed to advance health and safety, improve productivity, reduce costs, improve work quality, while mitigating social risks and reduce environmental impacts. Inherent site factors such as terrain, residual stumps, harvest residues and interrow width, together with increases in equipment capital cost has inhibited the advance of modernisation. Harvesting residuals, high stumps and soil compaction as a result of prior operations are hindrances to the effective application of mechanised re-establishment equipment on a site (Ramantswana, et al., 2021). Mulching of harvest residue offers a solution to this problem, especially on sites which have been coppice, bad harvesting practices have occurred or sites where increased amounts of defect timber is left behind.

2.3 Residue management in South Africa

Residue management is a well-known and widely accepted practice for controlling various soil physical, chemical, and biological functions. Residue management refers to process in which residue from harvesting is managed before any reestablishment operations start. Crop residue management offers temporary shelter from the elements, as well as adding organic matter to the soil, which enhances soil moisture retention (Turmel et al., 2015). Depending on the landscape and type of crops being planted, different residue management practices are used, which include mulching and/or burning. The selection of the residue management method is dependent on company policy, the previous crop, site type, terrain accessibility, and cost. Other methods such as chopper rolling, broadcasting of slash, slash windrowing have been used as slash reduction techniques in the past (Ramantswana, et al., 2020).

Mulching presents several advantages such as preventing soil erosion and the preservation of nutrients in the soils. Burning as a crop residue management technique is also commonly used in agriculture. Despite contributing to greenhouse gasses, many small-holder farmers still practice burning as a residue management as it is considered a cost-effective way of removing stubble. Unfortunately, burning may also negatively affect the quantity of nutrients available on a site (Naresh,et al., 2021).

2.3.1 Burning as a management practice

The use of burning as a residue management practice, is widespread in South African plantation forestry (Madikizela, 2014). Burning has the potential to positively or negatively affect the soils biological, chemical, and physical properties, which subsequently impacts tree growth (Certini, 2005). Burning can facilitate the transformation of organic nutrients to inorganic forms, which are often more readily available for plant use (Christensen & Abbott, 2013; Morris, 1986). Residue burning is cost-effective, quick and makes mechanical land preparation easier by clearing potential impediments to the machine movement (Madikizela, 2014).

A study by Toit, et al., (2008) based on a *Eucalyptus grandis* pulpwood stand found that prior burning of slash, and fertilizing promoted increases in initial volume, leaf area and forest floor litter concentrations. Removing of slash resulted in lower volume production and inferior leaf area growth. All other treatments in this study had no effect on stand growth.

In another study, du Toit et al., (2010) based a review of South African research for improved stand quality on concerns that multiple rotations of forestry could ultimately cause a decline in soil physical properties and carbon due to the frequent use of slash burning before establishment.

Disadvantages on the use of burning of residues have been reported, including modification of litter decomposition rates and nutrient release, which in long-term productivity have an influence on nutrient availability patterns (Dovey, 2012). DeBano, (1990) reported that carbon and nitrogen can be lost either as particulates or in volatile forms due to heating. This has significant effects on the soil organic carbon and some nutrients (Mendham et al., 2002; Prieto-Fernández, et al., 2004). Choromanska & DeLuca, (2002) reported that carbon and nitrogen mineralisation decreased after fire and did not improve within their study period. Furthermore, the other disadvantage of burning is that increased leaching of residues might occur since combustion mobilises nutrients locked up in the residues and surface soil (Powers et al., 2005). DeBano, (1990) extends the problem of leaching caused by burning to include leaching of potassium below the rooting zone and, attribute large volatile losses of other nutrients, particularly nitrogen to burning.

The effects of burning are dependent on the soil surface temperatures during the process of burning. Thus, hot fires are considered to cause greater damage. The physical and hydrological properties of soils under eucalypt plantations have been reported to be altered by burning (Rab, 1996). This in turn has a negative impact on site productivity and can result in increased rates of erosion. Furthermore, Zavala et al., (2010) reported that water repellence can be induced as well as being enhanced using fires.

Apart from the effects discussed above repetitive burning of harvest residues can cause degradation of plantation site fertility (O'Connell et al., 2000). Soil pH tends to increase after residues are burnt; mainly because of the hydrolysis of the base cation oxides, which are plentiful in ash (Ballard, 2000). Studies done in the *Eucalyptus grandis* study in South Africa showed that soil pH was high after burning, with a significant increase being observed between planting and two years of age for all the treatments, and a decline back to the initial levels being recorded after seven years (du Toit, et al., 2008) and was attributed to the increased decomposition of residues.

From an ecological point of view, burning results in habitat loss for insects and has knock on effects on the overall biodiversity of the ecosystem (Aliaga, et al., 2017). Insects have been identified to possess the ability of detecting changes in the functioning of forest ecosystems and as such can act as an early warning system in any disturbances in the forest or plantation ecosystem (Aliaga, et al., 2017).

2.3.2 Mechanical mulching as a management practice

Mechanical mulching is an alternative measure to residue burning and as a method of residue management. It involves converting plant residue from the previous harvest as mulch for the next crop. Walsh et al., (1996), states that mulch refers to any material that forms a protective cover over the land surface of the soil. Mulching is divided into two basic types: organic mulch materials, which is grass, straw and bark and non-organic mulch materials such as, stones, small chips of brick and plastic (Maphumulo, 2017).

The effectiveness of mulch varies widely with the material. Apart from that, mulches are applied differently to the surface. By various physical forms, which include the particulate matter and continuous sheets, in which the particulate mulch consists of small pieces of materials applied so as to create a deep, porous layer on the soil's surface and the sheet mulches are thin, homogeneous material layers. Their application to the ground leads to the creation of a uniform protective barrier. Mechanical mulching refers to the machinery which can shred vegetation and crop residues (Forge et al., 2003).

Despite the numerous benefits of mulching, mechanical mulching in general is noted in literature as a costly process (McEwan & Steenkamp, 2014; Foelkel, 2007). In addition to the high capital cost of mechanical mulching, the costs, increases when the soil contains rock that damages mulching tips (McEwan & Steenkamp, 2014.) Additionally, mechanical mulchers, need skilled operators, (McEwan & Steenkamp, 2014).

Recently, the forestry industry of South Africa started adopting mulching as the preferred residue management practice. Mulching improves access to the site, increases soil moisture retention, reduces nutrient loss, and lowers fire risk. But the high costs are still a limitation (Ramantswana, et al., 2020). Moreover, suppression of weeds, maintaining/retaining moisture of the soil, and prevention of evaporation, which in turn regulates soil temperature are also benefits of mulching. Mulches have been reported to prevent water, and wind-induced compaction and erosion (Sinkevičienė et al., 2009). Mulch improves soil quality by enhancing physical and chemical properties of soil, which in turn increases plant production (Jordán et al.,2010).

2.4 Effects of residue management on forest soil nutrients.

Harvest residues from eucalypt and pine plantations can be retained on the forest floor. (Nambiar et al., 2000) highlighted that eucalypt can produce substantial quantities of biomass, which can be a significant nutrient source. Eucalyptus residues typically include stringy bark, from in-field debarking which makes it somewhat different to pine residue. Many nutrients in crop residues are contained in the foliage and bark, and these can be kept on site after stem-wood harvesting. Apart from being a nutrient store, residues are a representation of a significant proportion of organic matter. Hence, managing them through retention will have an impact on the longer-term productivity of the plantations achieved through soil organic carbon changes and nutrient supply (Mendham et al., 2002). Studies have shown that the retention of these residues during successive rotations improves pine growth (Smith et al., 2000; Tiarks, et al., 2000) and eucalypt (Jones et al., 1999) plantations. (Shammas et al., 2003) also reported that these residues have the potential to act as a buffer against nutrient losses through leaching reduction at the early stages of plantation development. During this period, roots have constrained spatial extent and are incapable to use all available nutrients.

Retained residues also serve as a source of beneficial soil nutrients. Forest ecosystem nutrients are available in below ground living biomass, forest surface and the soil.

According to Bijay-Singh et al., (2008), residue management has recently gained attention due to the quest for sustainable agricultural practice. Soil organic carbon (SOC) after harvesting of tropical forest plantations and replanting under tropical conditions was found to increase by retaining the residues on the soil surface (Tiarks & Ranger, 2008). In addition, changes in soil pH were observed and were constant with the depth, time and treatment. A study by Mendham et al., (2003) highlighted higher exchangeable K^+, Ca^{2+}, and Mg^{2+} in the 0.05 to 0.20 m soil while Ca^{2+} and Mg^{2+} initially increased at the 0 to 0.05 m depth after burning but decreased within two years. However, du Toit, et al., (2008) observed a significant increase in exchangeable soil Ca^{2+}, but no effect on exchangeable soil Mg^{2+} when residues were retained.

The study by Madikizela, (2014) on a eucalyptus plantation in Northern KwaZulu-Natal showed that residue management (burning and mulching) resulted no significant effect on soil pH, exchangeable K^+, Ca^{2+}, Na^+ and Mg^2, soil acidy texture and effective cation exchange capacity (ECEC). Residue mulching led to an increase in the SOC after two years of performance. SOC assists in the ability of soil to improve aggregation, and losses will raise the sensitivity of the site to degradation.

The productivity of a plantation or its ability to capture resources, can be measured at any time (Mead, 2005). Stand productivity is reflected in leaf area which in turn is determined by genetics, stand development and degree of stocking (Mead, 2005). Mavimbela et al., (2018), determined the effects on forest productivity when using different slash-retention scenarios with the suggested amounts of fertiliser in Usutu Forest, and concluded that harvest residue retention/residue management increases forest productivity.

2.5 Downstream operations

2.5.1 Manual and mechanised pitting operations

Pitting refers to the digging of a hole in which to plant a seedling. The physical environment where a seedling is to be planted can be improved by preparing a planting pit. The benefits of pitting include (Sappi Tree Farming Guidelines 2021):

- reduction of soil bulk density and the physical strength.
- infiltration rates of water are improved.

- oxygen diffusion rates are promoted.
- the rates of organic matter decomposition in the topsoil are increased; and
- weed competition around the seedling is removed.

Pitting is a crucial re-establishment technique to loosens the soil, allowing easy planting, better root-to-soil contact due to reduced bulk density, and better water infiltration (Grossnickle, 2005). When these advantages are combined, they produce an environment conducive to better seedling survival.

Pit preparation might be manual, motor-manual or entirely mechanised. Pit quality of manually prepared pits might vary. According to Ndlovu et al., (2019) and Dovey, (2016), pit quality of manually formed pits can vary due to a mixture of soil type, presence of slash, and differing degrees of labour competence. Furthermore, manual pitting is time-consuming, particularly on steep slopes and sites with heavy slash loads, and/or rocky terrain (Ndlovu et al., 2019). When compared to manually prepared pits, the soil in motor-manual prepared pits are often more friable, with few or no clods (Dovey, 2016). Different pit preparation methods, particularly manual versus motor-manual, may affect soil friability, bulk density, and hence water hygroscopicity, and these may influence seedling survival if no water or hydrogel is applied at, or after planting.

Hechter, et al., (2020) observed that there were no significant differences in seedling growth between the two pitting methods (manual and motor-manual) (pitting methods x Watering regimes what do you mean here). A supplementary study by Hechter, et al., (2020) investigated four manual pitting implements (notch, agricultural hoe, mattock and road pick) and three distinct motor-manual heads (inverted A, Archimedes screw, and Mondi-designed pitting head) to determine influences on pit size/quality and in seedling growth. This study's findings revealed that the pitting method had no significant impact on re-establishment success or plant performance (Hechter, et al., 2020). This indicated that the soil type studied, and the eucalypt species planted were resistant to any unfavourable tillage impacts caused by the tillage, or the soil did not strictly require any form of tillage (Hechter, et al., 2020). Furthermore, no differences were discovered between approaches for soils pitted in the winter and planted the following year versus pitting and planting in the summer rainfall area in South Africa. As a result, it may be deduced that other considerations should be addressed while selecting pitting methods. Extrapolation of these results requires testing a variety of soil texture classes, carbon and moisture contents, and the use of guidelines for various soil types and situations (Ndlovu et al., 2019).

The application of mechanised pitting must be cost efficient, which means that the pitting machines must be reasonably productive and cost effective, high technical availability, and an appropriate yearly capacity utilization. Consequently, Hechter, et al., (2020) suggested that cost, productivity, physiological workload and ergonomics must be judged in order to select a pitting method, together with plant performance. Manual pitting has raised numerous ergonomic concerns, which has led to an increased use of motor-manual pitting implements according to Hechter, et al., (2020) .

Generally, motor-manually prepared pits are more friable than manually prepared pits and contain few to no clods. Motor-manual and mechanised pitting however costs more compared to manual pitting, even though it yields a higher productivity. With manual pitting we observe a productivity between 300–450 pits unit^{-1} day^{-1} whereas, approximately 900 pits unit^{-1} day^{-1} are observed in motor-manual pitting (Myers & Williams, 2015).

Since 2010 and variety of different pitting equipment has been tested in South Africa including multipit and single-pit technology such as motorised augers and compact excavators fitted with a rotating pitting head (Figure 2.1). But despite ergonomic addition motor manual machines tend to pose significant safety risks. Modern excavator based pitting machines like the Novelquip Mpat RS-electronic equipped with GPS system are able to eliminate safety and ergonomic related risks normally faced by manual and motor manual pitting operators.

With mechanised operations machine components include a pitting head with two tungsten tines and a centre auger body designed to effectively break the soil without smearing the side walls. An electronic control system that uses a micro-computer to monitor the entire pitting process, fitted with a touch screen to display information to the operator is included in these machines. In addition, the electronic system also logs all the pits made and records pitting productivity data. Real-time kinematic (RTK) GPS guidance, together with the machines management system is the latest addition to this modernisation of mechanised pitting operations. This provides solutions to achieving consistent in spacing accuracy, eliminating the need for manual marking of planting spots, increases land utilisation by generating compartment maps optimising pits with GPS points with an accuracy of 100 mm, and operating efficiency by making fewer manoeuvres with the base machine by snapping to the next GPS node (planned pitting location) (Viljoen, 2021).

Figure 2.1: Volvo compact excavator, (EC55B) fitted with the, Mpat pitting head and control system (Chapman, 2015).

2.5.2 Manual and semi-mechanised planting methods.

Manually planting a seedling has remained a common practice since the inception of plantation forests. The trowel and hoe method are still the most popular manual planting method in South Africa. These solutions, on the other hand, take time and necessitate a lot of teamwork (Ramantswana, et al., 2020). fortunately, Planting tubes and tractor drawn planters, have emerged over the last decade and a half. These ergonomically friendly planting tube systems have now been widely employed (Kaakkurivaara & Kaakkurivaara, 2021) and are more productive than manual planting. With a planting tube, a person can combine pit preparation and the planting. Semi-mechanized tractor drawn planting equipment, are manufactured readily in South Africa. An example of such a machine includes the ANCO MP300 planter (Figure 2.2.B), KISS planter, and the self-driven Fiori, equipped with four to six planters that apply hydrogel (Ramantswana, et al., 2020).

Mechanisation of the planting process has had a significant impact on planting productivity and cost-effectiveness. A study by Kaakkurivaara & Kaakkurivaara, (2021) in Thailand revealed that the planting tube system could be a viable alternative to cut costs and boost productivity without unduly loading the operating personnel. This study showed that the planting tube was more cost-efficient and more ergonomically friendly when compared to the planting stick system (you have not spoken about the planting stick method at all yet you should have done that already – start with manual and move further.

Planting with the planting tube was cheaper and faster taking 16.6 seconds and costing R0.11 per seedling, in comparison to the stick method taking 21 seconds and costing R0.83 per seedling. Plant growth after one growing season, on the other hand, revealed no overall significant variations in height growth or root collar diameter increment between planting with the planting tube or planting stick techniques (Kaakkurivaara & Kaakkurivaara, 2021).

Globally, labour shortages and rising labour costs have prompted research and development on planting machines. Forestry contractors are finding it increasingly difficult to get labour to complete planting contracts due to a rapid shift in the labour market towards metropolitan regions (Shammas et al., 2003). As a result many contractors have no choice but to consider further mechanization of planting operations.

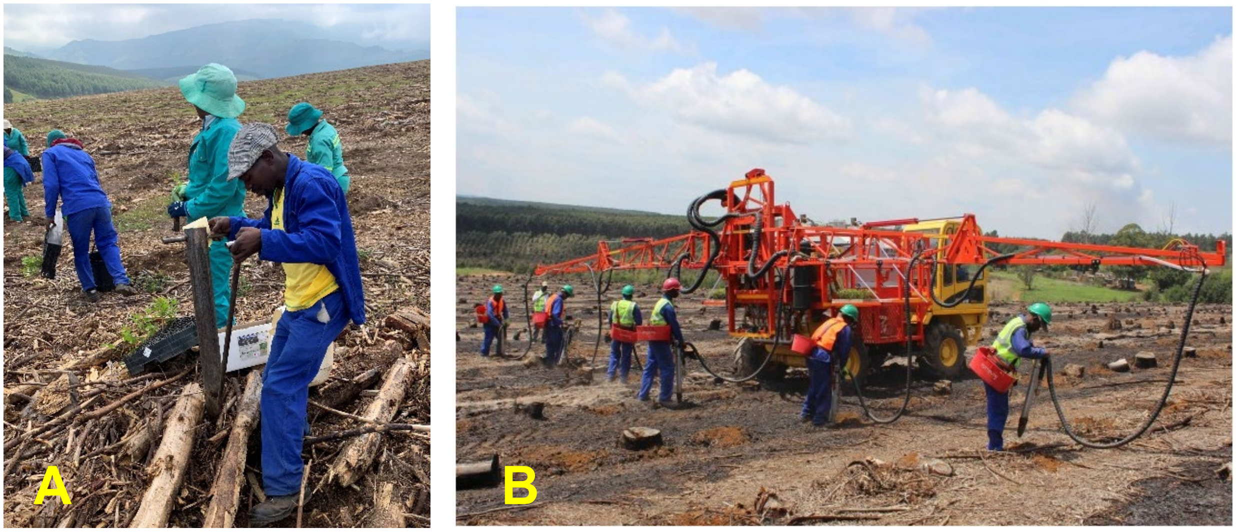


Figure 2.2: A- manual planting operation. B- Anco semi mechanised planter (Chapman, 2015).

2.6 Financial and economic profitability of mechanical mulching

Forestry industry is one of the most labour-intensive industries in South Africa. Manual labourers are employed at all stages from planting to harvesting. The advent of mechanization has positive influences on industries (Clarke, 2018). With mechanisation of processes, comes the need to evaluate the financial and economic feasibility of the processes. For instance, a study by Uys, (2018) revealed that mechanising the harvesting of eucalypts was advisable whilst the other case studies showed otherwise. This was attributed to the significantly low cost of labour compared to the cases that would benefit from mechanisation.

Historically, there has been a reluctance on the part of forestry companies to support mechanical mulching in place of burning (Soman, et al., 2019). According to Chapman (2021), the reluctance has been exacerbated by the fact that mulching is one of the toughest operations in forestry on both man and machine.

Mulching has an impact on practically every aspect of tree growth and harvesting (Tiarks & Ranger, 2008). Mechanical mulchers, according to a report from Chapman, (2021), operate close behind the harvesting team, saving time and increasing efficiency. According to Chapman, (2018) mulching reduced time taken between harvesting and re-planting from 3-6 months to just 1 month, by eliminating the burn window in Zululand

Variations in mulching operational costs can be attributed to the differences in the volumes of biomass in place, and operational and stand conditions. Unfortunately, few studies have looked at the impact of residue management procedures on the cost/benefits of subsequent operations (Soman, et al., 2019). Interestingly, we notice an absence of detailed economic studies focusing on profitability and feasibility of mulching technology as opposed to the commonly used burning method. Despite the burning technique being viewed as cheaper, the use of fire may generate losses by nutrient depletion form erosion and mismanaged fires that not only negatively affect the landowners and farmers but also society (Soman, et al., 2019).

2.7 Costing in forestry operations

Considering the objectives of this research, we looked at concepts and practices involved in the costing of silvicultural operations. The European Cooperation in Science and Technology (COST) Action FP0902 model is widely used for costing in forestry. Calculations based on this costing model have been standardised to reflect current costing in the South African forestry industry.

According to (Ackerman, et al., 2014), this model requires the following inputs

- Machine type: Specifying the machine being studied in the model.
- National currency in which the calculations must be done (Rands).
- The costing unit: the unit of production the costs are expressed in (m^3)
- Fixed cost inputs: Fixed or standing costs are costs that need to be recovered by machine owners regardless of the amount of work a machine does or the revenue it earns.
- Variable cost inputs: Variable or running costs are incurred when the machine is working.
- Operator: The total cost of employing the operator, including wages, benefits, and overhead costs.
- Productivity: Contains aspects of productivity, machine utilization, working days or hours and the profit margin.

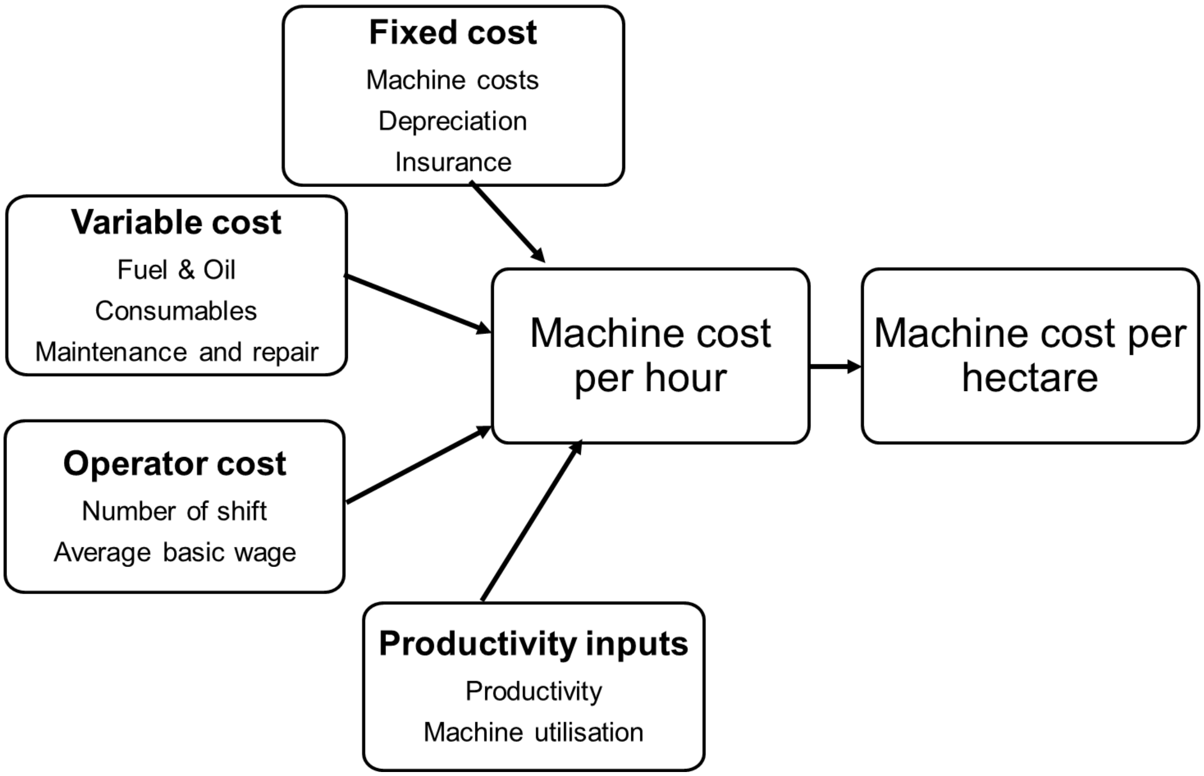


Figure 2.3 Flow diagram highlighting input costs (fixed, variable, operator cost and productivity) which are used to calculate machine cost based on the European costing model.

According to (Ackerman, et al., (2014), machine costs are divided into fixed costs and variable costs (Figure 2.3). Fixed costs need to be recovered by machine operators irrespective of the amount of work a machine does or the revenue it earns and are associated only with owning the machine. Variable or running costs are incurred when the machine is working, whether performing its intended task or travelling empty, or at least when the engine is running. These are the costs for fuel, lubrication, maintenance, and repair, running gear, and other consumables. These costs are expressed as either cost per productive machine hour (PMH) or cost per scheduled machine hour (SMH) if a reasonable utilisation factor is known. Machine rate is calculated by adding fixed and variable costs. The machine rate is divided into labour costs, operating costs and ownership costs. Labour costs include the wages of the operator. By totalling all these costs together, divided by the expected life span of the machine in hours, a cost per machine hour is calculated (Ackerman et al., 2014)

2.8 Summary

Although burning of residues is favoured over mechanical mulching, an evaluation of burning versus mulching shows that both are associated with a unique set of advantages and disadvantages. These can, include cost, nutrient or organic matter loss, as well as sometimes significant delays linked to the availability of production factors or in the case of burning, suitable conditions within a limited season.

Given that land available for plantation forestry is limited, there is a strong incentive to maximise production on the available land base. Mulching offers a solution for the comminution of residues almost immediately after harvesting. Reducing the period between successive rotations contributes to maximising land utilisation, especially so in short rotation forestry.

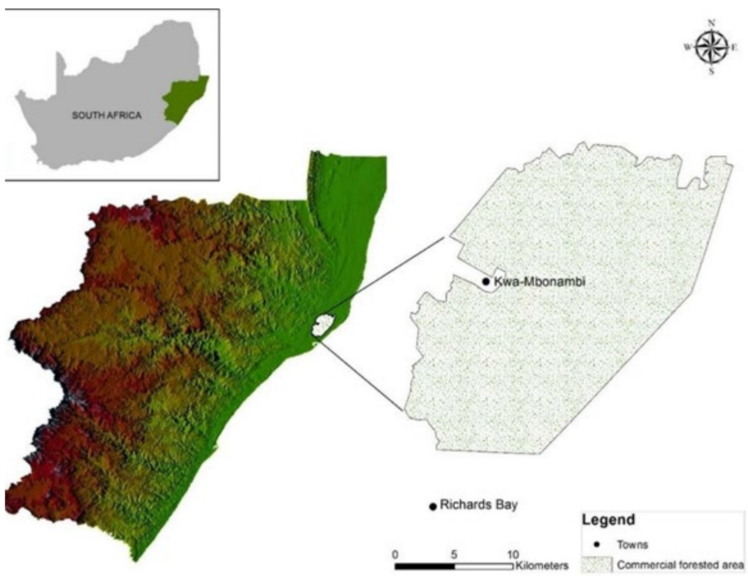
However, there is a lingering belief that mulching is too costly, and foresters are largely discouraged from employing mulching due to these high costs. However, no scientific research has been done to confirm or refute this belief.

3 Materials and Methods

3.1 Study areas

The study was conducted on three sites representing different forestry regions, different soils and climates, and different silvicultural regimes. The first site represented fast growing eucalypts plantations on sandy soils, the second site represented a pine pulpwood regime on clay soils, and the third, residue management after a pine sawtimber regime, also on clay soils as follows:

3.1.1 Site 1: KwaMbonambi Zululand



The Sappi managed KwaMbonambi area (Figure 3.1) falls in north-eastern part of KwaZulu Natal, co-ordinates S28° 62'22.88 and E32° 18'15.97and located along the eastern coastline of South Africa, 30 km northeast of Richards Bay (Stanger, et al., 2012). Sappi is a South African pulp and paper company. This area is representative of majority short rotation pulpwood management.

The Zululand area is characterized by a subtropical climate with a mean annual temperature of 22°C. This area has annual average rainfall of 1200 mm, which is seasonal in the summer months peaking between November and February (Melesse & Zewotir, 2017). The landscape of Zululand is predominantly flat terrain consisting of quaternary alluvial sediments of clay sands of aeolian deposits and soil with little organic matter. Most soils are deep sands belonging to the Fernwood soil form characterized by low (<0.5%) organic carbon content (Graham, 2018). However, Zululand soils differ in terms of nutrient resource, but their high penetrability permits rapid leaching of soil nutrients, conditions which are favourable for fast-growing Eucalyptus plantations.

3.1.1.1 Compartment selection

Three compartments with similar characteristics, in terms of species, slope and period of harvesting were selected. The chosen eucalyptus pulpwood compartments were J31a, J31b.and K19 (Table 3.1).

Table 3.1: KwaMbonambi plantation compartment Information

Compartment	**J31a**	**J31b**	**K19**
Compartment size (ha)	19.18	18.45	29.42
Dominant slope class (%)		0 -12	
Ground roughness		Even	
	Before residue management		
Previous rotation species		*Eucalyptus grandis x Eucalyptus urophylla*	
Spacing (m)	1.9 X 3.4	1.9 X 3.4	1.9 X 3.4
Date planted	09-09-2011	11-09-2011	24-10-2011
Date harvested	24-10-2019	24-10-2019	01-10-2019
Harvest method	Mechanised Cut-to-length	Mechanised Cut-to-length	Mechanised Cut-to-length

3.1.2 Site 2: Bulwer

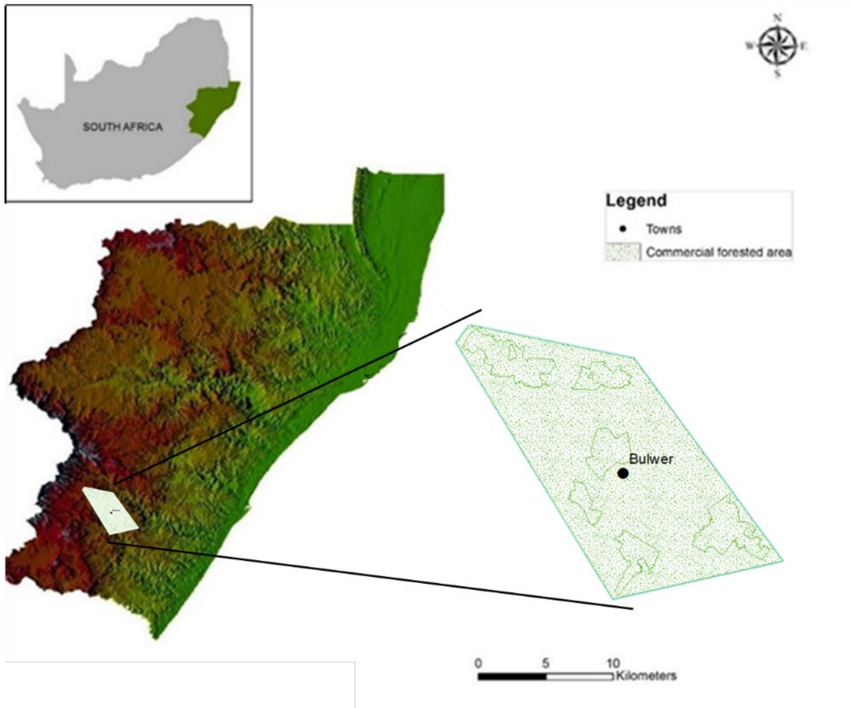


Figure 3.2: Map showing location of Bulwer area, adapted and enhanced form (Xulu et al., 2018)

Bulwer is located in KwaZulu Natal's southern Drakensberg region (Figure 3.2). It is situated between Boston and Underberg, co-ordinates 29° 48'S 29° 46'E. The mean temperatures in the area vary between a maximum of 30.5°C and a minimum of 25.1°C for the wet summer months (Nov – Apr) whilst the dry winter months (May – Oct) recorded a maximum of 10.6°C and a minimum of 5.8°C Precipitation mainly in the form of rain and mist are common in the area. Annual rainfall normally ranges between 750-1000 mm (Nel, 2009).

The geology of the area consists of mudstone with dolerite being present in a few areas. The study site comprises of thin humic topsoil and the lithocutanic B subsoil. Humic topsoil is characterised by abundant content of humus, which facilitates well drained soil of 450 mm thickness. Such topsoils are usually limited to areas of high rainfall and cool temperatures and are associated with a high degree of weathering on gentle to moderate slopes. (Soil Classification Working Group, 1991).

3.1.2.1 Compartment selection

The assessment was conducted on three unthinned pine pulpwood compartments, M31b, M37 and M38a (Table 3.2) situated in Sappi's Epsom plantation near Bulwer. These sites were selected as they were comparative in terms of harvesting residue load, and topography. It is important to state that all three compartments had experienced snow damage in 2012 as this influence the amount of defect material left on site.

Table 3.2:Epsom plantation compartment Information

Compartment	**M31b**	**M37**	**M38a**
Compartment size (ha)	10.17	26.11	16.07
Dominant slope class (%)		0 -12	
Ground roughness		Even	
	Before residue management		
Previous rotation species	*Pinus patula*	*Pinus patula*	*Pinus patula*
Spacing (m)	2.0 X 3.0	2.0 X 3.0	2.0 X 3.0
Date planted	April-2005	February-2005	February-2005
Date harvested	December-2020	December-2020	January-2020
Harvest method	Mechanised Cut-to length	Mechanised Cut-to-length	Mechanised Cut-to-length

3.1.3 Site 3: Jessievale

The study was based at York timbers, Jessievale plantation (Figure 3.3). The area falls in the Mpumalanga highveld with the plantations situated approximately 64 km east of Ermelo. Its coordinates are 26º15'0'' South and 30º 31'60'' East. York timbers manages their pine plantations for sawn timber on a 20-year rotation (York Timbers, 2020).

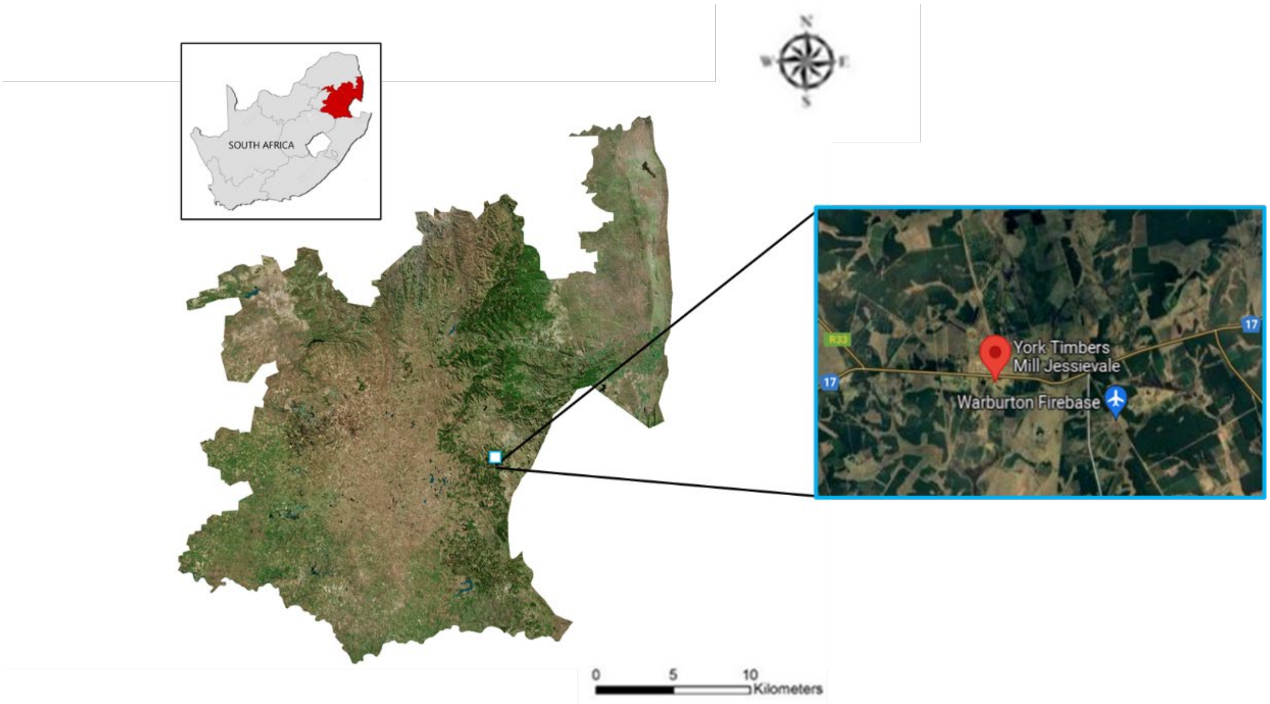


Figure 3.3: Map of Jessievale

Jessievale is in the summer rainfall with a mean annual precipitation (MAP) of 614mm and about 80% of its rainfall is between September to February. The area falls into the Highveld ecological zones (Mamba & Chirwa, 2013). The Highveld zone is approximately 1741 m above sea level with gently undulating plateaus.

The dominant climate is temperate mesothermal having temperatures vary between 12 and 21°C with the coldest month ranging from -3°C 18°C. Jessievale experiences dry and cold winters. Frost is common and can be expected from the beginning of winter whereas snow may occur in high lying areas (Phairah et al., 2016). However, the overall dominate vegetation is grassland.

3.1.3.1 Compartment selection

The assessment was conducted on three thinned pine sawtimber compartments, C38d, C40 and C42b, selected by York timbers (Table 3.3). Both had recently been clear felled using mechanised cut-to-length systems.

Table 3.3:Jessievale compartment information

Compartment	C38d	C42b	C40
Compartment size (ha)	2.89	4.67	3.94
Dominant slope class (%)	10	15	10
Ground roughness		Even	
	Before residue management		
Previous rotation species	*Pinus patula*	*Pinus patula*	*Pinus patula*
Initial spacing (m)	3.0 X 3.0	3.0 X 3.0	3.0 X 3.0
Date planted	December-2002	December -2002	December-2002
Stems per ha (Rotation)	651	507	579
Date harvested	May-2021	May-2021	May-2021
Harvest Method	Mechanised Cut-to-length	Mechanised Cut-to-length	Mechanised Cut-to-length

3.2 Research Design

A total of three compartments per region with similar characteristics were selected, comprising sites to be mulched and burnt. Field visits were conducted over three weeks. The visits comprised of planning and setup of the sites, and various site-specific time studies. The feasibility of mulching was assessed against the current practice of burning.

Subsequently, the Jessievale site focused mainly on investigating mulch quality specifically looking into the relationship between biomass loads, number of passes and machine speed.

The flow diagram in Figure 3.4 shows the sequence of studies as per study site.

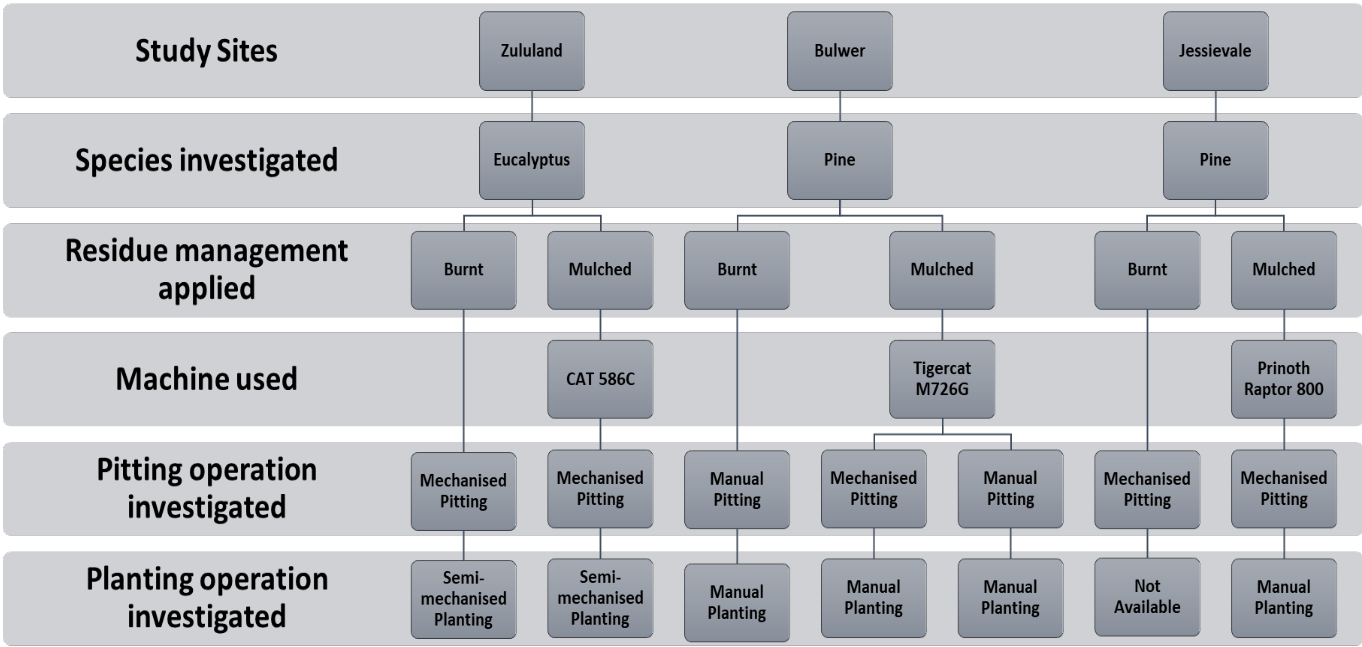


Figure 3.4: Overview of residue treatments, pitting and planting operations

3.2.1 Zululand assessment description

The KwaMbonambi site in Zululand was used to assess the effect of mechanical mulching on coppiced Eucalyptus species on subsequent operations. Since Sappi Zululand plantations has a ‘no burn policy’ of harvest residue, a direct comparison study between mulching and burning could not be done. However, Mondi Zululand, provided comparable data based on residue burnt sites.

The full operational flow of mulching, pitting and planting was done on the same site, except for the planting operation representing compartment J31a. Planting in compartment K19 was studied as a proxy for this. The flow diagram in Figure 3.5 shows the sequence of the events that were studied.

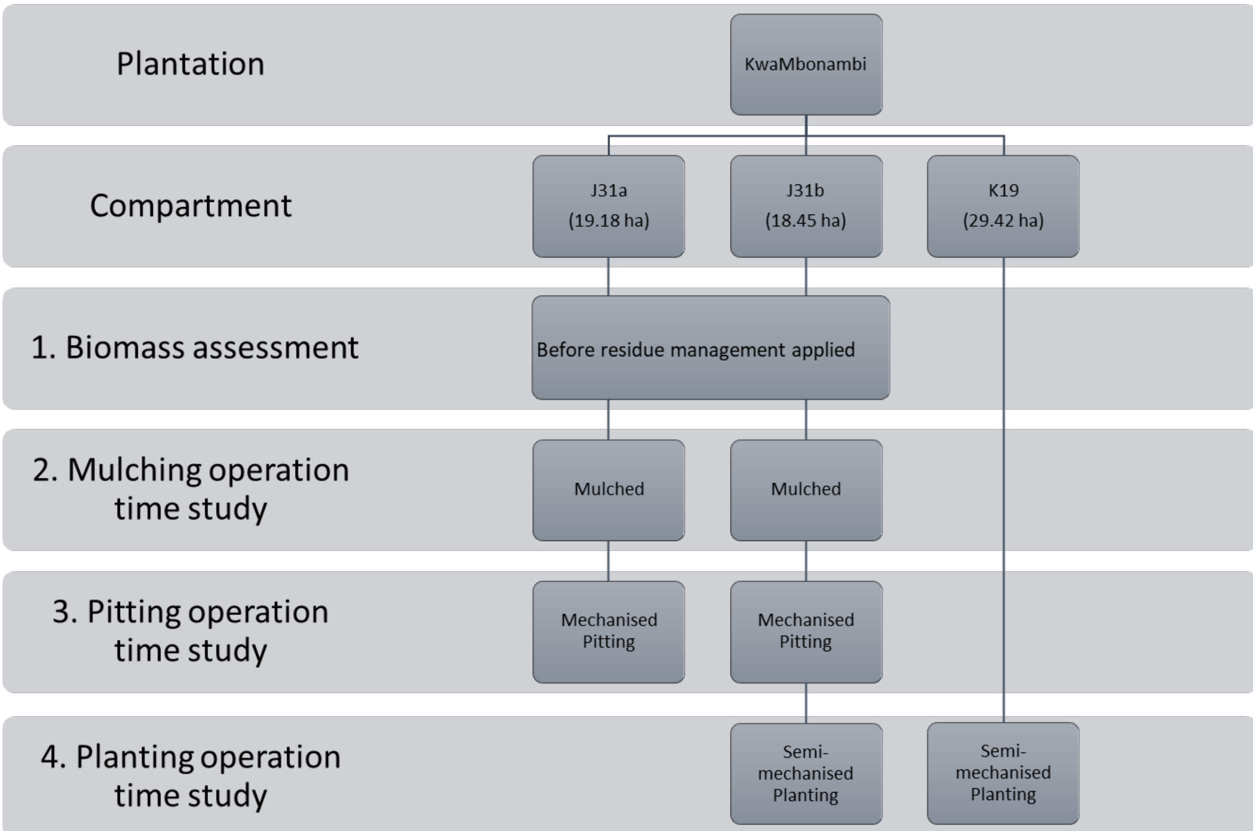


Figure 3.5 Zululand field study sequence.

3.2.2 Bulwer assessment description

The aim of this study was to assess the application of two different residue management regimes namely a mechanical-mulching operation and the burning of pine residues on the effect on subsequent operations, namely pitting and planting.

The full operational flow of residue management, pitting, and planting was done on each of the sites. On M31b, residues were burnt and not mulched, while on M37, mechanised pitting was applied as compared with manual pitting on the other two compartments. Figure 3.6 illustrates the sequence of events that was studied.

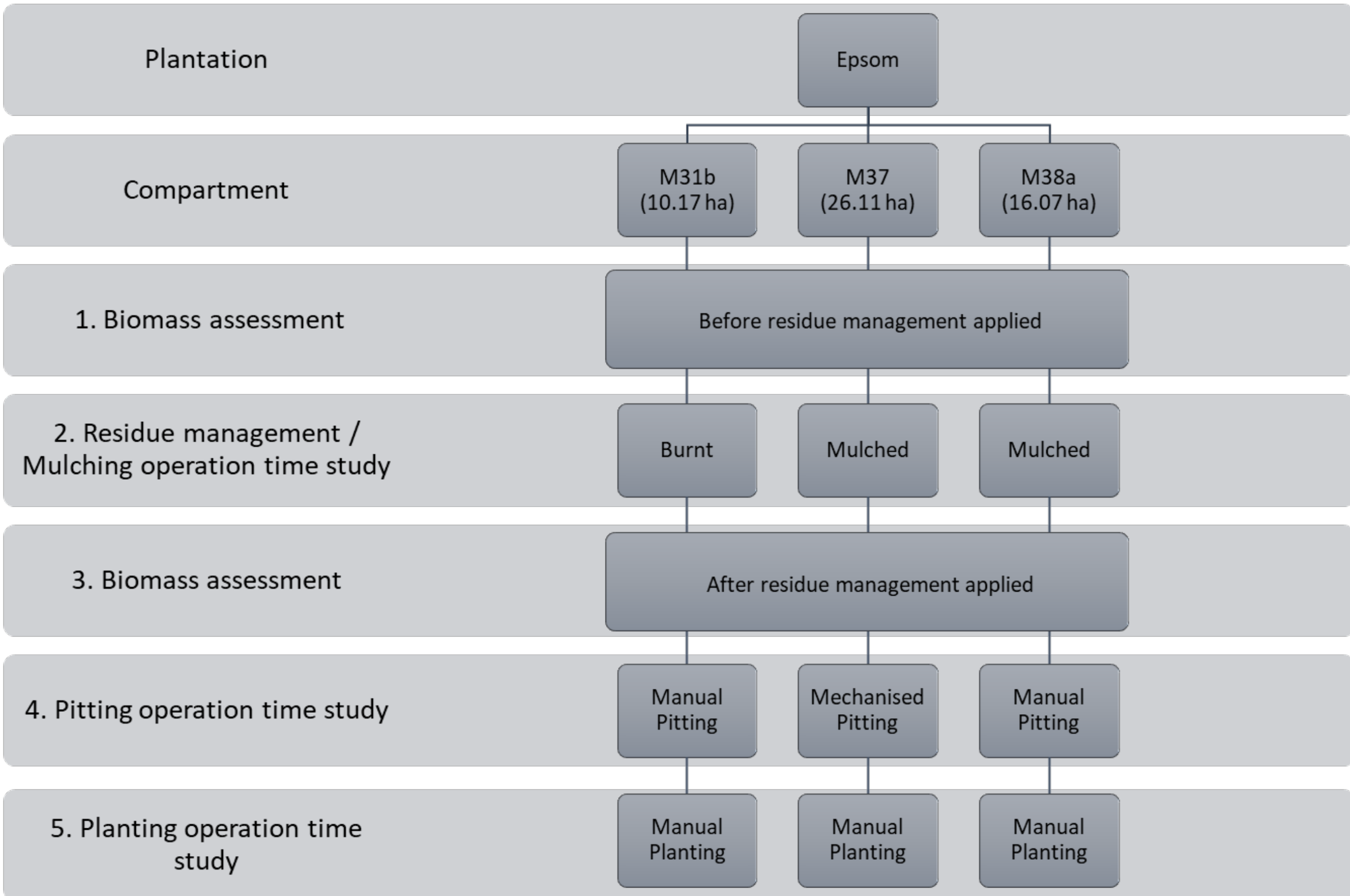


Figure 3.6 Bulwer field study sequence

3.2.3 Jessievale assessment description

This study was divided in to two parts; the first part was based on productivity studies of mulching, mechanised pitting, and manual planting (Figure 3.7). The operational flow (mulching, pitting and planting) was not conducted on the same site (compartment C40), as time constraints did not allow us to wait until the whole site has been completed before starting the next set of measurements. However, compartments with similar characteristic to compartment C40 was chosen as a proxy site.

The second part aimed to assess mulching as a residue management method, focusing mainly on mulch quality by investigating differences between biomass loads, number of passes and machine speed based on a thinned *Pinus patula* stand.

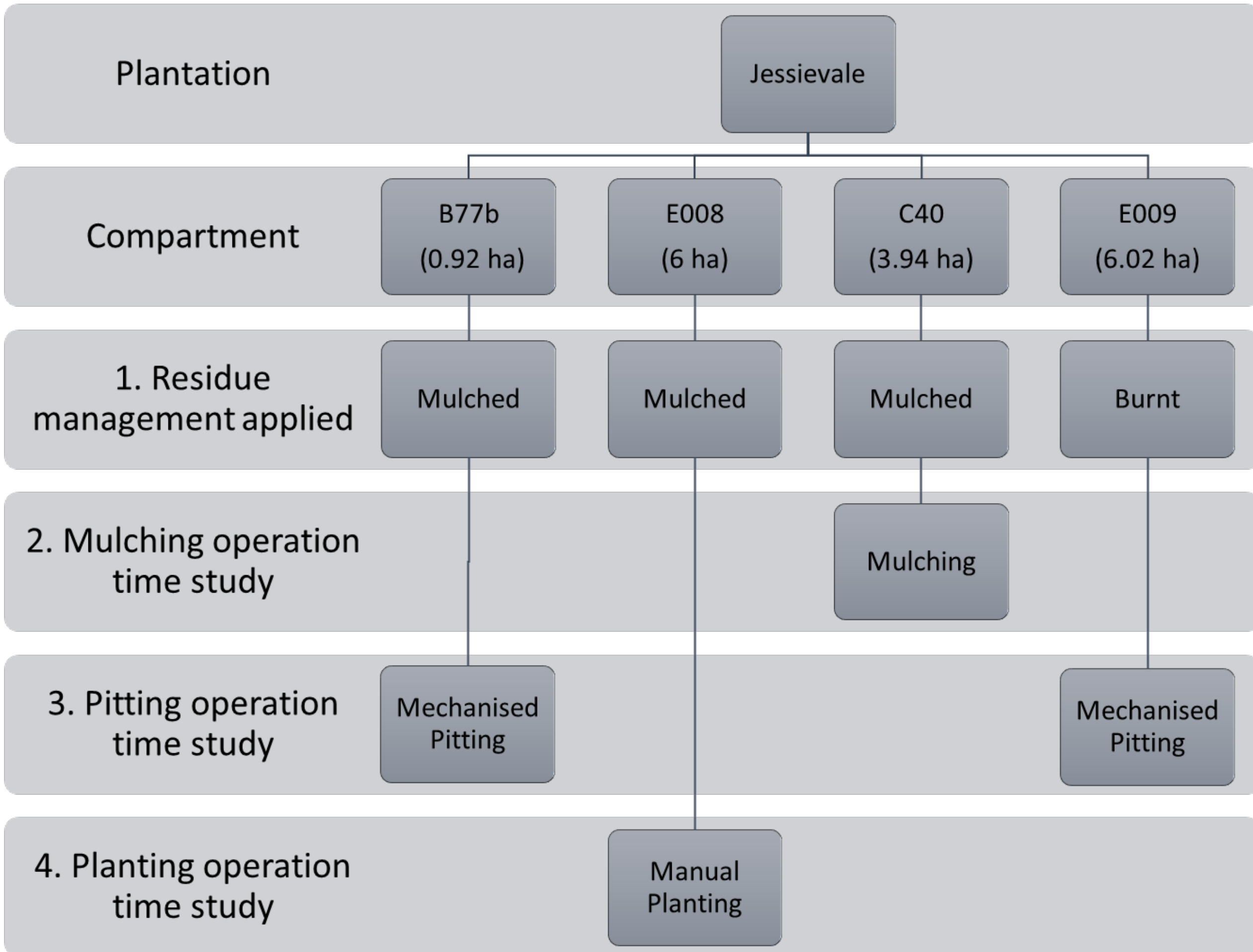


Figure 3.7 Jessievale field study sequence part 1

The second part of the study involved allocating treatments to compartments C38d and C42b, setting up measurement plots in each treatment, assessing biomass volumes before mulching, studying the mulching operations themselves, then assessing intact biomass volumes after mulching to be able to evaluate the effect of the various treatments (Figure 3.8).

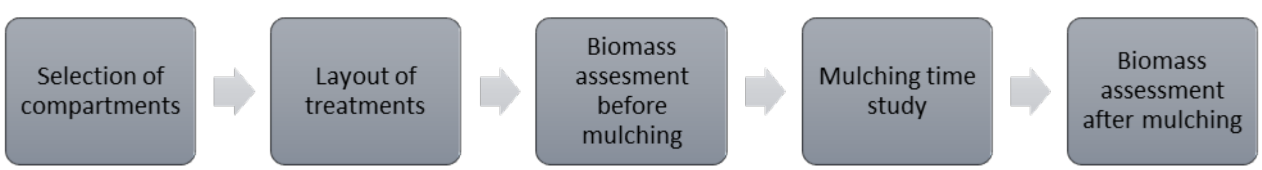


Figure 3.8:Flow diagram illustrating the investigative procedure of field study part 2

3.2.3.1Trial Layout

Compartment C42b and C38d were chosen for the study. The larger C42b was mulched on a downhill slope of approximately 15% from south to north, while C38d was mulched from north to south on a downhill slope of roughly 10%. For both operations, and adjacent road embankment proved somewhat of a hindrance to turning but was not considered to affect performance on the corridors that were used in this study.

Each compartment was divided into four treatments (S1P1, S1P2, S2P1, S2P2) (Table 3.4). Within each treatment, three rectangular sample plots of 2m x 20m were used for measurement of treatment effect. Speeds of 1.6 $km{\cdot}hr^{-1}$ and 3.2 $km{\cdot}hr^{-1}$ were chosen to be the two speed levels assessed as they were within slowest and fastest rage of the machines conventional speed of 2.2 $km{\cdot}hr^{-1}$. One pass versus two passes were chosen to be evaluated.

These plots were place at the beginning, middle and end of each treatment (Figure 3.9).

Table 3.4:Demarction of treatments applied

	Speed 1 (1.6 $km{\cdot}hr^{-1}$)	**Speed 2 (3.2 $km{\cdot}hr^{-1}$)**
Pass 1 (one pass)	Speed 1, 1 Pass (S1P1)	Speed 2, 1 Pass (S2P1)
Pass 2 (two pass)	Speed 1, 2 Passes (S1P2)	Speed 2, 2 Passes (S2P2)

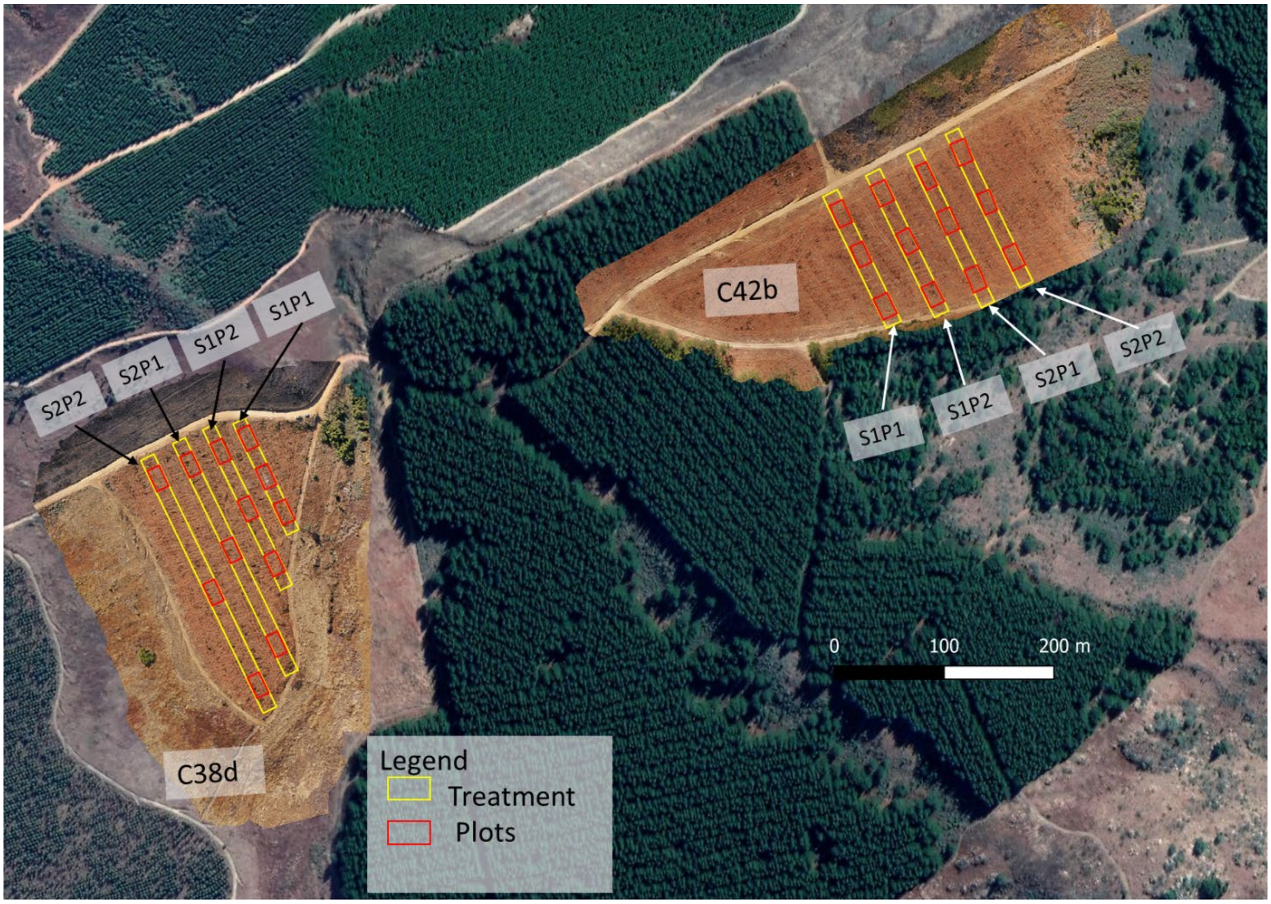


Figure 3.9: A snapshot of the field layout for mulch quality trial.

3.2.4 Biomass assessment

For all study areas on-site biomass assessment was completed in two phases prior to any residue management being applied to any compartment. In the first phase, the stump volume per hectare was calculated using a zig-zag sampling method. Secondly, harvest residues which are made up of branches, tops and off-cuts from the log making process were measured using the Line Intercept Method. The first step was to measure stumps in compartments. After that, a line intercept biomass assessment was conducted in agreement to a study by Karpachev, et al., (2020), estimating logging residues using line intercept method.

3.2.4.1 Stump assessment

Stump assessments were done in a zig-zag sampling design to eliminate bias brought on by spatial variation in growing conditions. A starting stump was randomly selected and measured using a diameter tape, then a further five stumps in each consecutive leg of the zig-zag pattern were selected until the full complement of 30 had been achieved. In total, thirty base and top diameters as well as stump heights were measured to calculate the average stump volume. Figure 3.10 illustrate the sampling method used.

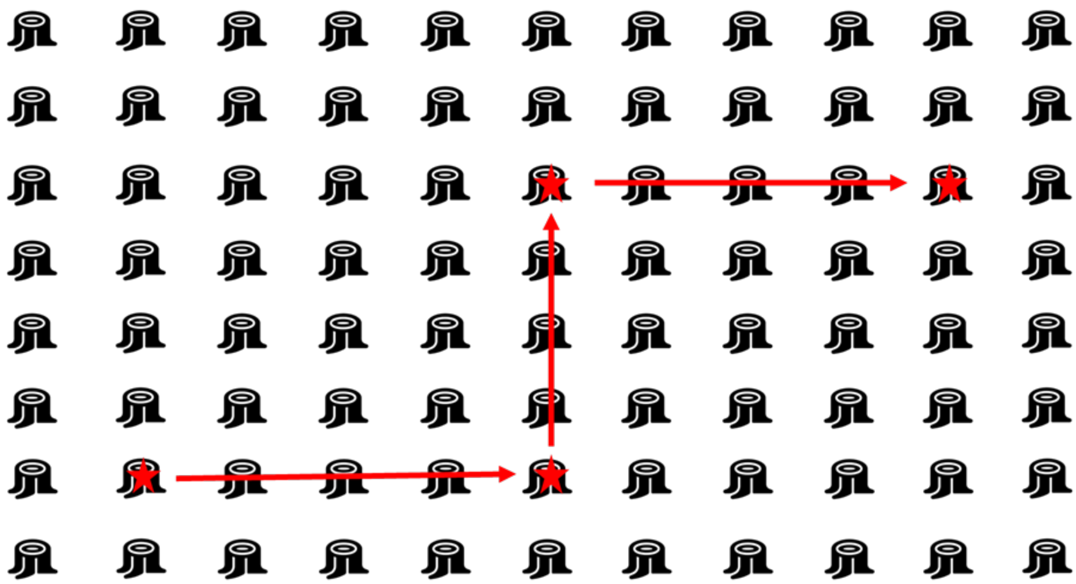


Figure 3.10: Zig-zag sampling method

The process used to determine the stump volume per hectare is as follows:

1. Determining the estimated volume for each stump by using the Neiloid of a frustum formula (Equation 1) and converting parameter values to reflect m^3

$$V = \frac{\pi h}{3}\left(\frac{R^2}{1} + Rr + \frac{r2}{1}\right) \qquad \textit{Equation 1}$$

   Illustration of the frustum superimposed on the stumps is shown in Figure 3.11.

2. Multiply the mean stump volume by number of planted trees per hectare. As per company planting standards, a total of 1548 stumps per hectare were assumed in

Zululand, 1667 stumps per hectare in Bulwer. 651 and 507 stumps per hectare in Jessievale C38d and C42b respectively.

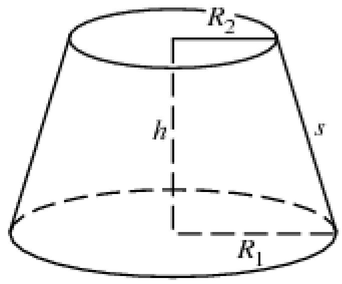


Figure 3.11: Elements of a frustrum, whereas h=height, R_1= radius of lower base and R_2= radius of upper base.

3.2.4.2 Harvest residue assessment

To estimating biomass volumes remaining after harvesting the line Intercept Method (LIM) detailed by Van Wagner in (1968) was applied. It requires that diameters of any residues are measured at the point of intersection with the sample line (Figure 3.12). The sum of the cross-sectional area is divided by length of the sample line, resulting in the volume per hectare.

The field procedure used was to lay out an equilateral triangle with strip (side) lengths e.g., 20 m. The triangle does not need to be closed exactly if the lengths of the side are accurately known. The starting point and first side angle were selected at random.

The process to determine the biomass on the site was done as follows:

1. Use this equation $\text{Volume}\ (m^3\ per\ hectare) = \frac{\Sigma d^2}{L}\ x\ 1.2337$

   Where *d* is the diameter (cm) of any biomass at the interception point
   L is the length of the sample line (60 m).
   and 1.2337 = $\pi^2/8$

To calculate the volume per hectare, the sum of all the diameter squared measured intersect at interception point is divided by the total length of the sample line, multiplied by 1.2337 (Bilbrough, 2005).

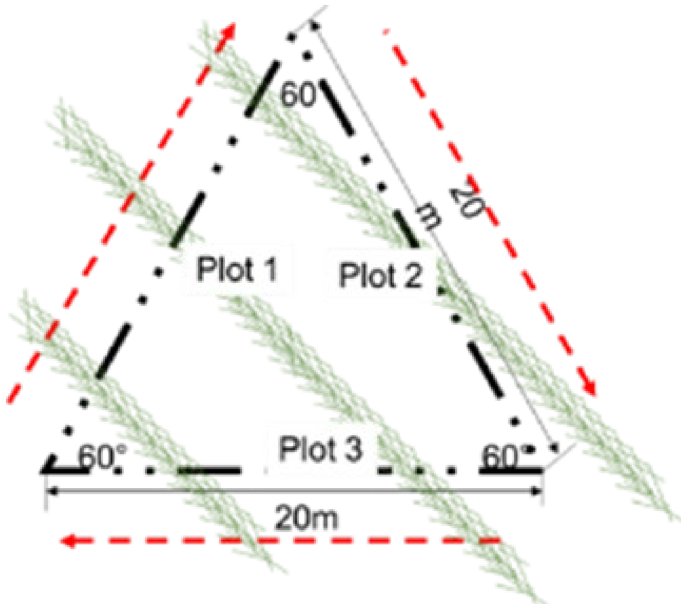


Figure 3.12:Diagram depiction of the line intercept method

A total of three sample triangles were done per compartment to estimate the mean harvest residue per hectare in that specific compartment. van Wagner, et al., (1982) recommend at least one 20 m equilateral triangle for every 20 ha of sampled area.

3.2.5 Burnt sites assessment

To compare productivities between residue mulching and burning, comparative sites with similar species and slope to that of the mulched sites were selected. These sites where chosen from the company's compartment list which were scheduled to be burnt or mulched relatively soon. Attributable to Sappi Zululand's no burn policy supplementary data from Mondi Zululand plantations was used. Due to operational challenges a single compartment, M31b at the Epsom plantation at Bulwer and compartment E009 at the Jessievale plantation at the Mpumalanga highveld were able to be used as the pine burn trial.

3.2.6 Time Studies

In addition to these assessments, time studies were conducted using a time study app (Ackerman et al., 2014) which was installed to an android tablet. These times studies include manual, semi-mechanised and mechanised operations which included mulching, pitting and planting operations were conducted on burnt and mulched sites at Zululand, Bulwer, Jessievale trail sites. Machine productive time was studied (All delays were considered regardless of length). Time was recorded in decimal minutes and distance travelled in metres. The data collected was imported into Microsoft Excel for pre-processing and analysed in R studio (Allaire, 2012), to test for differences in machine productivities

It is important to note that to avoid variations in comparing burnt and mulched residue treatment machine operators and manual workers where not changed throughout each site's investigation.

3.2.6.1 Mulching operations

Mulching operations were conducted on all three study sites. Compartment J31a and J31b were selected for the eucalyptus mulching trial at Zululand, compartments M37 and M38a at the pine mulching trial at Bulwer.

These compartments were assessed and areas where there were impediments to mulching, e.g. rocky outcrops, were demarcated not to be mulched. Zululand and Bulwer trials were done with the support of Savithi mulching company's machine. The Cat 586c base machine fitted with an FAE 300U mulching head (Figure 3.13.A) was used on the Zululand eucalyptus trial, whilst the Tigercat M726G mulcher with a Tigercat 4061 mulching head was used on the Bulwer pine trial (Figure 3.13.B).

For the Jessievale pine trial compartment C38d, C40 and C42b were selected by the company, York Timber's. The Prinoth Raptor 800 mulcher with a M900 mulching head (Figure 3.13.C) was used in this study.

Figure 3.13 Horizontal drum mulching machine investigated, A- Cat 586C base machine with a FAE 300U mulching head. B- Tigercat M726G mulcher. C- Prinoth Raptor 800 mulcher.

Machine specification for the three mulching machines are shown in Table 3.5 below.

Table 3.5 Mulching machines specifications

Specifications	**CAT 586C**	**Tigercat M726G**	**Prinoth Raptor 800**
Engine	Cat C9 ACERT	Tigercat FPT C87	CAT C18
Engine Power	261 kW (350 hp)	275 kW (370 hp)	470 kW (640 hp)
Steering	Frame	Frame	Skid
Fuel Capacity	494 L	570 L	820 L
Number of Wheels	4	4	-
Number of Tracks	-	-	2

Weight (less attachment)	17 214 kg	13 560 kg	20 750 kg
Controls	Electrohydraulic pilot joysticks	Hydraulic pilot Joystick for boom and steering 2-foot pedals for forward/reverse travel	Hydraulic pilot Joystick
	Mulching Head attachment		
Model Name	FAE 300U	Tigercat 4061	M900
Head Working Width	2540 mm	2440 mm	2300 mm
Weight	3850 kg	3970 kg	5250 kg
Number of teeth	58	50	54

The mulcher's work method was observed in operation and was not changed as it mulched a swath (distance the machine travelled in a single elements). Time and distance were measured throughout the compartment. The Mulcher was tested on two different work elements as shown in Table 3.6.

Table 3.6 Self-propelled mulcher elements (Ackerman et al., 2014).

Elements	Break points	Detail required
Mulch	From the time the **machine starts mulching** a row until it **mulches the last stump** in the row	Time (t) and distance (d)
Turn	**From the time the** last stump in the row is completed **until the** mulching of the first stump in the new line **starts**	Time (t) and distance (d)

It was observed that the Cat based mulcher applied two passes per swath, initially mulching in a forward direction until the end of the swath, then mulching in a reversed direction without turning to its initial start point. Afterwards the mulcher moved to the adjacent swath as illustrated in Figure 3.14.A.

The Tigercat and Prinoth mulcher shared the same work method, mulching one pass per swath in a forward direction to the end of the swath and then turning into the adjacent swath (Figure 3.14.B).

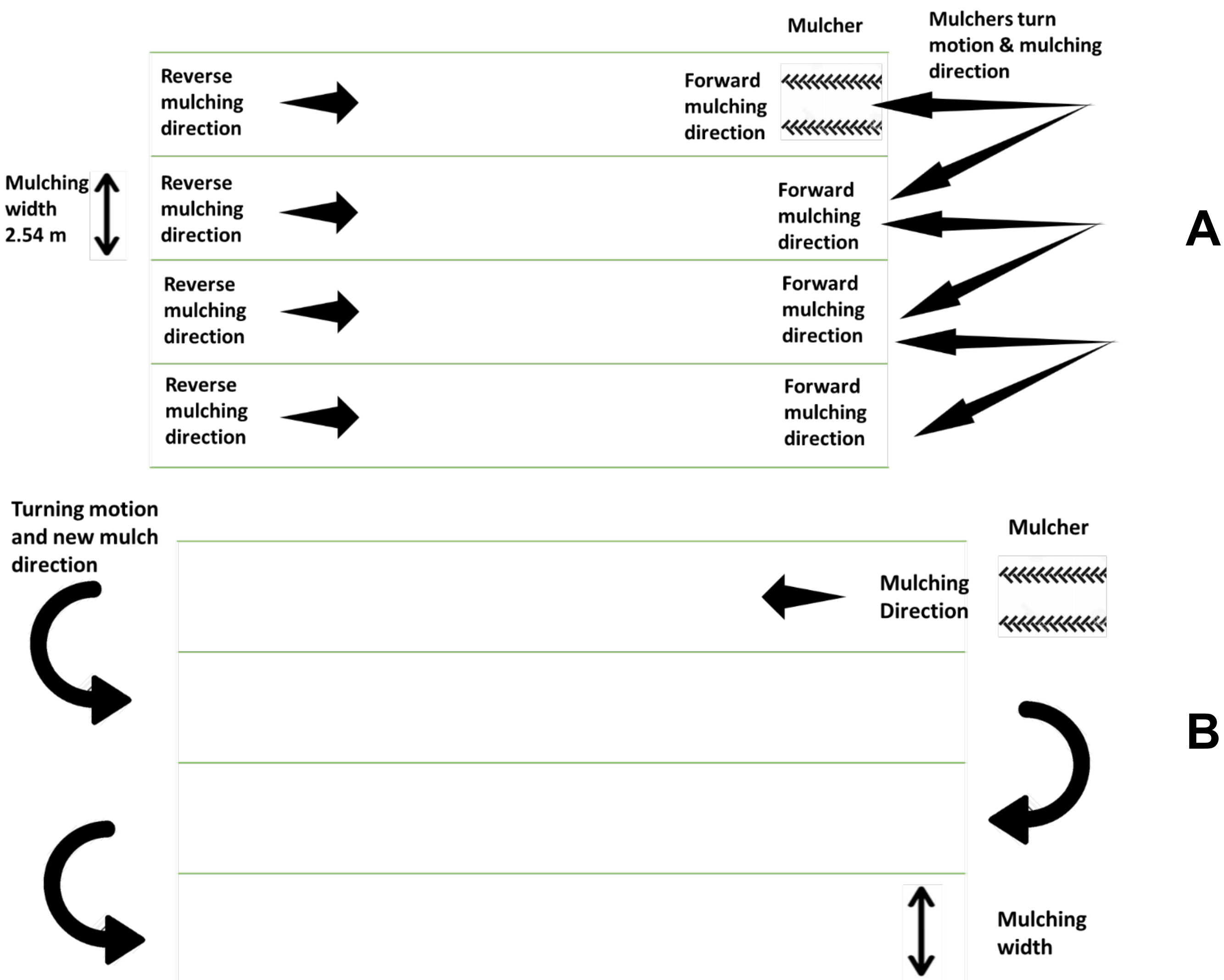


Figure 3.14 Work method of the mulchers, A- Zululand site work method. B- Bulwer and Jessievale site work method.

3.2.6.2 Biomass assessment after application of residue management.

Biomass assessments after the application of burn or mulch residue management were conducted on two sites in Bulwer and Jessievale. The assessment was a replication of the same procedures done on the biomass assessment prior to residue management (heading 3.2.4) As prior, on-site biomass assessment was assessed per compartment.

In the first phase, the stump volume per hectare was assessed using a zig-zag sampling method. Secondly, harvest residues which were made up of branches, tops and off-cuts from the log making process that were either burnt or mulched, were measured using the Line Intercept Method.

In the case of the Jessievale site this assessment was done to investigate the interaction between speed and number of passes on mulch quality. Due to the mulched swath being narrow (2.3m), the line intercept method had to be modified, a 20-meter sample line was laid out linearly along the mulched swath and was sampled at three locations per treatment.

3.2.6.3 Pitting Operations

Pitting operations at the Zululand, Bulwer and Jessievale trial sites were done mechanically using a Volvo Mpat EC55B Pro excavator-based mechanised pitting machine with GPS pitting system (Figure 3.15.A). The Mpat system analyses the GPS point file generated by a webserver to allow the operator of the machine to navigate to the individual planned planting points using the GPS guidance system installed on the machine.

In addition to the mechanised pitting at Bulwer trial site, manual pitting operations (Figure 3.15.B) were also studied, as manual pitting in the area is common. Table 3.7 shows the Mpat excavator based pitting machine specifications.

Figure 3.15 Pitting methods, A- Mechanised Mpat single pit pitting machine. B- Manual pitter equipped with a Pick.

Table 3.7 Mechanised pitting machine specifications (Viljoen, 2021)

Specifications	**Volvo EC55B Pro Excavator**
Engine	Kubota engine (TIER 3)
Engine Power	38 kW (50 hp)
Maximum Torque	201Nm at 1400 rpm
Fuel Capacity	90 L
Number of Tracks	2
Weight (with attachment)	5 330 kg
Controls	Power assisted hydraulic controls
Pitting Head attachment	
Model Name	Multipit R-S-E Precision
Pit Size	350 mm across and 350 mm deep, Center of pit 400 deep
Weight	40 kg
GNSS System	Included

The mechanised pitting machine and manual pitting was tested on three different work elements as shown in Table 3.8 and Table 3.9 respectively.

Table 3.8 Multi-pit pitting machine elements (Ackerman et al., 2014).

Elements	**Break points**	**Detail required**
Pit	From the time the **pitting head makes contact with the ground** on the **1st pit**, until the pitting head leaves the ground on the **last pit per stop**	Time (t) and number of pits competed
Move	From the time the pitting head **leaves the ground after the last pit per stop**, until the pitting **head makes contact with the ground for the 1st pit** of the next cycle	Time (t) and distance (d)
Turn	From the time the pitting head **leaves the ground after the last pit in the row**, until the pitting **head makes contact** with the ground for the first pit in the new line	Time (t) and distance (d)

Table 3.9 Manual pitting elements (Ackerman et al., 2014)

Elements	**Break points**	**Detail required**
Pit	From the time the **pick makes contact with the ground**, until the operator marks the pit with a stick **per stop**	Time (t)
Move	From the time the operator marks the pit with a stick after the **last pit per stop**, until the pick **makes contact with the ground for the 1st pit** of the next cycle	Time (t) and distance (d)
Turn	From the time the pit is market **after the last pit in the row**, until the pick **makes contact** with the ground for the first pit in the new line	Time (t) and distance (d)

Pitting work methods were not adjusted and reported as seen at the various trial sites. The Zululand mulched site adopted an eight pit per cycle method, which involved the machine pitting eight pits across four rows in a circular motion, before moving forward, repeating that action across the compartment. Figure 3.16.A shows the work method of this mechanised pitter.

The Zululand burnt, Bulwer mulched and Jessievale sites were observed to have four pits per cycle. This involved the pitter pitting four pits across four rows in an arc-shape before moving forward repeating that action across the compartment (Figure 3.16.B).

Manual pitting operations were studied at the Bulwer trial site comprising of two compartments; one burnt and the other mulched, where pitting was done manually with a road pick mattock. The basic procedure of manual pitting involves pit preparation through repetitive swinging of a pick to loosen the soil and is done at given planting espacement across the compartment using either a chain, stump line or brush line as a guide. A pit quality instrument was used to accesses quality of pits in terms of dept and width in both mechanised and manual pitting operations.

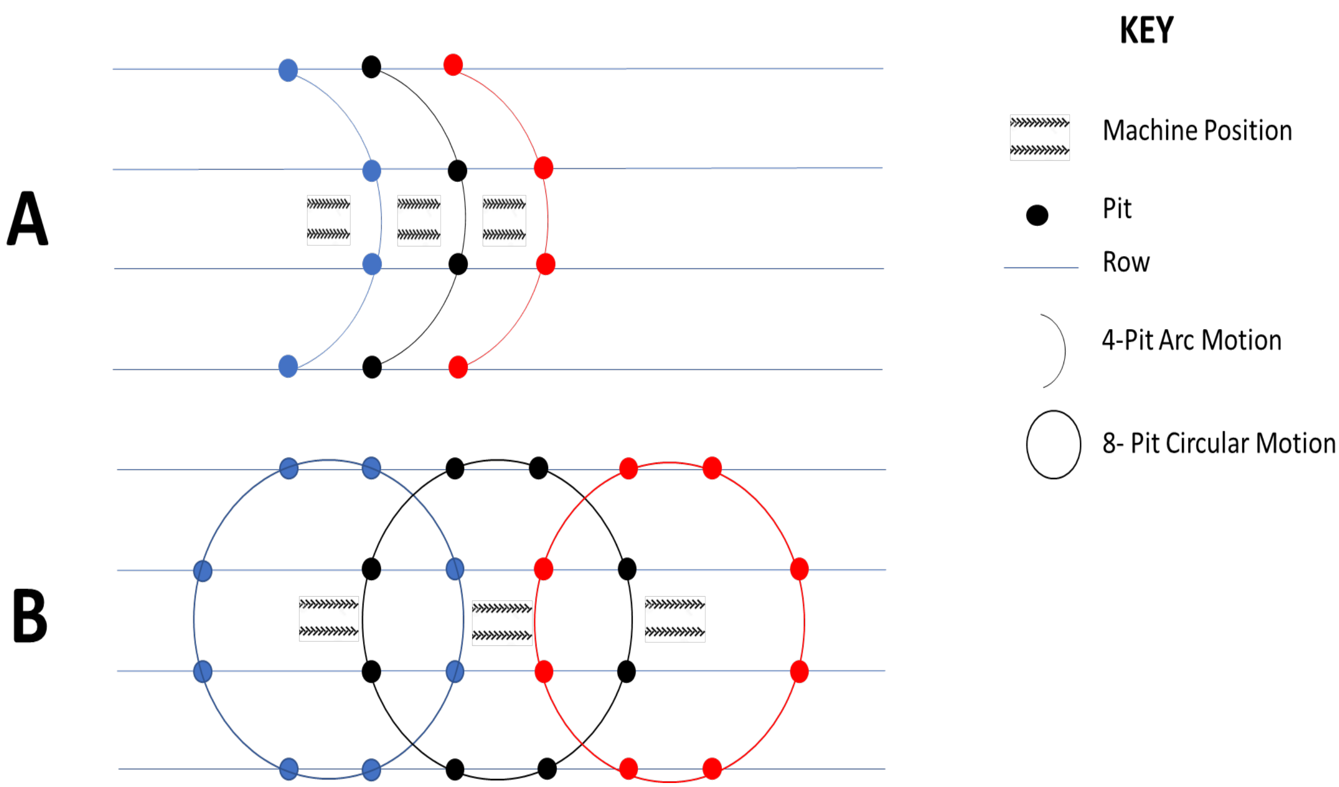


Figure 3.16 Work method of the mechanised Mpat single pit pitting machine. A- 4 pit Arc motion work method. B- 8-pit circular motion work method.

3.2.6.4 Planting Operation

Zululand planting operations were all semi-mechanised which included a tractor drawn planter. The planter differed between mulched and burnt sites, it was observed that the planter used on the mulched sites was equipped with seven-planting tubes (Figure 3.17.A) as compared to the six-planting tube machine used on the burnt sites (Figure 3.17.B). The semi-mechanised planting team is basred on 13 to 14 personnel depending on the 6 or 7 planters used, one person per planting tube, two seedling replenishers, two persons blanking (in case of a mistake), one tractor operator, one supervisor and one fire truck operator.

Figure 3.17 Planting operations. A- semi-mechanised 7-planter tractor drawn system. B- semi-mechanised 6-planter tactor drawn system. C- manual planting system.

Table 3.10 illustrates the tractor drawn planter machine specifications below.

Table 3.10 Semi-mechanised tractor drawn planter specifications (landini, 2021)

Specifications	**Landini Global Farm 100 Tractor**	**Landini 5F-110h Tractor**
Engine	Perkins engine (1104A-44T)	Perkins engine (1104D-44TA)
Engine Power	75 kW (100 hp)	75 kW (100 hp)
Drive system	4 wheel-drive	4 wheel-drive
Maximum torque	366 Nm at 2200 rpm	416 Nm at 2200
Fuel Capacity	90 L	102 L
Number of wheels	4	4
Weight (with attachment)	3 830 kg	3 850 kg
PTO with ground speed rpm	540/100	540/100
Hydraulic pump capacity	52.3 L/min	53.0 L/min
Planter attachment		
Model Name	Purpose built	Anco easyplant 6300
Number of planters	7	6
Water tank capacity	3 000 L	3 000 L

The Bulwer and Jessievale planting operations were done manually, based on a single manual planting team (Figure 3.17.C), which constitutes of two people, a planting tube, 20 L bucket, a tray of seedlings, and a container of Suppositree™ tablets which serves as a systemic insecticide control of sucking and chewing insects.

The manual planting operation observed was based on a 62 personnel team which includes two supervisors, 24 planters paired with 24 supporting staff (carrying seedlings and Suppositree™ tablets) i.e. four seedling replenishers, two persons supplying Suppositree™ tablets to the planter, two persons filling up the two 200L drums, two persons in charge of setting up the pipeline from the fire truck to the drums, and two fire truck operators.

For the semi-mechanised tractor-drawn planter, three work elements were monitored. and four elements and manual planting are shown in Table 3.11 and Table 3.12 respectively.

Table 3.11 Semi mechanised tractor drawn planter elements (Ackerman et al., 2014)

Elements	Break points	Detail required
Plant	From the time the planting **tube makes contact with the ground**, until the planting tube makes **contact with the ground again** for the next plant	Time (t)
Turn	From the time the **planter starts walking after completing the last plant of the row**, until the planting **tube makes contact with the ground for the 1st plant** of the next row	Time (t) and distance (d)
Fill	**From the time the** machine stops to be filled, **until the hose is removed and tank closed and** machine is started	Time (t) and potentially distance (d) if the machine has to move to refilling area

Table 3.12 Manual planting elements (Ackerman et al., 2014)

Elements	Break points	Detail required
Plant	From the time the planting **tube makes contact with the ground**, until the operator secures the plant with his/her feet.	Time (t)
Move	From the time the **plant is secure** until the **planting tube makes contact with the ground** of the next cycle.	Time (t) and distance (d)

Turn	From the time the **planter starts walking after completing the last plant of the row**, until the planting **tube makes contact with the ground for the 1st plant** of the next row	Time (t) and distance (d)
Fill	**From the time the operator** stops to be filled, **until the bucket is full, and the operator** resume planting	Time (t) and potentially distance (d) if the operator has to move to refilling area

The complete work cycle of both the manual and semi-mechanised planter (Figure 3.18) (including support staff) was timed starting from planting, which commences when the planting tube ma contact with the ground, a seedling placed inside it and then filled with a litre of hydrogel. Move time constitutes the time from after the planter secures the seedling in the ground with his feet until the planting tube makes contact again for the next plant.

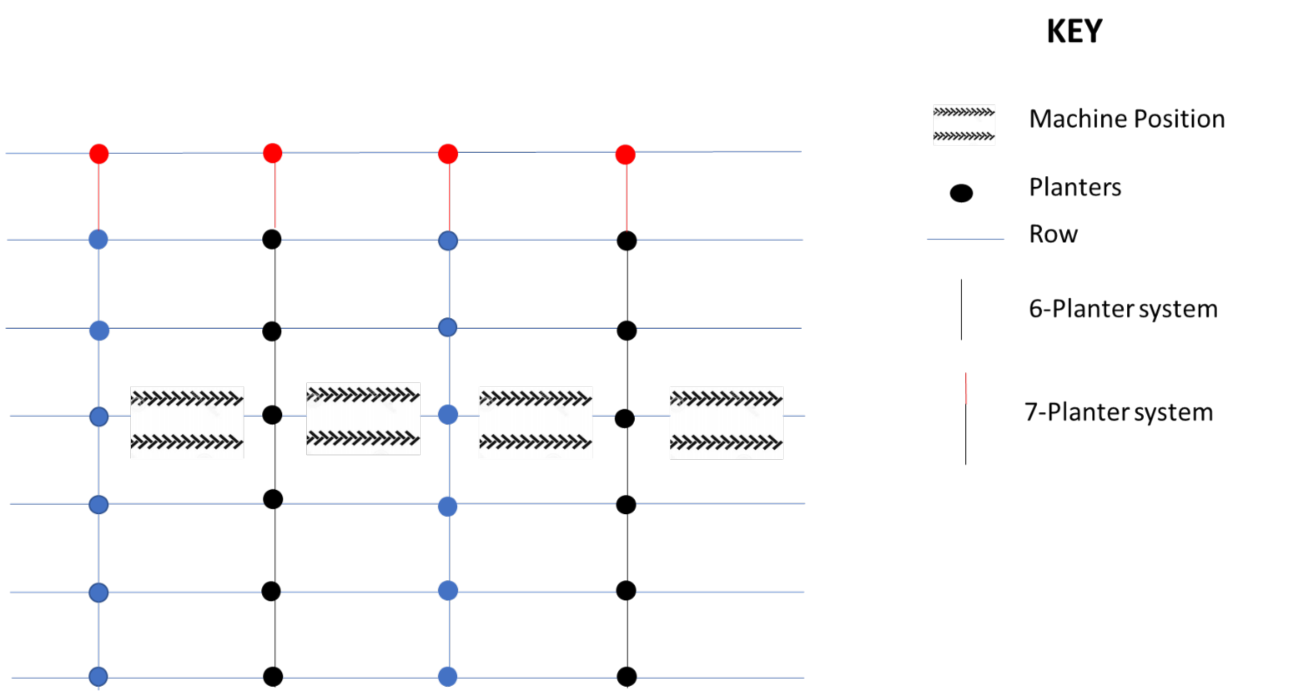


Figure 3.18 Semi-mechanised planter work method (6/7 interchangeable planter system)

3.2.7 Machine costing

The COST (European Cooperation in Science and Technology) Action FP0902 was be used for costing. Machine costs were calculated based on the replacement costs of the mulchers, mechanised pitter and tractor drawn planters and their respective fuel consumption rates. Variable machine costs and operator costs were derived from the participating forestry company. Machine productivity rates were derived from time study.

Machine prices were based on retail prices from dealers in South Africa. Licensing, and other miscellaneous costs were not considered, as they would be too variable for the purposes of this study. Fuel prices were based on commercial retail price (October 2021). Machine transfer costs are allocated to the tracked machine only. Fuel consumption for each of the machines was based on an infield fuel study. Machine, attachments, and component working lives and costs are those acquired and used by the contractors.

Table 3.13 Mulching machine cost elements

Item	Cat 586C Base Mulcher	Tigercat M762G Mulcher	Prinoth Raptor 800 Mulcher
	Fix Inputs		
Machine cost (R)	6 287 400	6 687 000	11 529 558
Expected Economic Life base machine (PMH)	20 000	20 000	20 000
Salvage cost machine (%)	20	20	20
Interest rate (%)	7.5	7.5	7.5
Machine insurance (base and attachment) (R)	270 000	270 000	495 000
Machine transfer cost (R)	-	-	140 000
	Variable Inputs		

Fuel (cost/litre) (R)	17.23	17.23	17.23
Fuel consumption (litre/PMH)	32	34	54
Oil and lubricant cost (%)	15	15	15
Maintenance and repair cost (base machine) %	100	100	100
Number of tracks or tyres	4	4	2
Cost per track or tyre	70 000	70 000	155 000
Estimated track or tyre life span (PMH)	8 000	8 000	9 000
Number of mulching teeth	58	50	52
Cost of mulching tooth (R)	1500	1500	
Estimated mulching tooth life span (PMH)	200	200	
	Operator Inputs		
Number of operators per shift	1	1	1
Average net wage (cost/hour) (R)	70	70	70
PPE cost per year	1500	1500	1500
Training per year	2000	2000	2000
	Productivity Inputs		
Number of working days per year	240	240	240
Number of shifts per day	1	1	1
Scheduled hours per shift	9	9	9
Estimated productivity: ha/PMH	0.38	0.35	0.45
Machine utilisation	0.85	0.85	0.85

Table 3.14 Mechanised and manual pitting cost elements

Item	Mpat Pitting Machine	Manual Pitter
	Fix Inputs	
Machine cost (R)	1 411 000	350
Expected Economic Life base machine (PMH)	15 000	10000
Salvage cost machine (%)	20	-
Interest rate (%)	7.5	-
Machine insurance (base and attachment) (R)	67 500	
Machine transfer cost (R)	50 000	-
	Variable Inputs	
Fuel (cost/litre) (R)	17.23	-
Fuel consumption (litre/PMH)	3.2	-
Oil and lubricant cost (%)	10	-
Maintenance and repair cost (base machine) %	100	-
Number of tracks	2	-
Cost per track	70 000	-
Estimated track or tyre life span (PMH)	9 000	-
	Operator Inputs	
Number of operators per shift	1	1
Average net wage (cost/hour) (R)	50	25
PPE cost per year	1500	1500
Training per year	2000	-

	Productivity Inputs	
Number of working days per year	240	240
Number of shifts per day	1	1
Scheduled hours per shift	9	9
Estimated productivity: ha/PMH	-	-
Machine utilisation	0.85	0.65

Table 3.15 Semi-mechanised planting machine and manual planting cost elements

Item	**Tractor drawn 7-planter**	**Tractor drawn 6-planter**	**Manual planter**
	Fix Inputs		
Machine cost (R)	600 000	600 000	800
Attachment cost (R)	390 000	350 000	-
Expected Economic Life base machine (PMH)	20 000	20 000	-
Expected Economic Life attachment (PMH)	20 000	20 000	-
Salvage cost machine (%)	20	20	-
Salvage cost attachment (%)	20	20	-
Interest rate (%)	7.5	7.5	7.5
Machine insurance (base and attachment) (R)	-	-	
Machine transfer cost (R)	-	-	-
	Variable Inputs		

Fuel (cost/litre) (R)	17.23	17.23	-
Fuel consumption (litre/PMH)	5	5	-
Oil and lubricant cost (%)	15	15	-
Maintenance and repair cost (base machine) %	100	100	-
Maintenance and repair cost (attachment) %	100	100	-
Number of tracks or tyres	6	6	
Cost per track or tyre	8 000	8 000	
Estimated track or tyre life span (PMH)	8 000	8 000	
	Operator Inputs		
Number of operators per shift	14	13	1
Average net wage (cost/hour) (R)	27	27	25
PPE cost per year	1500	1500	1500
Training per year	-	-	-
	Productivity Inputs		
Number of working days per year	240	240	240
Number of shifts per day	1	1	1
Scheduled hours per shift	9	9	9
Estimated productivity: ha/PMH	1.66	1.15	0.45
Machine utilisation	0.85	0.85	-

3.3 Plant growth assessment

Growth response trials were established on sites where mulching versus burning residue management had been applied on *Pinus patula* compartments at the Jessievale area, Mpumalanga highveld. Two sites, E064a and E008, were identified as previously mulched and burnt, respectively.

Complimentary data from Sappi based on *Eucalyptus grandis X urophylla* growth response to burning versus mulching of residue at compartment C31b KwaMbonambi plantation in Zululand was used to compliment this data set.

The sites where identified as areas with similar soils, terrain and were planted to the same previous crop. To determine the growth response on these sites, plots were established out across the site with three replications per treatment (blocks of 10 trees each). The survival and growth assessments were done at random intervals from planting. Since pine is a slow grower, height and ground line diameter (GLD) were recorded.

Jessievale trials were established in December 2020, where both sites were planted. The sites were measured in February 2021 and April 2021. Growth responses were calculated for the last measurement at in April at 4 months. Due to operational challenges, York Timber was not able execute the latest growth measurement at the point of this thesis being submitted.

Sappi KwaMbonambi trial was in established November 2020 and the analyse was conducted on a year of growth.

Growth responses such as mean diameter (GLD in Jessievale and DBH in Zululand), height (Ht), and survival percentage were used to compare the initial growth results between treatments. Donald et al., (1987) suggested using biomass index (BI) to accurately compare diameter, height and survival percentage in growth response trails. Using Equation 3, growth responses were compared between burnt and mulched trials.

$$Biomass\ Index = (Diameter)^2 \times Height \times Survival\ percentage \qquad \textit{Equation 3}$$

These trials will be maintained and measured regularly until rotation age by the respective companies to obtain long term growth response data based on burnt versus mulched residue treatment on pine and eucalyptus sites.

3.4 Data Analysis

The analysis of the data was done using an open-source statistical software R (3.1.1) and R-commander (R Core Team, 2014). Statistical analysis included developing generalised linear models and utilising analysis of variance (ANOVA) to analyse the effect of residue management on productivity of downstream operations and plant growth response. This analysis does indicate if there is any significant difference (at 95% confidence levels) between mulched versus burnt pitting and planting productivities and growth response.

ANOVA test assumes equality of variance between treatments (homoscedastic). A Levene's test was applied for variance homogeneity to test this assumption. In some cases, the assumption was met, and ANOVA could be used. In most cases heteroscedasticity was observed voiding conventional t-test and ANOVA use. For these instances a non-parametric Mann-Whitney U test was used which is more robust against homoscedasticity breaches (Ott & Longnecker, 2015).

4 Results

This Chapter follow the same configuration as that of Chapter 3. It presents the results from the biomass assessment volumes, time studies for the mulcher, mechanised pitter semi-mechanised planter, manual pitter and planter, machine costing and finally plant growth response.

4.1 Biomass assessments before residue management

On-site biomass was assessed in two phases prior to the application of residue management. The first phase included stump volume estimation, and the second dealt with harvest residues estimation.

4.1.1 Stump assessment

Table 4.1 Illustrates the stump assessment summary values and stump volume per study site. The Bulwer site had a mean stump volume of 23.1 m^3 ha^{-1}, followed by Zululand site with 22.5 m^3 ha^{-1} and lastly the Jessievale site with 9.8 m^3 ha^{-1}. It is important to note that the Jessievale site had the lowest mean stump volume as the compartment experienced two thinnings during the course of the rotation.

Table 4.1 Summary of stump values and stump volume results

Comp.	Species	Area (ha)	Mean stump height (cm)	Mean stump thick end diameter (cm)	Mean stump thin end diameter (cm)	Mean stump volume (*l*)	Stump volume (m^3 ha^{-1})
Zululand (SPHA - 1548)							
J31a	*E.gxu*	19.18	30.7	29.0	20.7	16.0	24.7
J31b		18.45	25.0	27.2	23.5	13.0	20.3
Mean			***27.9***	***28.1***	***22.1***	***14.5***	***22.5***
Bulwer (SPHA – 1667)							
M31b		10.17	18.1	31.1	29.6	15.2	25.3
M37	*P.pat*	26.11	19.1	31.0	28.5	13.5	22.6
M38a		16.07	20.2	27.2	24.7	12.7	21.3
Mean			***19.1***	***29.8***	***27.6***	***13.8***	***23.1***

Jessievale (SPHa 651 & 507)							
C38d	*P.pat*	2.89	18.6	38.3	36.6	19.7	10.9
C42b		4.67	16.7	34.1	33.0	17.1	8.6
Mean			***17.7***	***36.2***	***34.8***	***18.4***	***9.8***

4.1.2 Harvest residue assessment

Harvest residue volumes per site and in the case of Jessievale per treatment are shown in Table 4.2. The Zululand site had a mean harvest residue volume of 26.0 m^3 ha^{-1}, even though compartment J31a had about twice the residue volume than compartment J31b. It was noted that all three compartments at the Bulwer site experienced snow damage in 2012, resulting in large harvest residue volume with a mean of 103.6 m^3 ha^{-1}. The Jessievale site was divided into treatments to investigate mulch quality as a function of mulching speed and number of passes. The harvest residue varied from treatment to treatment as expected. A mean of 42.5 m^3 ha^{-1} and 40.6 m^3 ha^{-1} was calculated in compartment C38d and C42b respectively.

Table 4.2 Residue volumes estimates per hectare, based on the line intercept method

Site	**Species**	**Area (ha)**	**Mean residue volume (m^3 ha^{-1})**
Zululand			
J31a	*E.gxu*	19.18	35.9
J32b		18.45	16.1
Mean			***26.0***
Bulwer			
M31b		10.17	129.0
M37	*P.pat*	26.11	78.1
M38a		16.07	103.8
Mean			**103.6**
Jessievale			
C38d (Treatments)		2.89	
S1P1			54.0
S1P2			28.3
S2P1	*P.pat*		42.3
S2P2			45.2

Mean			***42.5***
C42b (Treatments)		4.67	
S1P1			23.3
S1P2	*P.pat*		34.3
S2P1			38.5
S2P2			66.1
Mean			***40.6***

4.1.3 Combined stump and residue volume

Table 4.3 shows the combined stump and harvest residue volume per site and in the case of Jessievale per treatment. The Bulwer site had the highest mean combined volume of 126.7 m^3 ha^{-1} followed by the Jessievale trial of 53.3 m^3 ha^{-1} and 49.1 m^3 ha^{-1} in compartment C31d and C42b respectively.

Table 4.3 Combined volume including stump and harvest residue volume per hectare

Site	**Species**	**Area (ha)**	**Stump volume (m^3 ha^{-1})**	**Residue volume (m^3 ha^{-1})**	**Combined volume (stump + residue) (m^3 ha^{-1})**
Zululand					
J31a	*E.gxu*	19.18	24.7	35.9	60.6
J32b		18.45	20.3	16.1	36.4
Mean			***22.5***	***26.0***	***48.5***
Bulwer					
M31b		10.17	25.3	129.0	154.3
M37	*P.pat*	26.11	22.6	78.1	100.7
M38a		16.07	12.7	103.8	125.1
Mean			***23.1***	**103.6**	**126.7**
Jessievale					
C38d (Treatments)		2.89			
S1P1				54.0	64.9
S1P2	*P.pat*		10.9	28.3	39.2
S2P1				42.3	53.2

S2P2			45.2	56.1
Mean		***10.9***	***42.5***	***53.3***
Jessievale				
C42b (Treatments)	4.67			
S1P1			23.3	31.8
S1P2	*P.pat*	8.6	34.3	42.8
S2P1			38.5	47.0
S2P2			66.1	74.6
Mean		***8.6***	***40.6***	***49.1***

4.2 Mulching time study analysis

Mulching productivity based on site and machine is shown in Table 4.4. Zululand and Bulwer sites had similar mean productivities of 0.38 ha PMH^{-1}and 0.35 ha PMH^{-1} respectively. Jessievale site had the highest mean productivity of 0.45 ha PMH^{-1} in the conventional work method in compartment C40. All treatments had different productivities with single passes having almost twice the productivity of double passes and faster speed with single pass having the highest productivity.

Table 4.4 Mean mulcher productivity per site and treatment in Jessievale

Site	Swath (m)	Mulch width (m)	Area (m^2)	Mulch (min)	Running meters PMH^{-1}	PMH ha^{-1}	ha PMH^{-1}	Mean Speed (km hr^{-1})
Zululand (Cat based mulcher)								
J31a	344.4	2.54	874.8	13.38	1542.4	2.62	0.40	1.54
J32b	280.5		712.5	12.32	1366.1	2.91	0.35	1.37
Mean			***793.6***	***12.85***	***1454.3***	***2.78***	***0.38***	***1.46***
Bulwer (Tigercat mulcher)								
M37	352.6	2.44	860.4	15.85	1285.0	3.19	0.31	1.29
M38a	305.6		745.6	11.10	1579.0	2.60	0.39	1.58
Mean			***803.0***	***13.48***	***1432.0***	***2.90***	***0.35***	***1.44***
Jessievale (Prinoth mulcher)								

Conventional work method								
C40	***188.4***	***2.30***	***433.3***	***5.36***	***2202.6***	***2.31***	***0.45***	***2.20***
C38d (Treatments)								
S1P1	141.0	2.30	324.2	5.52	1532.0	2.84	0.36	1.53
S1P2	195.5		449.6	13.43	873.4	4.98	0.20	1.74
S2P1	236.8		544.7	4.29	3315.5	1.31	0.76	3.32
S2P2	254.0		584.1	9.68	1573.8	2.76	0.36	3.15
C42b (Treatments)								
S1P1	133.6	2.30	307.2	5.14	1557.8	2.79	0.36	1.56
S1P2	140.1		322.3	10.88	773.0	5.62	0.18	1.55
S2P1	157.8		363.0	3.00	3156.2	1.38	0.73	3.17
S2P2	171.5		394.4	6.18	1664.4	2.61	0.38	3.33

When delivering a productivity measure to plan future compartments, the productivity per hectare gives the forester a good best-operating practice idea on how to predict the performance of the machine. The measure of mulching minutes per 100 m along with the machine width allows a finer scale planning of future compartments of any shape and size.

Table 4.5 showing the standardised mulching productivity (mins $100m^{-1}$) and mean turn time (min). Turning time is dependent on the shapes and sizes of a compartment. The Zululand site had mean mulch time of 4.13 min $100m^{-1}$ and 0.31 min $turn^{-1}$. The Bulwer site had a mean mulch time of 4.06 min $100m^{-1}$ and 0.56 min $turn^{-1}$. Jessievale site had the fastest mean mulch time of 3.19 mins $100m^{-1}$ and a turn time of 0.65min $turn^{-1}$.

Table 4.5 Mulching results standardised per a 100 running meters and mean turn time per site

Compartment	**Area (ha)**	**Mulch (mins 100m^{-1})**	**Turn (min)**
Zululand (Cat based mulcher)			
J31a	19.18	3.89	0.37
J31b	18.45	4.39	0.11
mean		***4.13***	***0.31***
Bulwer (Tigercat mulcher)			
M37	26.11	4.49	0.61
M38a	16.07	3.63	0.51
mean		***4.06***	***0.56***
Jessievale (Prinoth mulcher)			
C40	3.94	3.19	0.65

4.2.1 Eucalyptus versus pine residue mulching productivity

To better understand the effects that these species have on mulching speed of highly comparable mulching machines (Cat based and Tigercat), we investigated mulching productivity differences between Zululand eucalyptus and Bulwer pine residue.

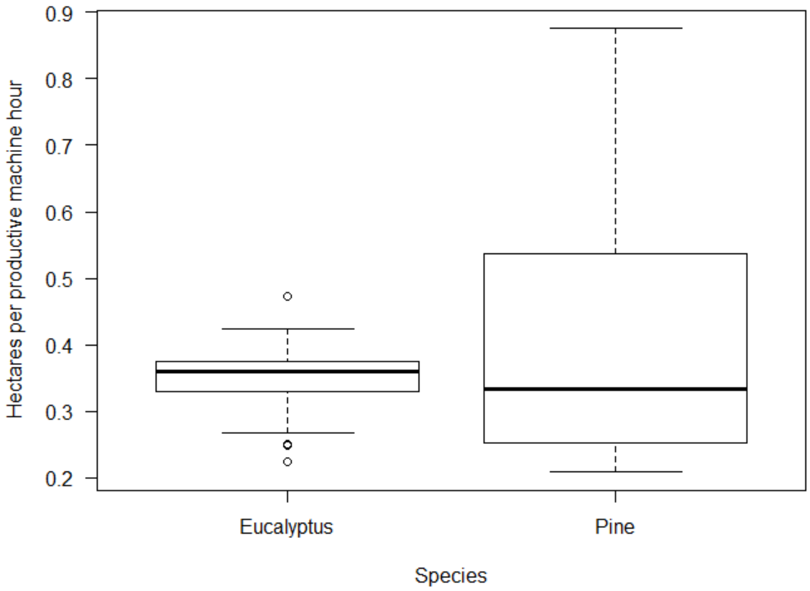


Figure 4.1 box plot showing variation of mulching productivity per treatment

Hypotheses 1

H_0: Mulching productivities between eucalyptus and pine are the same.

H_1: Mulching productivities between eucalyptus and pine differ.

A Mann-Whitney U test was conducted to compare the two treatments. The mean productivity for eucalyptus residue mulching was 0.38 ha PMH^{-1} and 0.35 ha PMH^{-1} for pine residue mulching (Figure 4.1). There was no significant difference between the two treatments (W=1422, p-value=0.71). We failed to reject the null hypothesis, and as such the mulching productivities between eucalyptus and pine residue were similar. It is important to note that the pine site had almost twice the biomass volume than the eucalyptus site and note should be taken as the generalised conception of these productivities.

4.3 Biomass assessment of after residue management

The second biomass assessment Table 4.6 was taken to record the amount of intact biomass remaining after residue management was applied. As previously mentioned, the second biomass assessment after residue management was not conducted at the Zululand site. A residue burn was applied to compartment M31b whereas compartments M37 and M38a were mulched at the Bulwer site. It was observed that residue burnt treatment (Figure 4.2.D) had the highest combined volume of 94.3 m^3 ha^{-1} compared to mulched treatments M37 and M38a (Figure 4.2.B) having 48.3 m^3 ha^{-1} and 46.2 m^3 ha^{-1} respectively. The Jessievale site compartments C38d and C42b were subdivided into different treatments which were mulched at different speeds and passes, where the treatment combined volume after mulching varied.

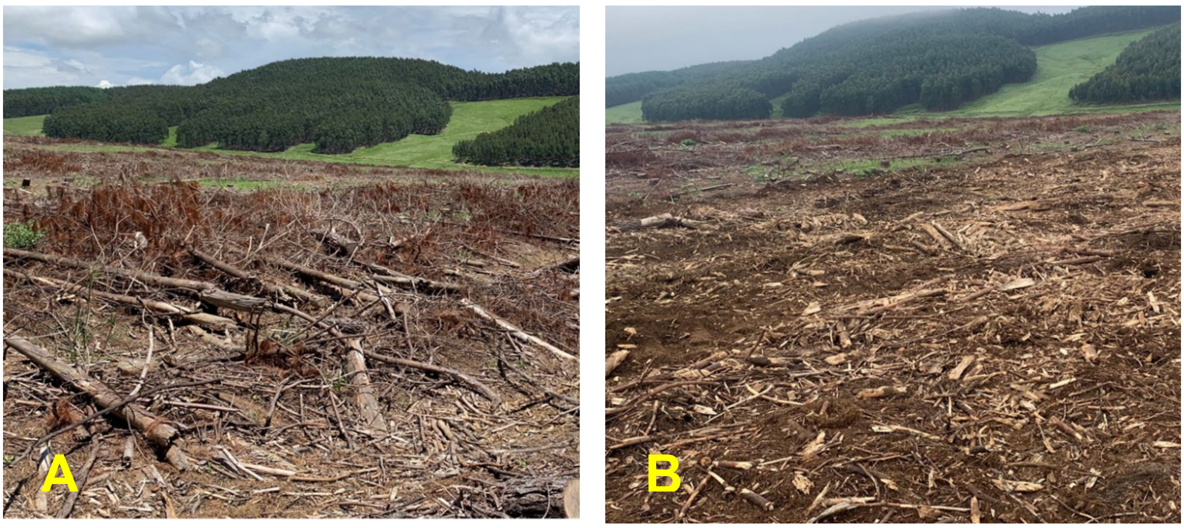


Figure 4.2 Images illustrating before and after application of residue management. A- before mulching. B- After mulching. C- Before burning. D- After burning.

Table 4.6 Combined intact stump and harvest residue volumes after applying residue management

Site	Residue Management applied	Area (ha)	Stump volume (m^3 ha^{-1})	Residue volume (m^3 ha^{-1})	Combined volume (stump + residue) (m^3 ha^{-1})
Bulwer					
M31b	*Burnt*	10.17	23.0	71.3	94.3
M37	Mulched	26.11	0	48.3	48.3
M38a		16.07		46.2	46.2
Jessievale					
C38d (Treatments)		2.89			
S1P1	*Mulched*		0	25.3	25.3
S1P2				72.3	72.3
S2P1				26.3	26.3
S2P2				43.5	43.5
Jessievale					
C42b (Treatments)		4.67			
S1P1	*Mulched*		0	67.1	67.1
S1P2				38.1	38.1
S2P1				47.2	47.2
S2P2				28.27	28.27

Table 4.7 illustrates the difference and reduction percentage of intact biomass after the application of residue management. We note that in Bulwer, residue mulching has the higher percentage reduction of intact above ground biomass. Compartments M37 and M38a (mulched) had a reduction of 52.0% and 63.1 % respectively and compartment M31b (burnt), 38.9%.

Considering the information on the Jessievale site mulch quality treatment in Table 4.7 below, it is apparent that there was a flaw in the experimental design directly relating to the swath layout and the sampling of biomass after mulching. The second biomass sampling resulted in volume estimates exceeding those of the first in some cases. This error is likely due to the linear dimension of the mulching swath and therewith the post mulching line intersect which, in some cases might have coincided with residue windrows generated by the harvesters, leading to a higher amount of biomass on the ground. By comparison, the pre-mulching estimation was always carried out in a triangular layout, essentially nullifying any such effect.

Table 4.7 Difference in intact biomass volumes after residue management were applied.

Site	Residue Management applied	Area (ha)	Combined volume (stump + residue) (m^3 ha^{-1})		Difference (m^3 ha^{-1})	Reduction percentage (%)
			Before	***After***		
Bulwer						
M31b	*Burnt*	10.17	154.3	94.3	60.0	38.9
M37	Mulched	26.11	100.7	48.3	52.4	52.0
M38a		16.07	125.1	46.2	78.9	63.1
Jessievale						
C38d (Treatments)		2.89				
S1P1	*Mulched*		63.9	25.3	38.6	60.4
S1P2			38.2	72.3	-34.1	-89.3
S2P1			52.2	26.3	25.9	49.6
S2P2			55.1	43.5	11.6	21.1
Jessievale						

C42b (Treatments)		4.67				
S1P1	Mulched		31.8	67.1	-35.3	-111.0
S1P2			42.8	38.1	4.7	11.0
S2P1			47.0	47.2	-0.2	-0.4
S2P2			74.6	28.3	46.3	62.1

4.4 Pitting time study analysis

Hypothesis 2 was used to determine the effect that residue management (burnt versus mulched) has on mechanised and manual pitting.

Hypothesis 2

H_0: Pitting productivities between burnt and mulched treatments are the same.

H_1: Pitting productivities between burnt and mulched treatments differ.

4.4.1 Mechanised pitting results

Table 4.8 shows the productivity result of the Mechanised Mpat pitting machine per site and treatment applied. Mean productivity at the Zululand eucalyptus site is 0.26 ha PMH^{-1} at 1548 SPHa in mulched treatment and 0.26 ha PMH^{-1} at 1481 SPHa on burnt treatments. At Bulwer mulched pine site 0.41 ha PMH^{-1} at 1667 SPHa. Jessievale pine site 0.57 ha PMH^{-1} and 0.46 ha PMH^{-1} in mulched and burnt site respectively at 1111 SPHa.

Table 4.8 Mechanised pitting productivity per site

Comp		Move (min)	Pit (min)	Total (min)	No pits	Min pit^{-1}	Pits PMH^{-1}	PMH ha^{-1}	ha PMH^{-1}
Zululand									
Mulched	J31a	0.17	1.11	1.28	8	0.16	374	4.14	0.24
(SPHa 1548)	J31b	0.13	0.97	1.10	8	0.14	436	3.55	0.28
	mean	***0.15***	***1.04***	***1.19***	***8***	***0.15***	***405***	***3.85***	***0.26***
Burnt	S1	0.11	0.46	0.58	4	0.15	400	3.70	0.27
(SPHa 1481)	S2	0.24	0.38	0.62	4	0.16	375	3.95	0.25
	mean	***0.18***	***0.42***	***0.60***	***4***	***0.16***	***387***	***3.82***	***0.26***
Standardised burnt results to SPHa 1548							***391***	***3.95***	***0.25***
***Bulwer** (SPHa 1667)*									
Mulched	M37	***0.08***	***0.29***	***0.37***	***4***	***0.09***	***680***	***2.60***	***0.41***
***Jessievale** (SPHa 1111)*									
Mulched	B77b	***0.07***	***0.30***	***0.38***	***4***	***0.10***	***636***	***1.80***	***0.57***
Burnt	E009	***0.11***	***0.39***	***0.50***	***4***	***0.13***	***515***	***2.17***	***0.46***

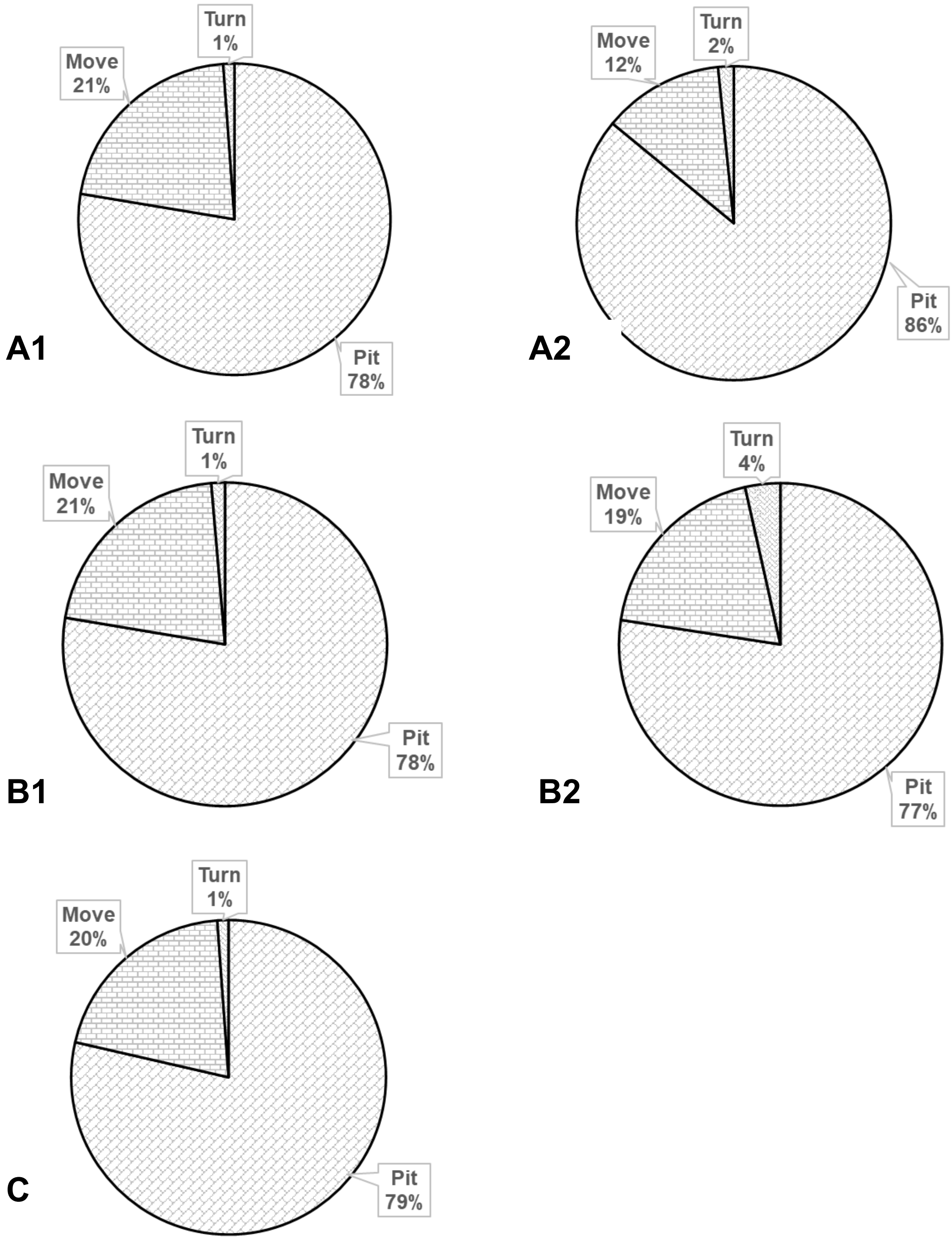


Figure 4.3 Time element distribution for mechanised pitting operations. ***A1- Zululand*** *pitting operation on* ***Burnt*** *treatment.* ***A2- Zululand*** *pitting operation on* ***Mulched*** *treatment.* ***B1- Jessievale*** *pitting operation on* ***Burnt*** *treatment.* ***B2- Jessievale*** *pitting operation on* ***Mulched*** *treatment.* ***C- Bulwer*** *pitting operation on* ***Mulched*** *treatment.*

Since each site had different pit spacing, we standardise this data to conclusively analyse the effects of pitting on a mulched versus a burnt site we investigated the pitting time elements to better understand these effects namely:

- Move speed in meters per second (m s^{-1})

- Pitting time in seconds per pit (s pit^{-1})

The variation of mean move speed, (The time which the pitter takes to move from one cycle position to the next, divided by the distance of the move). Below are the results based on the Mpat mechanised pitter in both burnt and mulched treatments.

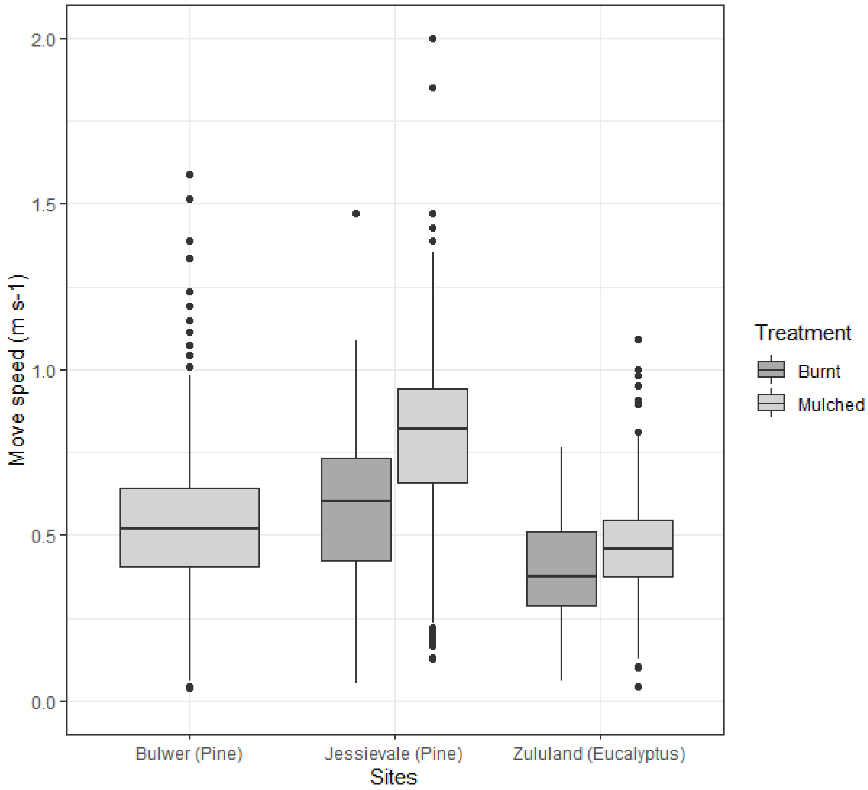


Figure 4.4 Variation of mechanised pitter 'move speed' within treatment per site

The boxplots (Figure 4.4) show that the mean move speed of the mechanised pitter in mulched treatments is slightly higher compared to burnt treatments in all sites. The difference in the move speed in the mulched treatment is 0.07 m s^{-1} and 0.21 m s^{-} faster than for the burnt treatments in Zululand and Jessievale sites. Table 4.9 below shows the summary statistics of the move speed.

Table 4.9 Summary statistics of move speed per treatment in meter per second

Treatment	Mean move speed (m s^{-1})	Standard deviation	p- value
Zululand			
Burnt	0.40	0.14	<0.0001
Mulched	0.47	0.15	
Bulwer			

Mulched	0.53	0.19	
Jessievale			
Burnt	0.59	0.22	<0.0001
Mulched	0.80	0.28	

From Table 4.9, mechanised pitting on a mulched residue treatment had a higher mean move speed (0.47 m s^{-1}) than on a burnt residue treatment (0.40 m s^{-1}) at the Zululand eucalyptus site. The one-way ANOVA revealed that there was a significant difference between mechanised pitting on a residue burnt treatment as compared to a mulched treatment $P \leq 0.0001$.

Mechanised pitting on the Jessievale pine site, as shown in Table 4.9, has a higher mean move speed on a mulched residue treatment (0.80 m s^{-1}) as compared to a burnt residue treatment (0.59 m s^{-1}). The Mann-Witney U test confirms that the treatments, residue mulched versus burnt, was statistically different $p \leq 0.0001$.

The variation of mean pitting time, (The time taken from when the pitter starts pitting the first pit up until the last pit is completed, divided by the number of completed pits in that cycle). The below results are based on the Mpat mechanised pitter in both burnt and mulched treatments.

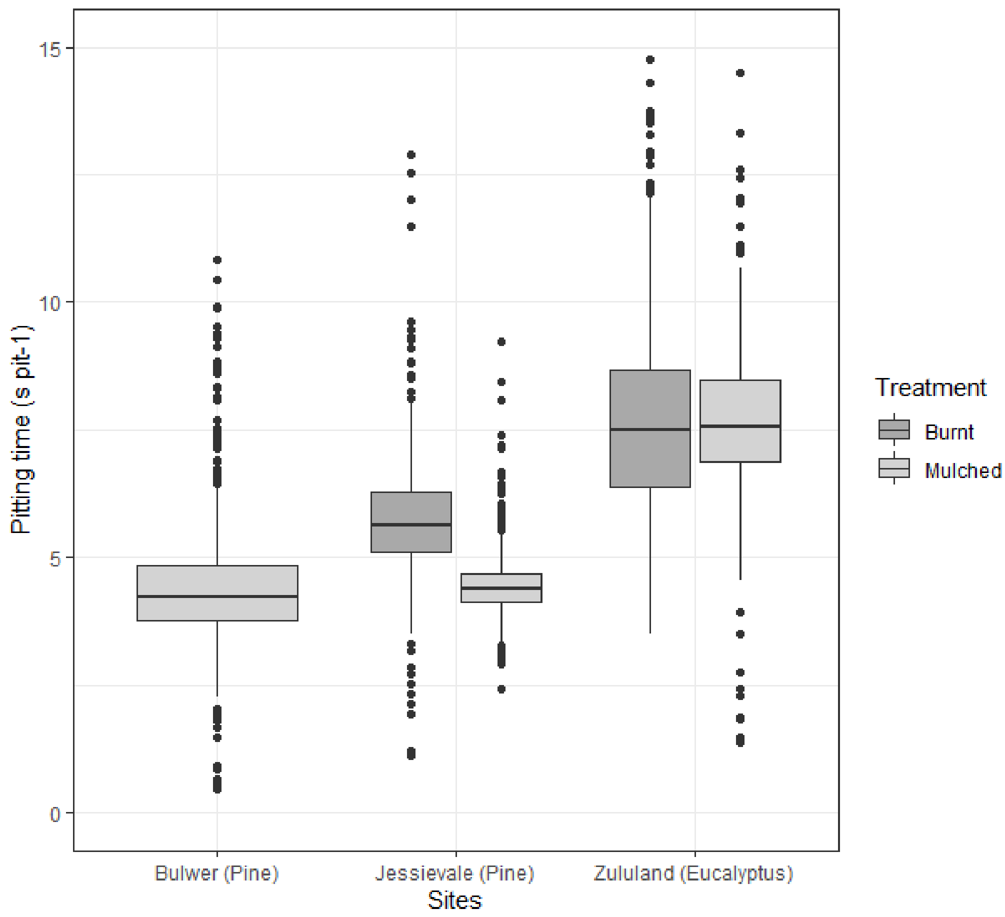


Figure 4.5 Variation of mechanised pitter 'pitting time per pit' within treatment based on sites

The boxplots (Figure 4.5) show that the mean pitting time per pit in mulched treatments to be slightly lower compared to the move time per pit in the burnt treatments. Table 4.10 below shows the summary statistics of the moving time.

Table 4.10 Summary statistics of moving time per treatment in seconds per pit

Treatment	Mean pitting time (s pit^{-1})	Standard deviation	p- value
Zululand			
Burnt	7.78	2.43	≥ 0.1
Mulched	7.70	1.62	
Bulwer			
Mulched	4.41	1.15	
Jessievale			
Burnt	5.82	1.60	≤ 0.0001
Mulched	4.51	1.00	

Table 4.10 shows that in Zululand eucalyptus trials, mean mechanised pitting time on the burnt (7.78 s pit^{-1}) versus mulched residue (7.70 s pit^{-1}) treatments are similar. The Mann-Whitney U test showed that there was no significant difference $P \geq 0.1$ between mechanised pitting time per pit on burnt residue compared to mulched residue treatment.

From Table 4.10, it is noticed that the mean mechanised pitting time on the residue burnt treatment (5.82 s pit^{-1}) was higher than the residue mulched treatment (4.51 s pit^{-1}) based on the Jessievale pine site. The Mann-Whitney U test showed that there was a significant difference ($p \leq 0.0001$) between mean mechanised pitting time per a pit on mulched residue compared to burnt residue treatments.

4.4.2 Manual pitting results

The productivity results based on the manual pitting operation on pine residue is shown in Table 4.11. Manual pitting on burnt residue (0.06 ha $PPH^{-1)}$ has the higher productivity than in mulched residue treatments (0.05 ha PPH^{-1}).

Table 4.11 Manual pitting productivity results based on burnt and mulched pine residue treatment at the Bulwer site

Site		Move (min)	Pit (min)	Total (min)	No pits	Min pit^{-1}	Pits PPH^{-1}	PPH ha^{-1}	ha PPH^{-1}
Bulwer									
Burnt	M31b	***0.21***	***0.35***	***0.60***	**1**	***0.60***	**101**	**16.38**	**0.06**
Mulched	M38a	***0.22***	***0.44***	***0.68***	**1**	***0.68***	**87**	**18.98**	**0.05**

As in mechanised pitting hereto, to conclusively analyse the effects of pitting on a mulched versus a burnt site, we investigate the pitting time elements to better understand these effects namely:

- Move speed in meters per second (m s^{-1})
- Pitting time in seconds per pit (s pit^{-1})

The variation of mean move speed, (The time from when the manual pitter moves from the completed pit to the next pit's location, divided by the distance of the move). Below are the results based on a manual pitter in both burnt and mulched treatments.

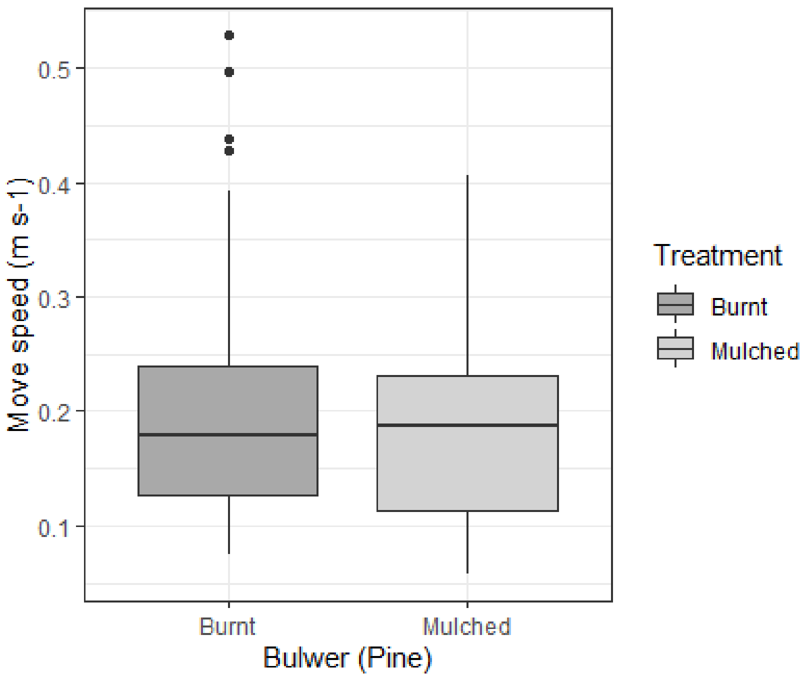


Figure 4.6 Variation of manual pitting 'move speed' on burnt and mulched treatments

The above boxplots (Figure 4.6) shows that the mean move speed of the manual pitter in the mulched treatment is similar compared to the burnt treatment at the Bulwer site. Table 4.12 below shows the summary statistics of the move speed.

Table 4.12 Summary statistic of the manual pitter move speed.

Treatment	Mean move speed (m s^{-1})	Standard deviation	p- value
Bulwer			
Burnt	0.19	0.09	≥ 0.1
Mulched	0.19	0.09	

As shown in Table 4.12 residue burnt, and mulched treatment had the similar mean move speed of 0.19 m s^{-1} at the Bulwer pine site. The one-way ANOVA revealed that there was not a statistically significant difference between manual pitting mean move speed on a residue burnt or mulched treatment P ≥ 0.1).

The variation of mean manual pitting time, (The time taken for a manual pitter to complete pitting a pit) The below results are based on the manual pitter in both burnt and mulched treatments.

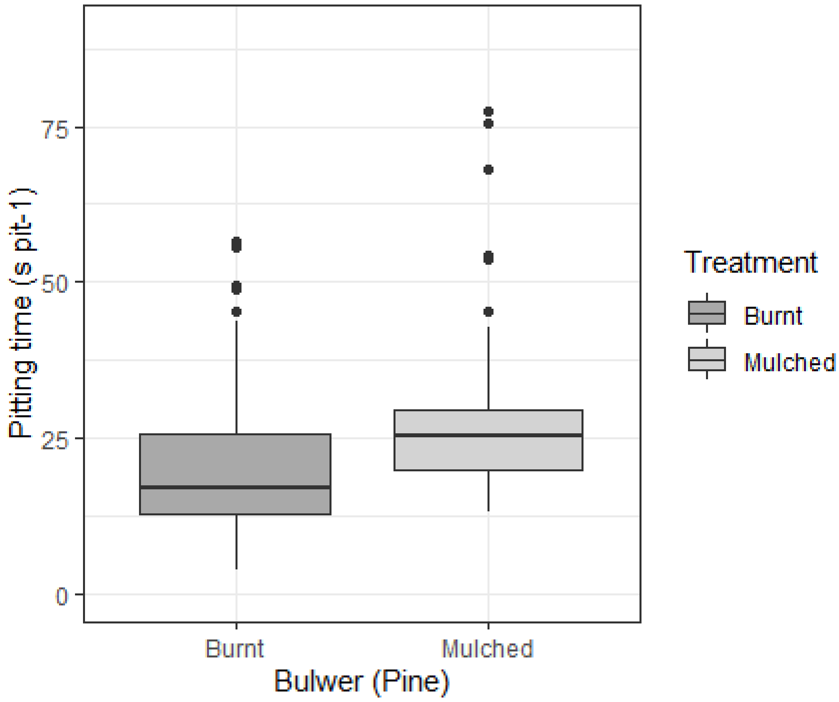


Figure 4.7 Variation of manual pitter pitting time per a pit based on burnt and mulched treatments

Figure 4.7 boxplots illustrates that the mean manual pitting time per pit in mulched treatments is higher compared to the move time per pit in the burnt. Table 4.13 below shows the summary statistics of the moving time.

Table 4.13 Summary statistic of the manual pitting time per residue treatment.

Treatment	Pitting speed (s pit^{-1})	Standard deviation	p- value
Bulwer			
Burnt	21.08	12.78	≤ 0.0001
Mulched	26.33	10.80	

From Table 4.13, it is noticed that the mean manual pitting time on the residue burnt treatment (21.08 s pit^{-1}) was lower than the residue mulched treatment (26.33 s pit^{-1}) based on the Bulwer pine site. The Mann-Whitney U test showed that there was a significant difference (P≤0.0001) between mean manual pitting time per a pit on mulched residue compared to burnt residue treatments.

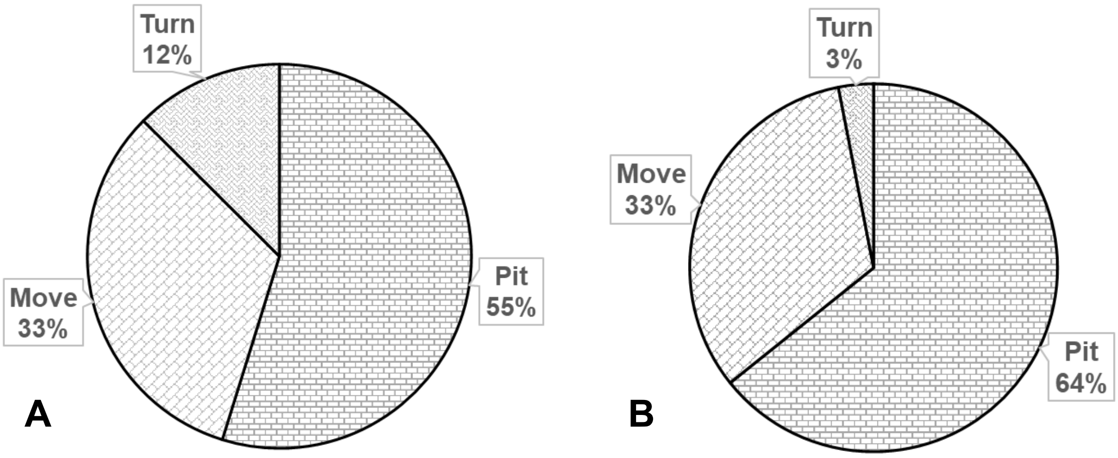


Figure 4.8 Bulwer manual pitting time elements distribution. A- pitting on Burnt treatment. B- pitting on a Mulched treatment.

4.5 Planting time study analysis

Hypothesis 3 is used to evaluate the effect of residue management (burnt versus mulched) on semi-mechanised and manual planting operations.

Hypothesis 3

H_0: Planting productivities between burnt and mulched treatments are the same.

H_1: Planting productivities between burnt and mulched treatments differ.

4.5.1 Semi-mechanised planting results

Table 4.14 shows the productivity result of the semi-mechanised tractor drawn planter on burnt versus mulched residue management treatment. From these results we cannot compare productivities as there is a difference in planting escapement and number of planters. The productivity is 1.70 ha PMH^{-1} at 1548 SPHa and 1.20 ha PMH^{-1} at 1667 SPha in mulched and burnt treatments respectively.

Table 4.14 Productivity results of the semi mechanised tractor drawn planter

Comp		Fill per row (min)	Plant per row (min)	Total per row (min)	Row per PMH^{-1}	Plants per row	Plant PMH^{-1}	PMH ha^{-1}	ha PMH^{-1}
Zululand									
Mulched (SPHa=1548)	K19	0.04	0.11	0.15	407	7	2848	0.56	1.84
	J31b	0.05	0.11	0.16	342	7	2393	0.67	1.55
	mean	***0.05***	***0.11***	***0.16***	***375***	***7***	***2621***	***0.60***	***1.70***
Burnt (SPHa=1667)	S1	0.06	0.14	0.24	250	6	1500	1.11	0.90
	S2	0.06	0.15	0.22	273	6	1638	1.02	0.98
	S3	0.06	0.12	0.19	315	6	1890	0.88	1.13
	S4	0.06	0.12	0.14	428	6	2568	0.65	1.54
	mean	***0.06***	***0.13***	***0.18***	***317***	***6***	***1899***	***0.88***	***1.14***
standardised burnt results to 7 planters and 1548 SPHa							***2058***	***0.75***	***1.33***

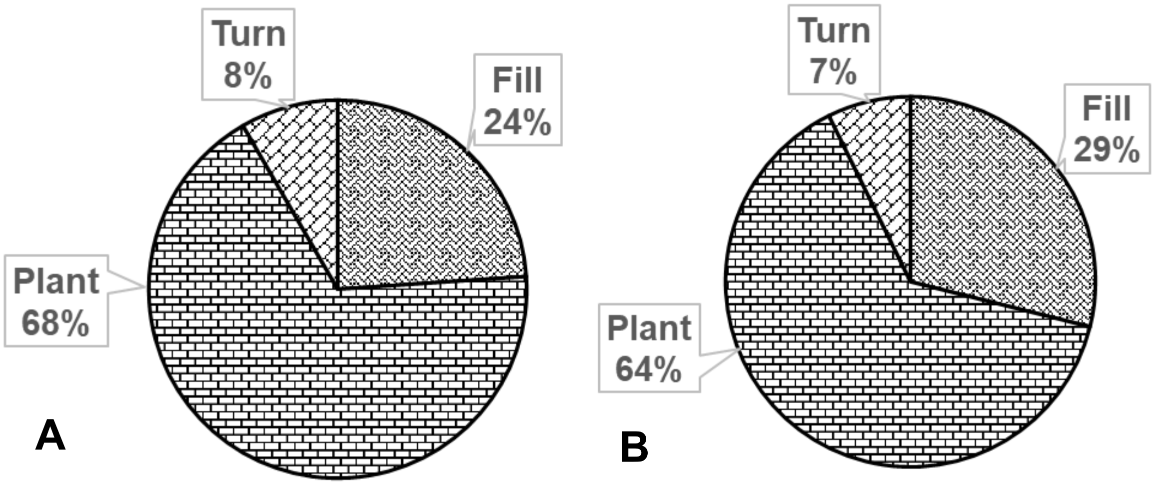


Figure 4.9 Time element results of Zululand semi-mechanised tractor drawn planter. A-planting operation on Burnt treatment. B- planting operations on Mulched treatment.

To conclusively analyse the effects of semi- mechanised planting on a mulched versus a burnt treatment we investigate the planting time elements to better understand these effects. Since the plant and move elements happen almost simultaneously, the data collected combined these two elements. Due to the planting escapement difference between the burnt treatment (2.0 m apart) versus mulched treatment (1.9 m apart), a standardized measure investigating whether it is easier to plant or move in a burnt compared to a mulched treatment. To investigate planting move speed, 38 m was used to standardise the treatment to analyse the effect of mulched versus burnt residue has on plant move speed. This means that the planter on the mulched treatment will plant 18 seedlings to reach 38m and the planter on the mulched treatment will need to plant 19 seedings to reach 38m. This was the lowest common difference to investigate this effect given this situation.

To investigate planting speed, we investigate the time taken to plant a single row even though there is a 10 cm difference between treatment emplacements

Important to note that for later studies this was rectified and separated into individual elements plant and move elements.

- Move speed in meters per second ($m\ s^{-1}$)
- Planting speed in seconds per row ($s\ row^{-1}$)

The variation of mean move speed is determined by how many meters it takes the planter to cover in a second. Figure 4.9 and table 4.15 are the results based on the semi-mechanised planters in both burnt and mulched treatments.

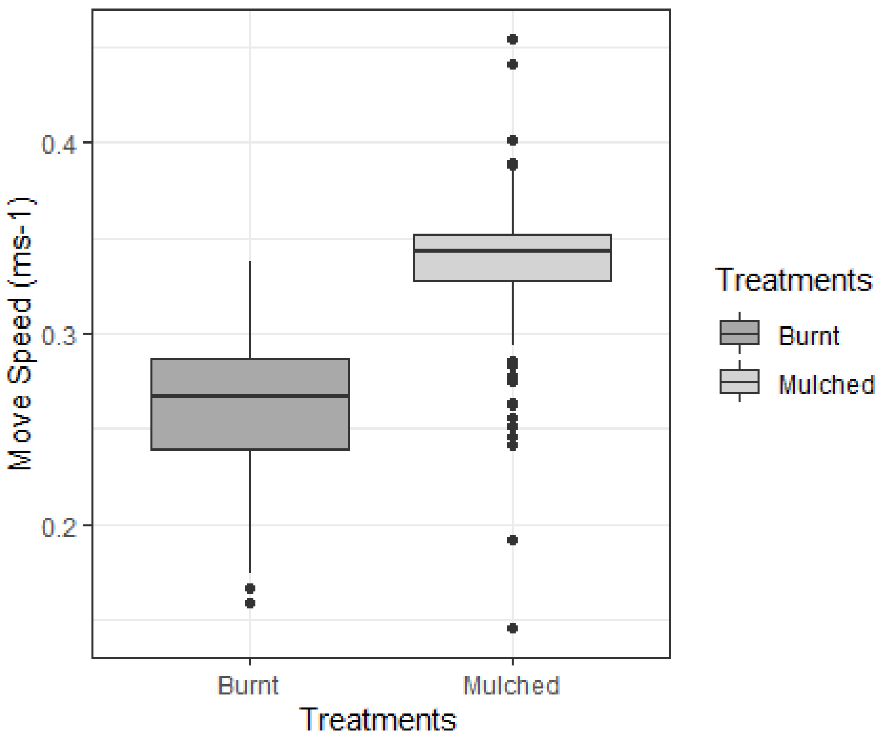


Figure 4.10 Variation of move speed based on a semi-mechanised tactor drawn planter per residue management treatment.

The boxplot (Figure 4.10) illustrates that the mean semi-mechanised move speed in mulched treatment is higher compared to the in the burnt. Table 4.15 below shows the summary statistics of the moving speed.

Table 4.15 Summary statistic of the semi-mechanised planter move speed per residue treatment

Treatment	**Plant move speed (m s^{-1})**	**Standard deviation**	**p- value**
Zululand			
Burnt	0.26	0.04	≤ 0.0001
Mulched	0.34	0.03	

As shown in Table 4.15 mean plant move speed on residue mulched (0.26 m s^{-1}) was higher than on residue burnt (0.34m s^{-1}) at the Zululand eucalyptus site. The Mann-Whitney U test showed that there was a significant difference (P≤0.001) between mean semi-mechanised planter move speed on mulched residue compared to burnt residue treatments.

The variation of planting time was determined by the time taken to plant a row. Figure 4.10 and table 4.16 are the results based on the semi-mechanised planters in both burnt and mulched treatments.

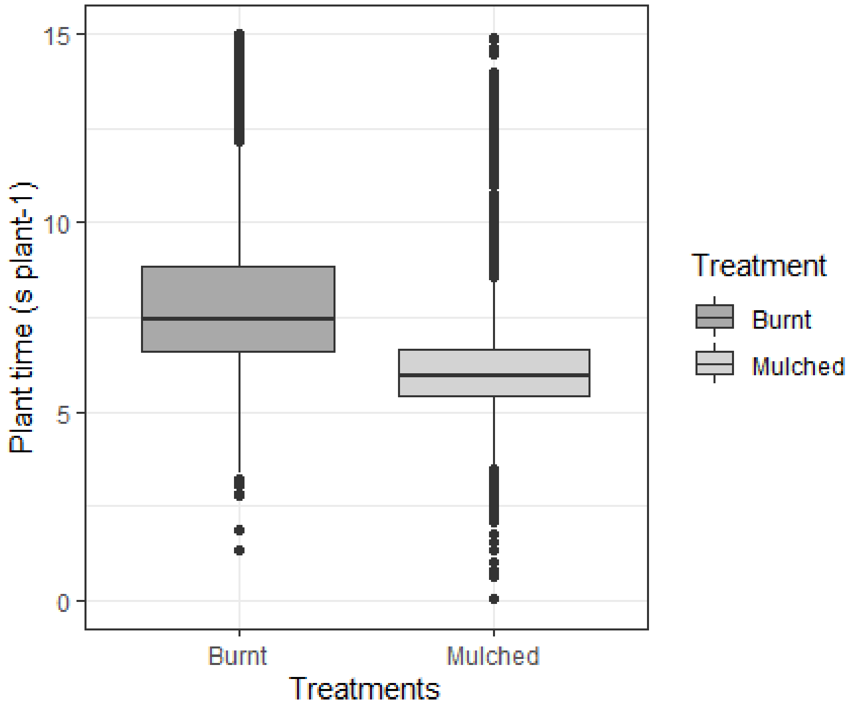


Figure 4.11 Variation of planting time based on a semi-mechanised tactor drawn planter per residue management treatment.

The boxplot (Figure 4.11) above indicates that the mean semi-mechanised planting time in burnt treatment is higher than that of mulched treatment. The Table 4.16 below shows the summary statistics of the planting time.

Table 4.16 Summary statistic of the semi-mechanised planter planting time per residue treatment

Treatment	**Planting time (s plant^{-1})**	**Standard deviation**	**p- value**
Zululand			
Burnt	8.24	2.98	≤ 0.0001
Mulched	6.32	3.14	

As shown in Table 4.16 mean planting time on residue burnt (8.24 s plant^{-1}) was higher than on residue mulched (6.32 s plant^{-1}) at the Zululand eucalyptus site. The Mann-

Whitney U test showed that there was a significant difference ($P \leq 0.0001$) between mean semi-mechanised planter planting time on mulched residue compared to burnt residue treatments.

4.5.2 Manual planting results

Manual planting productivity results (Table 4.17) are based on one planter which comprises of two persons (one who carries the planting tube and hydrogel bucket and doing the actual planting, whilst the assistant carries the seedling tray and Suppositree™ tablets). The productivities were worked out per productive planting team hour (PPTH). Bulwer manual planting productivity at 1667 SPHa on a mulched treatment (0.06 ha $PPTH^{-1}$) is higher than a burnt treatment (0.08 ha $PPTH^{-1}$). Jessievale manual planting productivity at 1111 SPHA (0.15 ha $PPTH^{-1}$) is the highest due to the lower number of stems planted per hectare.

Table 4.17 Productivity results of the manual planter based on pine residue at Bulwer and Jessievale sites

Comp		Fill (min)	Plant (min)	Move (min)	Total (min)	No. plants	Plant $PPTH^{-1}$	PPT H ha^{-1}	ha $PPTH^{-1}$
Bulwer									
Burnt	M31b	0.06	0.19	0.24	0.62	1	96	17.30	0.06
Mulched	M37	0.10	0.17	0.08	0.46	1	129	12.91	0.08
	M38a	0.05	0.20	0.10	0.47	1	126	13.17	0.08
Mean		***0.08***	***0.19***	***0.09***	***0.45***	***1***	***128***	***13.04***	***0.08***
Jessievale									
Mulched	E009	0.03	0.17	0.11	0.41	1	146	7.66	0.15

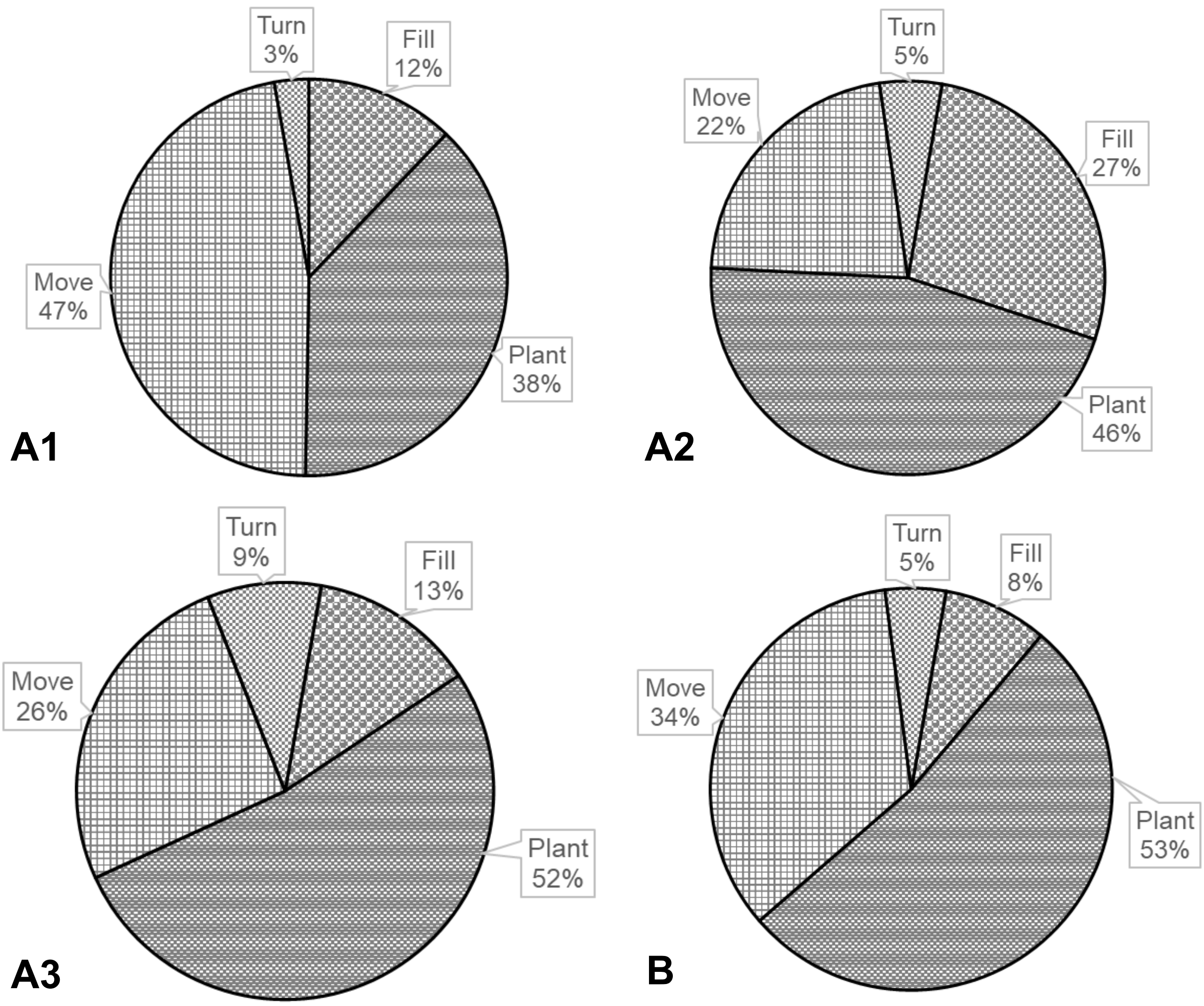


*Figure 4.12 Time element distribution for manual planting operations. **A1- Bulwer** planting operation on **Burnt** treatment. **A2- Bulwer** planting operation on **Mulched** treatment after mechanised pitting. **A3- Bulwer** planting operation on **Mulched** treatment after manual pitting. **B- Jessievale** planting operation on **Mulched** treatment.*

As in the semi-mechanised planting hereto we standardise the results to conclusively analyse the effects of manual planting on a mulched versus a burnt site we investigate the plant time elements to better understand these effects namely:

- Move speed in meters per second (m s^{-1})
- Planting time in seconds per plant (s $plant^{-1}$)

The variation of mean move speed, (The time at which the planter moves from one cycle position to the next, divided by the distance of the move). Below are the results based on the manual planter in both burnt and mulched treatments.

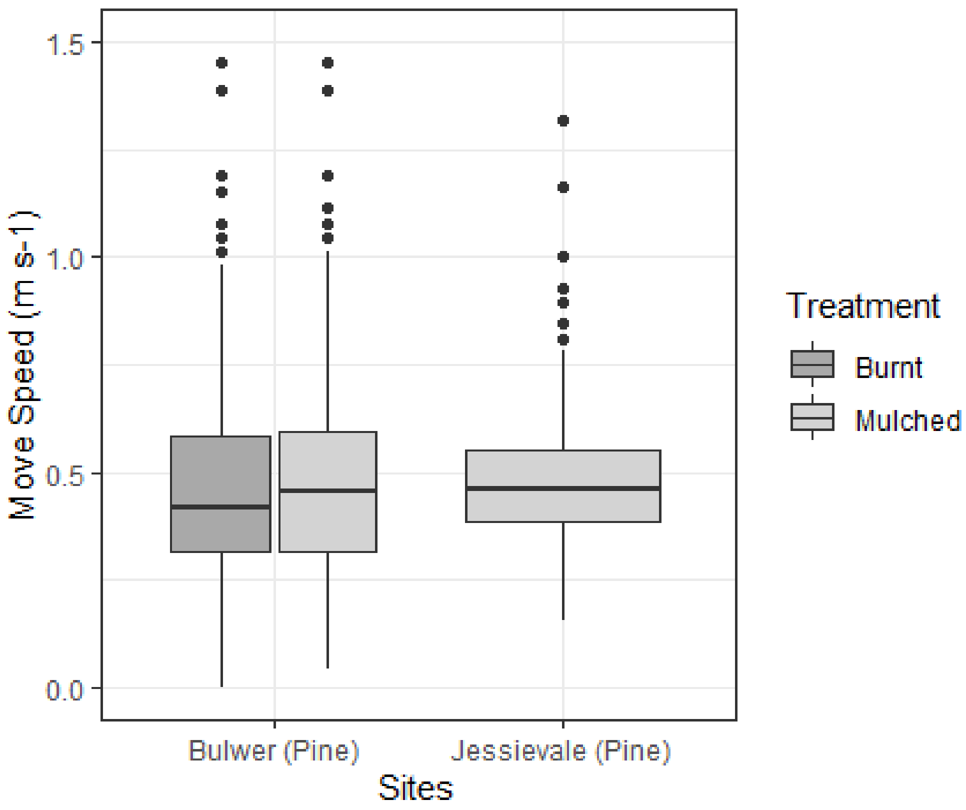


Figure 4.13 Variation of manual planter 'move speed' within treatment per site

Figure 4.13, the boxplot suggest that the mean move speed of the manual planter in both Bulwer and Jessievale mulched treatment is slightly higher compared to the burnt treatment. Table 4.18 below shows the summary statistics of the move speed.

Table 4.18 Summary statistic of the manual planter planting time per residue treatment

Treatment	**Plant move speed (m s^{-1})**	**Standard deviation**	**p- value**
Bulwer			
Burnt	0.38	0.22	≤ 0.1
Mulched	0.46	0.21	
Jessievale			
Mulched	0.48	0.17	

As shown in Table 4.18 residue burnt, and mulched treatment had the similar mean move speed of 0.38 m s^{-1} and 0.46 m s^{-1} respectively, at the Bulwer pine site. The one-way ANOVA revealed that there was a statistically significant difference between manual planter mean move speed on a residue burnt as compared to residue mulched treatment ($P \leq 0.1$).

The variation of planting time was determined by the time taken to plant a single plant. The below are the results based on the manual planter in both burnt and mulched treatments.

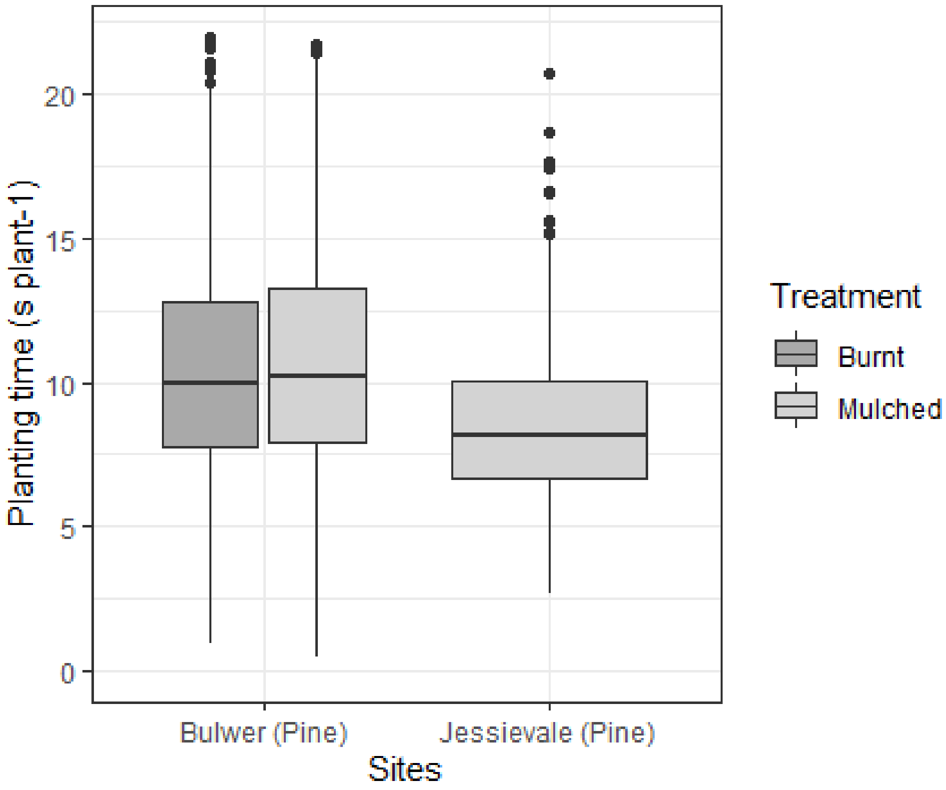


Figure 4.14 Variation of manual planter 'planting speed' within treatment per site

The above Figure 4.14 shows that the mean manual planter planting time in the residue mulched is similar to the residue burnt treatment at the Bulwer study site. Table 4.19 below shows the summary statistics of the plant time per plant.

Table 4.19 Summary statistic based on the manual planter mean planting on burnt residue compared to mulched residue treatments

Treatment	Planting time (s plant^{-1})	Standard deviation	p- value
Bulwer			
Burnt	11.47	6.44	≥0.1
Mulched	12.02	6.63	
Jessievale			
Mulched	10.48	6.54	

From the above Table 4.19 residue burnt, and mulched treatment had the similar mean move speed of 11.47 s $plant^{-1}$ and 12.02 s $plant^{-1}$ respectively, at the Bulwer pine site. The one-way ANOVA revealed that there was not a statistically significant difference between manual planter mean move speed on a residue burnt as compared to residue mulched treatment ($P \geq 0.1$).

4.6 Machine and system costing analysis

Table 4.20 shows the individual machine and person cost for the total system as per study site and residue treatment. Bulwer pine residue burnt, manual pitting and manual planting have the lowest re-establishment cost (R2 356.07/ha^{-1}) compared to Jessievale pine residue mulched, mechanised pitting and manual planting (R8 853.71/ha^{-1}).

Table 4.20 Machine and person system costing

Site	Mulcher cost		Mechanised pitting cost		Manual pitting cost		Semi-mechanised planting cost		Manual planting cost		**Total system cost**	
	R ha^{-1}	R PMH^{-1}	R ha^{-1}	R PMH^{-1}	R ha^{-1}	R PPH^{-1}	R ha^{-1}	R PMH^{-1}	R ha^{-1}	R PPH^{-1}	**R ha^{-1}**	**R PH^{-1}**
Zululand												
Mulched	5 452.14	2 064.78	2 029.45	527.66	-	-	576.27	976.85	-	-	**8 057.86**	**3 569.29**
Burnt	*N/A*	*N/A*	2 120.76	527.66	-	-	736.59	976.85	-	-	**2 857.35**	**1 504.51**
Bulwer												
Mulched	6 165.14	2 150.77	1 286.97	527.66	-	-	-	-	1 272.93	112.21	**8 725.04**	**2 790.64**
Mulched	6 165.14	2 150.77	-	-	790.60	39.53	-	-	1 272.93	112.21	**8 228.67**	**2 302.51**
Burnt	*N/A*	*N/A*	-	-	658.83	39.53	-	-	1 697.24	112.21	**2 356.07**	**151.74**
Jessievale												
Mulched	7 249.09	3 262.09	925.72	527.66	-	-	-	-	678.90	112.21	**8 853.71**	**3 901.96**
Burnt	*N/A*	*N/A*	1 147.08	527.66	-	-	-	-	-	-	**-**	**-**

4.7 Plant growth response analysis

4.7.1 Jessievale pine growth results

The below Table 4.21 shows the variation of ground line diameter (GLD) and height (Ht) at four months after planting between burnt and mulched treatment.

Table 4.21 Summary of ground line diameter and height growth at four months after planting between mulched and burnt treatments.

December to April

Ground line diameter (GLD)				
	Mean GLD (cm)	Mean GLD Growth (cm)	Standard deviation	p-value
Mulched	0.63	0.36	0.21	<0.001
Burnt	0.49	0.19	0.20	
Height (Ht)				
	Mean Ht (cm)	Mean Ht Growth (cm)	Standard deviation	p-value
Mulched	25.13	17.56	0.21	<0.001
Burnt	24.02	14.51	0.40	

Ground line diameter and height growth – December to April

From Table 4.21 the measurement results indicate a mean GLD on mulched site of 0.63 cm and that of burnt sites of 0.49 cm. A higher mean GLD growth of 0.36 cm was observed on mulched sites compared to burnt sites (0.19 cm), with a 0.17 cm difference.

An ANOVA was conducted was done using the mean of the GLD growth between the mulch and burnt compartment. A $P \leq 0.001$ was obtained suggesting that there is significant difference between the mean growth. The results suggest that the mulched treatment GLD growth after four months was greater than that of the burnt treatment.

As shown in Table 4.21 Height measurement results indicate a mean height on the mulched site was 25.13 cm, vs. that of the burnt site 24.02 cm. A higher mean height growth of 17.56 cm was observed on mulched sites compared to burnt sites (14.51 cm), with a 3.05 cm difference.

A Mann-Whitney U test was done using the mean of the growth height between the mulch and burnt compartment. A $P \leq 0.001$ was obtained suggesting that there is significant difference between the means. The results suggest that the mulched treatment height growth after four months from planting was greater than the burnt treatment.

Seedling survival

In terms of seedling survival, Figure 4.15 below indicates the overall survival between the two treatments at four months. It is found that the mulched treatment had a higher seedling survival of 98% as compared to the burnt treatment of 93%.

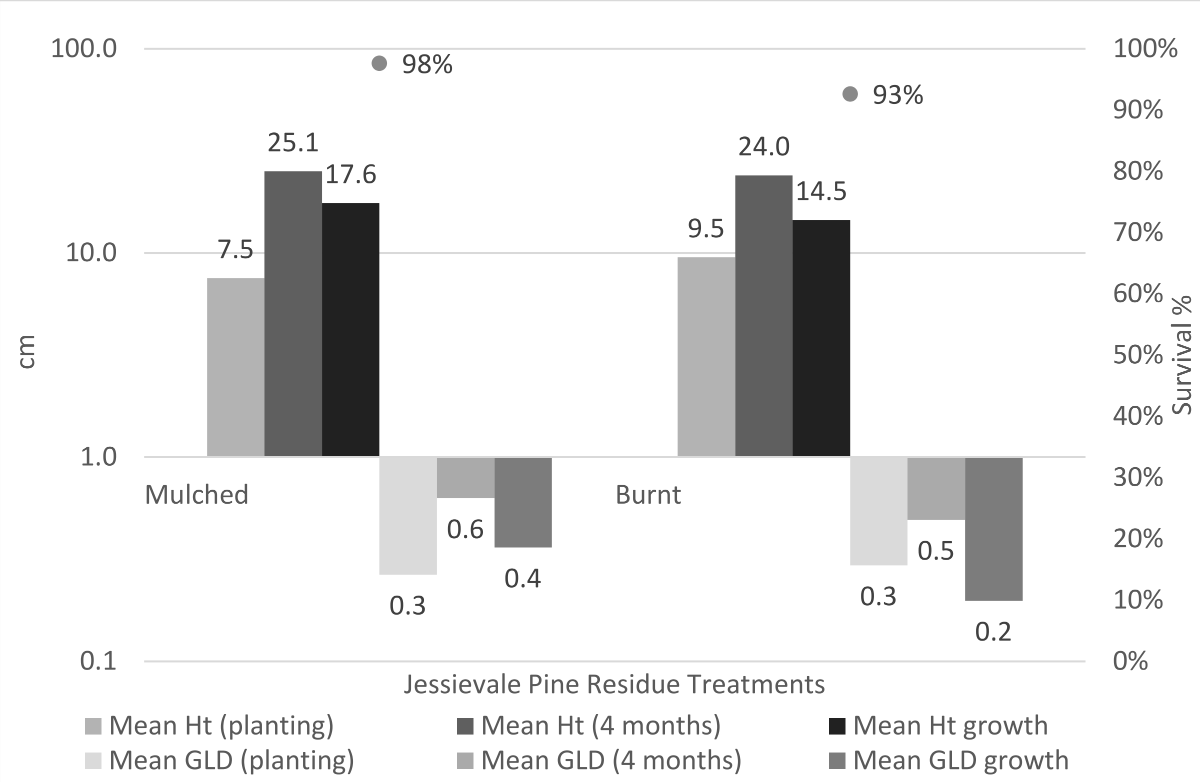


Figure 4.15 The above figure is a graphical representation of the pine growth response results between mulched and burnt residue treatment, highlighting mean ground line diameter (GLD) in cm and height (Ht) in m at planting and four months.

Overall based on the results, there appears to be an initial seedling growth and survival benefit to mulching stands. These results are based on four months of data and need to be viewed as preliminary as more measurements should be taken.

4.7.2 Zululand Eucalyptus growth results

Unlike the Jessievale pine growth data, eucalyptus growth measurement data at the one-year of age was supplied by the company as the ran pre-existing trials. Analyse of mean survival percentage, diameter at breast height (DBH) and height (Ht) per treatment of burnt versus mulched residue as shown in the below Figure 4.15.

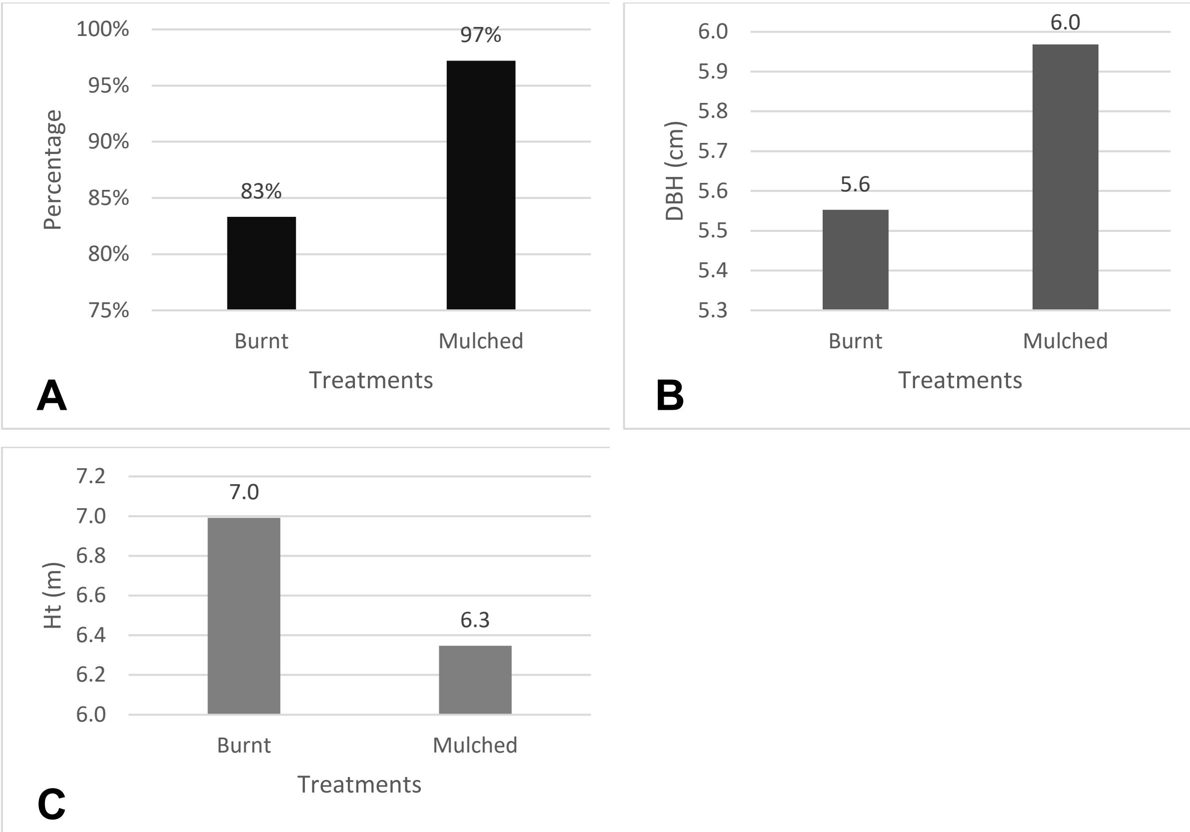


Figure 4.16 Eucalyptus growth response between mulched and burnt residue treatment. A- survival percentage per treatment. B- Mean diameter at breast height (DBH) per treatment. C- Mean height (Ht) per treatment.

From Figure 4.16A it is noted that the mulched treatment had an improved survival percentage (97%) at year-one when compared to the burnt treatment (83%). A 14 % increase in survival rate was observed on mulched as compared to burnt treatments.

Figure 4.15B shows the mean diameter at breast height (DBH) variation between the burnt and mulched treatment. Mulched treatment had a higher mean DBH of 6.0 cm at year-one, when compared to the burnt treatment (5.6 cm). It was noted that an additional increase of 0.4 cm in mean DBH was observed in mulched treatment when compared to the burnt treatment.

Mean height (Ht) variation between treatments is shown in Figure 4.15C. The burnt treatment had a greater mean height of 7.0 m when compared to the mulched treatment of 6.3 m at year-one. The burnt treatment had an increase of mean height of 0.7 m.

4.7.3 Biomass Index

From Table 4.22both eucalyptus and pine trail show improved growth with mulched residue as compared when to burnt residues. This is supported by the higher biomass index on mulched residue treatment.

Table 4.22 Biomass index based on Pine and Eucalyptus growth

Pine growth at 4 months				
	Survival%	GLD (cm)	Height (cm)	Biomass Index
Mulched	98	0.63	25.13	9.77
Burnt	93	0.49	24.02	5.36
Difference	5%	0.14	1.11	4.41
Eucalyptus growth at 12 months				
		DBH (m)	Height (m)	Biomass Index
Mulched	97	0.06	6.30	0.03
Burnt	83	0.05	7.00	0.02
Difference	14%	0.04	-0.70	0.01

Based on these results, there appears to be an initial plant growth and survival benefit in mulched stands. These results are based on one year after planting and need to be viewed as preliminary as more measurements has should be taken.

5 Discussion

The Chapter follows the same structure as that of Chapter 4. It contains a discussion of the results of the biomass assessments, time studies for mulching, pitting and planting, system costing and seedling growth responses.

5.1 Biomass assessments

From Table 4.3 the combined volume (stump and residue) was the highest at the Bulwer pine site (126.7 m^3 ha^{-1}), as a result of the 2012 stand snow damage event. This resulted in inordinately high quantities of defect timber after harvesting. The volumes of biomass left on the Zululand eucalyptus sites varied with J31a having twice the volume of J31b. Even though the compartments were planted and harvested at approximately the same time, the high levels of biomass in J31a could have been a result of poor harvesting practice. Jessievale sawtimber pine site had a combined volume of 49.5 m^3 ha^{-1} which was below normal according to Ross and du Toit (2004). stump heights in this study exceeded the company's stump height policy of 10 cm with Zululand being the greatest.

5.2 Mulching

Even though the Zululand eucalyptus and Bulwer pine pulpwood trials were done with different brands of horizontal drum mulchers, both machines were considered highly comparable as they were powered by 350 -370 hp engines. Very similar mulching productivity rates (0.35 ha PMH^{-1} - 0.36 ha-PMH^{-1}) were achieved across these sites (Figure 4.1). This was not expected as pine stump and residue volume exceeded those of the eucalyptus site. Mulching productivity appeared not to be influenced by the amount of residual biomass (36.4 -125.1 m^3 ha^{-1}) which could indicate that these machines have adequate mechanical capacity to perform their task.

Depending on site, mulchers did one or two passes to achieve the desired mulch quality, however mulch quality is not clearly defined and can be subjective. To understand cost of mulching clearer quality standards, need to be generated. However mulching productivities and mulch quality has studies are few and far between. Mulching cost on both eucalyptus and pine pulpwood regime sites were comparable even though pine mulching costs higher at R6 165.14 when compared to eucalyptus mulching costing at R5 452.14. This difference in cost (R713.00) is directly related to machine purchase price and not species difference.

Jessievale pine sawtimber mulching was completed the large (640 horse-power) Prinoth mulcher. Even though this machine achieved the highest productivity (0.45 ha PMH^{-1}) of all mulchers studied, the high fuel consumption (54 L PMH^{-1}) and purchase price did lead to this machine costing R1 796.95 ha^{-1} more than the CAT based mulcher used in the eucalyptus site.

From the Bulwer site we notice that mechanical mulching was better equipped to reduce intact biomass compared to burning. However, Mulching had an 18.7% increase in reduction in intact biomass than compared to burning. Residue mulching transforms this biomass to smaller particle size spread out across the compartment, whilst residue burning removes the biomass and leaves 91% of stumps intact.

5.2.1 Mulching quality

The main focus of the Jessievale study was to investigate the effect of machine travel speeds and number of passes on mulching quality, defined as the measured reduction in intact biomass volumes after treatment. Unfortunately, this was not fully achieved as the strong coincidence of mulching swath and residue windrow orientation, brought on by slope, influenced the sampling design. The prevailing slope resulted in mulching lines coinciding and overlapping to a smaller or larger degree with harvester-forwarder extraction routes. This meant that in some cases, the measured mulching swath could have occurred within a windrow, implying that volume density distributions were skewed. To avoid the effect of this in future, swaths and sampling point should be clearly marked before mulching, and measurements taken between the same points.

There is a gap in our common understanding or classification of mulching quality and how it should be defined. This study collected handheld camera and UAV based imagery of the mulch samples (before and after) which will be used to develop a precursor to a standard for mulch classification. This will be covered in another forest operations master's thesis currently underway, which will be beneficial to understanding mulching productivity with respect to a desired quality grade.

By demonstrating that speed settings do indeed translate to corresponding speeds over ground in an operational context, the study does highlight the need for greater specificity in terms of treatment and desired mulching outcome. Comparing two different speeds with single or double passes gives as factor 4 difference in productivity (and cost) between the treatments. It would therefore be in the interests of all parties to promote further investigations into resultant mulch quality, the requirements on this in facilitating effective re-establishment, and in determining which treatment would provide this at the lowest cost.

5.3 Pitting

Both manual and mechanised pitting were done immediately the various residue reduction operations were done. Due to all sites having different planting espacement, pitting productivity (ha PMH^{-1}) could not be used to determine direct differences arising from different residue treatments.

5.3.1 Mechanised pitting

This study found that mechanised pitting in eucalyptus stands on burnt and mulched treatments had the same productivity of 0.26 Ha PMH^{-1}, but at different espacement. The mulched treatment was at 1548 SPHa and burnt treatment was at 1481 SPHa. For this reason, we had to standardise the burnt treatment pitting data to directly give us a direct comparison.

We found that even though mechanised pitting move speed was 17.5% faster on mulched eucalyptus residue compared to burnt residue, pitting time was not significantly different. The faster move speed on mulched residue could be directly attributable to the presence of stumps and un-combustible material on burnt treatment. It was noticed that pitting productivity for each of the Zululand mulched compartments did not differ significantly with an average productivity of 0.26 ha PMH^{-1}. It is apparent that like the mulcher, the pitter was not affected by the differences in initial intact biomass between the two compartments.

By standardising pitting productivity in burnt stands, cost per single pit and thereafter transforming this result to 1548 SPHa, we were able to compare burnt and mulched treatments. The transformed productivity for mechanised pitting on burnt residue is 0.25 ha PMH^{-1}. Even though the pitters move speed was faster on eucalyptus mulched residue, this resulted in 0.01 ha PMH^{-1} (4%) increase in pitting productivity in comparison to burnt residue.

Planting densities were similar for mechanised pitting for both mulched and burnt sites in the one sawtimber studies. It was noticed that pine residue moving speed and pitting time differed statistically between the two. Even though move speed and pitting time was 35.6% and 29% faster on mulched residue than burnt residue respectively, this correlated to a 24% increase in mulched residue pitting productivity compared to burnt residue. It is believed that this could be as a result of large un-combustible residue and stumps effected the productivity of mechanised pitting on mulched residue (0.57 ha PMH^{-1}) compared to burnt residue (0.46 ha PMH^{-1}).

Interestingly, mechanised pitting time on mulched or burnt eucalyptus residue took longer than on pine residue, even though eucalyptus sites where predominately sandy soils compared to the clay rich pine soils. This difference in species pitting time is partially attributed to operator efficiency. The mechanised pitting rates in eucalyptus averaged from 405 pits PMH^{-1} in mulched residue and 391 pits PMH^{-1} in burnt residue, were within range of the of the manufactures rates of 285 – 500 pits PMH^{-1} (Viljoen, 2021). However, sawtimber pine pitting rates (Highveld) averaged from 515 pits PMH^{-1} in burnt residue to 658 pits PMH^{-1} on mulched residue, exceeded the manufactures rate.

Mechanised pitting on mulched eucalyptus residue was R92.88 per hectare cheaper than burnt and R221.36 per hectare cheaper in mulched pine residue compared to burnt residue.

5.3.2 Manual pitting

Manual pitting on pine burnt residues productivity increased by 16% when compared to mulched residue. It was noted that manual pitting on burnt residue was faster (0.06 ha·PPH^{-1}) than that in mulched residue (0.05 ha·PPH^{-1}). Further analysis of each element revealed that move speed did not differ significantly between treatments, however pitting speed differed significantly. It was noticed that pitting speed was quicker in burnt residue (21.08 s pit^{-1}) than in mulched (26.33 s pit^{-1}).

The number of manual pits made on burnt residues (101 pits PPH^{-1}) differed significantly to the number on mulched sites (87 pits PPH^{-1}). The manual pitter was not hindered by unburnt or mulched material when moving across the treatments however manual pitting on mulch residue was difficult, as pitters are required to clear away excessive mulch at the pit site. This was not the case for mechanised pitting

Figure 4.7 shows the proportions in percentage of time spent in the manual pitting cycle per residue management treatment. Of all treatments the pitting element took the longest followed by move then turn. It is important to note that turn time is directly influenced by the shape and pitting direction in a compartment and not residue management.

Using the basic wage of R39.53 per PPH^{-1} for a manual pitter, pitting on residue mulched cost R790.60 per hectare and R658.83 per hectare for residue burnt. It is approximately R131.77 ha^{-1} cheaper to manually pit on burnt residue as opposed to mulched residue.

It was found that mechanised pitting on clay rich soils pine mulched sites required 2.6 PMH ha^{-1} at R 1 286.97 ha^{-1} and R 527.66 PMH^{-1} at 1667 SPHa. This mechanised productivity was matched and equates to the productivity of 7.3 manual pitters costing R750.28 ha^{-1}. and in the case of mulched eucalyptus sandy soils (1548 SPHa) required 3.85 PMH per hectare costing R2029.45 ha^{-1} at R527.66 PMH^{-1}, equating to five manual pitters at R760.95 ha^{-1}. It is evident that manual pitting on mulched clay rich and sandy soils are R536.69 ha^{-1} and R1 268.50 ha^{-1} cheaper when compared to mechanised pitting. A study by Hechter, et al., (2020) found that while pitting methods created pits with varying dimensions and tilth, all were effective in reestablishment and performance, although other factors such as variable pit quality, operational costs, efficiency, and ergonomics should be considered in the selection of the most appropriate pitting methods, instead of tree performance.

5.4 Planting

Planting trials included fully manual and semi-mechanised (tractor drawn) planters,

5.4.1 Semi-mechanised planting

It is important to note semi- mechanised planting used only two work elements, plant and fill. As elaborated on in Chapter 3, the aim was to standardise these measures, so as to whether it was easier to plant or move in a burnt versus mulched residue.

This study provided evidence that the move speed (m s^{-1}) and plant time (s $plant^{-1}$) in semi-mechanised planting were significantly faster on mulched eucalyptus residue as opposed to burnt residue. This suggested that the presence of incombustible material and stumps impeded the semi-mechanised planting operation on burnt sites. It was deduced that semi-mechanised planting was 27% faster on mulched residue than on burnt.

The semi mechanised planter planted 375 rows PMH^{-1} on mulched residue and 317 rows PMH^{-1} on burnt residue. The semi-mechanised planting was the fastest operation of the three (mulching, pitting and planting), yielding an average productivity of 1.70 ha·PMH^{-1} on mulched residue and 1.33 ha PMH^{-1} on the burnt residue.

According to Chapman (2015), the Anco manufactured semi-mechanised planter can plant and average of 40-50 plants a minute with six planters on burnt sites. This translates to an average of between 2 400 to 3 000 plants PMH^{-1}. Burnt sites performs below this average at 1 899 plant PMH^{-1}, whilst the purpose built the semi-mechanised seven planter used on the mulched trial performed at 2 621 plants PMH^{-1}.

The filling component in planting occurred at approximately every 50 min on mulched sites, due to the 3 000-litre tank running out of hydrogel. It took on average 29 mins to refill the planter including time taken for the reserve water tanker to drive into the compartment, lay out its pipes and replenishing the seedlings holders. It was observed that the mulched site planter had to refill more often when compared working on burnt sites, due to an additional planter and increased productivity. The planting operation had almost no other limitations.

Figure 4.8 shows the proportions in percentage of time that made up the semi mechanised tactor dawn planter cycle per residue management treatment. We noticed that in all treatments, planting took the longest followed by fill and then turning. It is important to note that turn time was directly influenced to the shape and pitting direction in a compartment and not residue management.

Semi mechanised planting on mulched sites costs R576.27 ha^{-1} and R736.59 ha^{-1} on burnt sites resulting in semi-mechanised planting on mulched residue being R 160.32 ha^{-1} cheaper.

5.4.2 Manual planting

Manual planting productivity results were based on one planting team which comprises of two persons (one carrying the planting tube and hydrogel bucket doing the actual planting, and an assistant carrying the seedling tray and Suppositree™ tablets).

One would expect that manual planting on burnt sites would be faster than on mulched sites, however this was not the case. It was observed that manual planting moves speed (m s^{-1}) and plant time (s $plant^{-1}$), on pine mulched residue differed significantly in comparison to burnt reside. Manual planting on mulched sites were 33% (4.26 PPTH ha^{-1}) faster than on burnt sites. This resulted in manual planting productivity on mulched residue (0.08 ha $PPTH^{-1}$) being faster than on burnt residue (0.06 ha $PPTH^{-1}$). The increase in productivity on mulched sites suggest that unburnt material and stumps hindered the planter's mobility taking into account the equipment load as compared to a single pick in the pitting operations. However, this result is likely due the higher-than-normally large size residual biomass left in the compartment from the snow damage that failed to combust and should not be seen as representative of residue burning in general. Neither manually nor mechanised pitting significantly influenced manual planting productivity on mulched sites.

From this study we notice that a manual planter (planter and assistant) could plant 146 plants $PPTH^{-1}$ on Jessievale mulched site and in Bulwer 128 plants $PPTH^{-1}$ on mulched sites and 96 plants $PPTH^{-1}$ on burnt sites.

Unfortunately, the manual planting data on Jessievale mulched site had no burnt data to match it with, as no burnt sites were available to plant at the time of this study. The high manual planting productivity is a result of the site being established as a sawtimber regime having a lower stocking of 1111 SPHa, compared to Bulwer's pulpwood regime stocking of 1667 SPHa.

Figure 4.11 shows the proportions in percentage of time that constituted the manual planter cycle per residue management treatment. In all treatments, planting took the longest time followed by move, from Figure 4.11 it is evident that there was an increased time taken to move on burnt site (47%) as compared to (22%) mulched site. This further showed that more time was taken to move across the burnt site. As a result of the higher productivity on mulched sites, the manual planter had to refill more often than on burnt sites.

Hydrogel refilling times varied between 2.48 - 5.92 $minfill^{-1}$, depending how close the planter was to the refilling station situated within the compartment.

Applying basic wage of R112.21 per $PPTH^{-1}$ for manual planting manual planting on residue mulched cost R1 272.93 ha^{-1} and R1 697.24 ha^{-1} for residue burnt. It is approximately R424.31 ha^{-1}cheaper to manually plant on mulched residue in comparison to burnt residue.

It was found that semi-mechanised planting at 1548 SPHa on mulched sites required 0.60 PMH $ha^{-1}$and cost R576.27 ha^{-1}, semi mechanised productivity was matched by, and equates to the productivity of 21.7 manual planters costing R1 463.21 ha^{-1} on mulched sites. Burnt sites required 0.75 PMH ha^{-1}at a cost of R736.59 ha^{-1}, with 23 manual planters costing R1 941.23 ha^{-1} at 1548 SPHa. It is evident that semi-mechanised planting on mulched and burnt sites are R886.94 ha^{-1} and R 1 204.64 ha^{-1} cheaper respectively as compared to manual planting.

5.5 Plant growth assessment.

Initial pine growth at four months after establishment at Jessievale indicated that mulched sites have a positive influence on plant growth. GLD and height measurements differed significantly. It an increase of 0.2 cm in GLD and 3.1 cm in height on mulched sites when compared to burnt sites. Mulched and burnt sites had a 98% and 93% survival rate respectively. This compartment was planted approximately six months after burning, which limited the ash bed effect. The biomass index on mulched site (9.77) was higher when compared to burnt site (5.36). This observation supports Reiner et al., (2009) study, which established that mulched treatments had significantly greater mean tree height growth than the burnt treatments in 25-year-old pine plantation.

Initial eucalyptus plant growth at year one suggested that mulching did improve DBH, and survival rate while residue burning improved plant height only. It was observed that mulched sites had an increase in plant survival of 14% and DBH of 0.4 cm when compared to burnt sites. Burnt sites displayed an increase in plant height of 0.7 m compared to mulched sites.

The biomass index on mulched site (0.03) was higher when compared to burnt site (0.02). This agreed with Laclau et al., (2010), which found that burning increased mean tree height growth compared to residue removal treatment. However, increased tree height growth in the burnt harvest residue area is believed to be temporary until tree canopy closure (Dovey, 2013). A finding from Machaka, (2017) was that eucalypts tree growth on the burnt area outperformed tree growth on mulched area across the majority of parameters assessed at 12 months after planting. This is most probably due to the ash bed effect However, it is believed that as harvest residues continues to decompose, it will release more nutrients into the soil and the mulched sites might outperform tree growth on the burnt sites at the end of rotation.

5.6 Data collection methods

In this study mechanised pitting and semi-mechanised planting time studies were done on eucalyptus mulched residue treatments. These were supplemented with burnt residue site data on areas where operations were not directly observed by the researcher. Tree growth data on Zululand eucalyptus was obtained from Sappi's research department as they had growth response trials at these study site. These growth response trails at Zululand was replicated at the Jessievale pine site to avoid variation.

One problem experienced was trying to match variation in residue volumes within the stand with time study observations. For this purpose, plots were laid out before mulching. This was however not entirely successful due to the strong coincidence of the mulching swath and residue windrow orientation as mentioned above.

5.7 Economics of treatments

The capital cost of the horizontal drum mulchers varied depending on brand, engine power rating of the individual mulchers and the currency exchange rate. According to Table 4.20 the mulcher with the highest capital outlay was the Prinoth Raptor 800 (640hp) costing R11 529 558. The Cat based (350hp) and Tigercat (370hp) mulchers cost R6 287 400 and R6 68700 respectively.

The Cat 586C with the FAE 300U mulching head has been discontinued by Southern Africa's Cat forestry dealer Barloworld, for this reason we make reference to Tigercat mulchers which are supported by AfrEquip South Africa.

From Table 4.20 the cost of mulching in eucalyptus residue was R5 452.14 ha^{-1}. Mechanised pitting speeds up with 4% after residue mulching, which equates to a R92.88 ha^{-1} and semi-mechanised planting speed up by 27% equates to R160.32 ha^{-1}. A total downstream saving of R253.20 ha^{-1} when residue mulching is done.

The total cost of mulching pulpwood pine residue is R6 165.14 ha^{-1}. It was found that manual pitting after mulching slows down productivity by 16% equating to R131.77. Manual planting speeds up productivity by 33% equating to R424.31 per ha. A total downstream saving of R292.54 per ha.

Mulching with the Prinoth costs R7 249.09 ha^{-1}. Mechanised pitting after mulching pine sawtimber speeds up by 24% equating to R221.36 ha^{-1}. Unfortunately, there was no productivity data on planting after burning to compare with planting after mulching.

In both pine and eucalyptus, increases in productivities in mechanised pitting, semi-mechanised planting and manual planting, except manual pitting, after mulching were seen. However, these save in cost, as pitting and planting productivity increase after mulching are not substantial enough to justify the expense of mulching.

By eliminating the no burn period, on average three months of a 72-month pulpwood eucalyptus rotation is saved equating to about 4% increase in productive land use. On a sawtimber pine rotation three months of a 240-month rotation is saved, which equates to 1.3% increase in productive land use.

If we choose to invest the cost of eucalyptus mulching per ha (R5 425.14) compounded over 6 years at 7% interest will yield a return of R8 182.19 per ha^{-1}, while investing the cost of pine mulching per ha (R6 165.14) over 20 years will return R23 857.15 ha^{-1}.

Forest managers must place a high value on the biological factors, moisture retention, biogeochemical, and fire prevention advantages of mulching for it to be justified from an economic point of view.

6 Conclusion

The main objective of this study was to assess the effects of residue mulching compared to burning of eucalyptus and pine plantations on downstream pitting and planting operations This was done by applying a productivity, and cost benefit study, and short-term growth assessment to analyse these operations in order to dismiss or justify mulching.

Although different of re-establishment methods are available, burning, though very inexpensive, is avoided because of the many disadvantages it presents, including the noticeable contribution to CO_2 emissions and long-term nutrient loss. Mechanical site preparations such as mulching are however gaining momentum. Although they are very expensive, mechanical mulching is fast and effective in re-establishment.

Both eucalyptus and pine pulpwood residue had similar mulching productivities, even if pine residue volumes exceeded that of eucalyptus residues (x2) in this study. Mulching productivity appeared not to be influenced by amount of residual biomass in the ranges experienced in this study. This is most likely due to the machine coping with the situations presented. It was noticed that it was common practice for mulcher operators to keep to a single constant speed across treatments even though biomass volumes varied. This allowed the operator to achieve an acceptable mulch quality which still needs to be classified by researchers. As in the productivity, mulching cost are also comparable between eucalyptus and pine sites. Although pine mulching is slightly more expensive this difference is directly related to machine purchase price being higher and not really any species differences. Unlike residue burning which removes 39% of the residue load, mulching reduces the amount of intact biomass between 52 - 63%.

Mechanised pitting on mulched eucalyptus sites had slightly higher productivity (4%) than burnt sites. Whereas mechanised pitting on pine sawtimber sites after mulching, had highest pitting productivity (24%) in comparison to burnt residues. Mechanised pitting after mulching had the lowest cost compared to burnt residues. Even though mechanised pitting productivity in mulched treatment was higher, productivity on burnt residues remained competitive.

The results showed that manual pitting after mulching was less productive than pitting after residue burning by 16%. Manual pitting on mulched sites was slower due to the pitter having to clear away mulch to pit directly into the soil. Manual pitting productivities could be matched to mechanised pitting productivities which was cheaper than mechanised pitting without compromising plant growth.

Semi-mechanised planting was the fastest operation. Semi-mechanised planting after mulching speeds up productivity by approximately 27% compared to planting in burnt residue. With high productivity, semi-mechanised planting also had the lowest cost. Just as in semi-mechanised planting, manual plant on mulched residue increased productivity by 33%. Unlike in pitting where semi-mechanised planting productivity was matched by manual planting productivity; semi-mechanised planting was still the cheapest.

From initial plant growth results, mulching helps improve survival rate, ground line diameter in pine, DBH in eucalyptus and height when compared to residue burning sites. It is noted from calculated the biomass index that residue mulching does increase productivity of a site. Mulching increased survival rate by 17% on eucalyptus sandy soils sites than on burnt residue.

This study successfully showed that residue mulching increases downstream operations productivity with regards to reestablishment as compared to residue burning. However, from an operational perspective these increases in productivities are not significant enough to offset the high cost associated with mulching. When considering mulching foresters should use a holistic approach assessing biological advantages, soil nutrients benefit as well as long term growth and yield gains, in addition to the increase in productivity of pitting and planting after mulching.

7 Recommendations for future research

Further research studies should, investigate other and alternative technologies to manage residue. These could include chopper-rollers,

Simulating the influence of mulching on reducing temporary un-planted (TU) areas

Development a mulching quality classification system, showing a scale of quality to cost ratio.

For further studies it is important that that variations in initial biomass volumes should be mapped an accurate spatial scale and allocated to plots and treatments before the study.

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