



The quantification of *Pinus patula* recovery and productivity of manually orientated biomass collection in post mechanised full tree and semi mechanised tree length harvesting operations

By

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DECLARATION:

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

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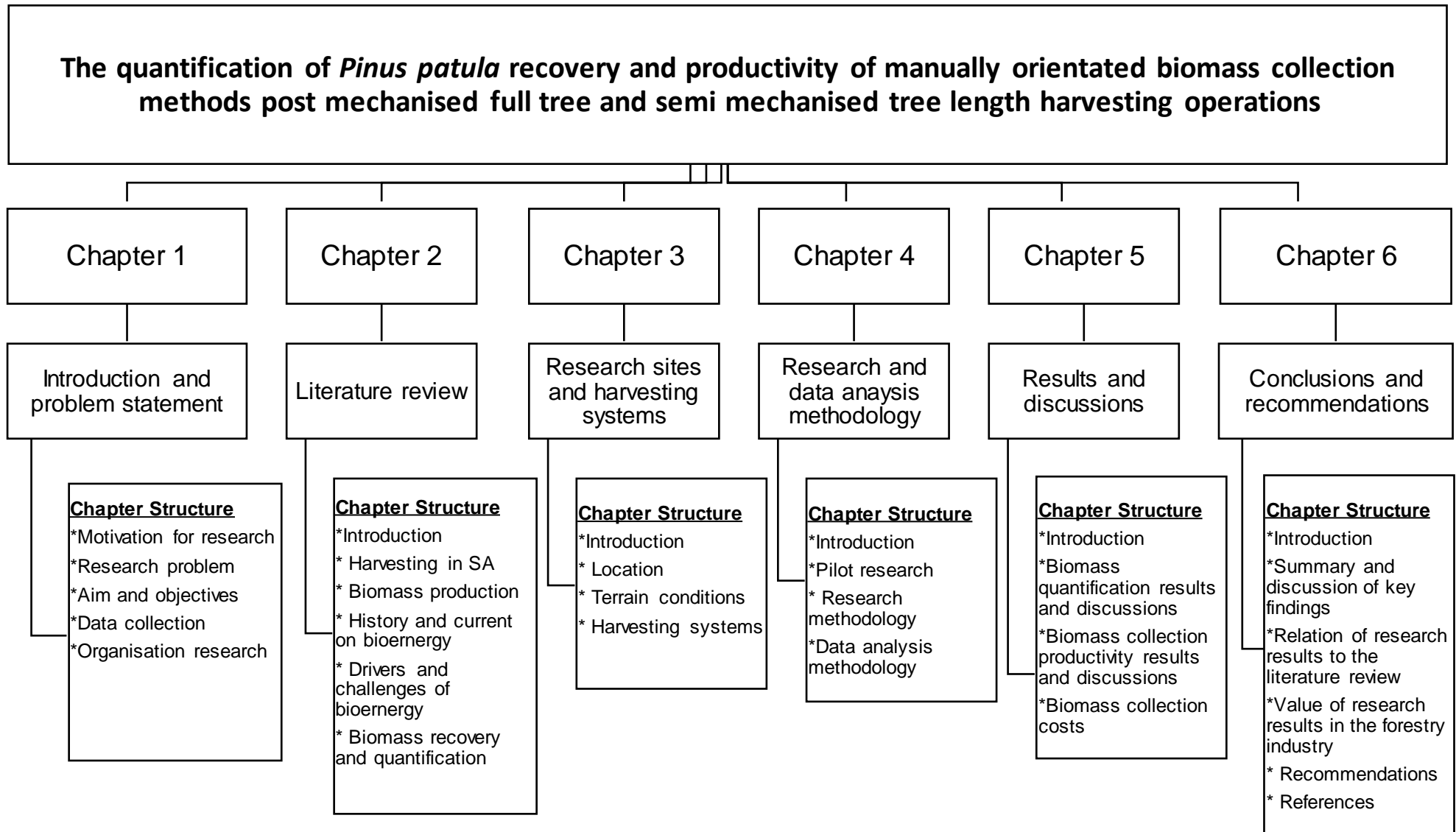
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LIST OF ABBREVIATIONS

1. CTL	-	Cut-to-length
2. FT	-	Full tree
3. TL	-	Tree length
4. DBH	-	Diameter at breast height
5. HGT	-	Height
6. Ha	-	Hectares
7. m ³	-	Cubic metres
8. m	-	Metres
9. H	-	Hours
10.T	-	Tonnes
11.ZAR	-	Rands
12.MC	-	Moisture content
13.ODT	-	Oven dry tons
14.GHG	-	Greenhouse gases

THESIS AT A GLANCE



ABSTRACT

The use of biomass as an alternate source of energy has grown in popularity. Different types of biomass are obtained from a variety of sources including natural forests, forestry plantations and agriculture residues. However, forestry residues have been identified as the most promising source, due to the wide variety of plant products including leaves, twigs, branches, merchantable stem, stumps and roots. The main sources of plantation forest biomass are residues from thinning, clearfell and conventional products such as pulpwood and sawn timber operations. These residues can accumulate between 4.3 to 9.4 billion tonnes annually around the world. The biomass availability in plantation forests has led to the development of different harvesting systems to help collect the products from infield to sawmill. Biomass harvesting has mainly been achieved through mechanised systems because of their high yields. However, the use of manual systems has been neglected due to technical limitations and financial viability. Thus, in South Africa, there is no scientific research looking at manual systems of collecting biomass from plantations. Because of this, different forestry stakeholders, including small growers and contractors using manual systems for biomass harvesting have limited knowledge regarding what to expect in terms of recoverable amounts, productivity and cost.

This research examines the productivity of the manual biomass collection and the quantification of recovered and unrecovered residues after mechanised full tree (FT) and semi mechanised tree length (TL) harvesting operations in *Pinus patula* compartments. A total number of 8 plots with +/-200 standing trees were marked in each system. The diameter and height of all marked trees were measured to determine tree volume. Moreover, the quantification of recoverable woody biomass was determined, where after, a residues assessment method using plots and line transects was used to determine the amount of unrecovered residues. The time taken for each operation including motor manual processing, manual extraction, and manual loading was assessed to determine the productivity (hours per ha and oven dry tons).

In the FT system, the results showed that the mean standing volume and log recovery was 91.5 m³/ha and 73.6 m³/ha respectively. In this system, the woody biomass recovered after conventional harvesting was 5.2 odt/ha. The productivity results revealed that motor-manual processing took 2.7 h/ha, manual extraction 9.9 h/ha and

manual loading 5.6 h/ha. Manual extraction was the least productive operation as it took 2 h/odt whilst motor manual processing and manual loading took 0.6 h/odt and 1.1 h/odt respectively. A breakdown of each operation's elements showed that in (i) motor manual processing, crosscutting (33%) and chainsaw inspection (2%); (ii) manual extraction, carrying (34 %) and stacking the logs (11%); (iii) manual loading, handing over logs (54%) and standing (5%) accounted for the most and least times per operation respectively.

For the TL system, the results revealed that the mean standing tree volume and log volume was 61.5 m³/ha and 50.2 m³/ha, respectively. In this system, the woody biomass recovered after conventional harvesting was 9.1 odt/ha. The productivity results revealed that motor-manual processing took 7.2 h/ha, manual extraction 23.8 h/ha and manual loading 9.9 h/ha. Manual extraction was the least productive operation as it took 2.8 h/odt whilst motor manual processing and manual loading took 0.8 h/odt and 1.1 h/odt respectively. A breakdown of each operation's elements showed that in (i) motor manual processing, crosscutting (33%) and refuelling (3%); (ii) manual extraction, log pickup (27%) and stacking the logs (23%); (iii) manual loading (the breakdown components was conducted only in the FT system).

For the unrecovered residues, the results showed that the FT system yielded 17.1 odt/ha whilst the TL system produced 12.7 odt/ha. The stemwood and branches were the largest parts remaining after harvest in both systems. The TL system had more woody biomass left on site while FT had less woody biomass left on site after harvesting. The TL harvesting system costed more in both ZAR/ha (827.9) and ZAR/ODT (95.9) whilst FT system costed less in both ZAR/ha (378.3) and ZAR/ODT (75.6).

The quantification of woody biomass recovery, manual collection productivity and cost estimates provided in this research will serve as important baseline information for forestry companies and contractors involved in this field. Furthermore, the accuracy of decision making will be improved when identifying and choosing manually oriented biomass harvesting systems and methods to enhance operational management and control.

Key words: woody biomass recovered, unrecovered residues, productivity, FT and TL harvesting system

DEFINITION OF TERMS

Key words and concepts used in the study are defined below to ensure that the interpretation and understanding of concepts in the text are clear.

- **Biomass residue:** includes both the above and below-ground components such as leaves, twigs, branches, merchantable stem, stump, and roots (Vasco and Costa 2009)
- **Bioenergy:** it is a form of renewable energy that is derived from living organic materials such as biomass, which can be used to produce transportation fuels, heat, electricity, and products (Hoffmann 2016)
- **Recoverable residues:** woody biomass that is recovered from merchantable timber (Spinelli, et al. 2019)
- **Unrecovered residues:** remaining residues including branches, needles and cones (Ghaffariyan, et al. 2017)
- **Harvesting system:** are tools, equipment and machines used to harvest an area (Längin, et al. 2010b)
- **Harvesting method:** the form in which trees are felled and extracted to the roadside for further processing (Längin, et al. 2010b)

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CHAPTER 1: INTRODUCTION AND PROBLEM STATEMENT

1.1 INTRODUCTION

The rationale for the study is presented at the beginning of the introductory chapter, which also covers the description of the study problem. This is followed by a summary of the research objectives and the significance. The organisation of the research is followed by a summary of the dissertation overall structure.

1.2 MOTIVATION FOR THE RESEARCH

Globally, biomass contributed about 17.7% of the total energy consumption in 2017 (World Bioenergy Association 2019). Biomass covers a broad range of different products which are of organic origin including forestry and agricultural residues (IEA 2009). These products can be utilised as a source of energy for electricity generation, heat production, and biofuel production. About 38-45% of biomass fuel is predicted to originate from agricultural waste, with the remaining supply coming from energy crops, forestry and residues products (Nanda 2020). Biomass fuel can be converted into secondary energy sources very efficiently (Preto 2011). Thus, bioenergy has emerged as the most widely used renewable energy source in various countries across the globe (McKendry 2002). These includes countries such as Brazil (39%), France (26%), and Denmark (22%) which have the highest biomass usage (Taylor, et al. 2015). The use of biomass fuel has reduced the use of fossil fuels and greenhouse gas emissions (GHG) improving global energy security. McKendry (2002) mentions that future studies will focus on identifying the suitable biomass species with higher energy outputs to substitute the usage of fossil fuel energy sources. To lower the cost of energy production, the species needed must have minimal energy inputs, uncontaminated material, and low nutrient requirements (IEA 2009).

Forest plantations are mainly grown to supply raw material for primary production purposes (e.g., sawtimber, pulpwood, and paper) and other uses such as fuel. The utilisation of forest residues is directly linked to timber harvesting. Hence, the collection of forest residue depending on the waste or by-product availability after the primary roundwood product has been produced (Vasco and Costa 2009). Rockwood, et al. (2004) added that forest residues are not only the preferred source of forest biomass energy, but short rotation timber also contributes to renewable energy production. It is estimated that by 2050 bioenergy usage will provide 30% of the world's energy

demand depending on land areas, yields, and recoverable biomass percentages (Guo, et al. 2015).

The future limitations on fossil fuel supply has strengthened the importance of developing sustainable sources of renewable energy (FAO 2018, National Research Council 2010). Wood biomass is a preferred source due to the potential income generation, improving access to forest areas, and reducing fire hazards (FAO 2018). The utilisation of forestry and agriculture residues not only has the potential to generate energy but also to generate employment opportunities (IEA 2009). Across various countries and regions, the use of bioenergy is encouraged by drivers such as improved energy security, environmental benefits, economic development (e.g. employment) and population growth (FAO 2018, Klass 1998). Employment opportunities produced by biomass operations will have a positive effect on economic activity especially in rural areas where forestry is prominent (IEA 2009).

In South Africa the main fossil fuel dominant source of energy is coal (Kohler 2014). Significant energy challenges have existed for the past 20 years, including unplanned power outages, power shortages, persistent underinvestment in energy infrastructure, energy poverty in low-income households, and high energy costs (Inglesi-Lotz and Pouris 2012, Pollet, et al. 2015). Pollet, et al. (2015) adds that 65% of the population is without power supply in Africa. Due to the global oil crisis in 1974, prices for fossil fuels such as coal and uranium increased, while those for power in South Africa remained comparatively low and constant (Kohler 2014). The relative change in electricity prices prompted South Africa to invest in alternative energy sources such as diesel and oil-fire generators. Eskom has exploited government benefits and interventions over the past 20 years by offering unmatched incentives such long-term coal purchasing contracts at fixed rates, free forward exchange cover from government organisations, and long-term tax exemptions (Tibane and Vermeulen 2014).

In the past, forest residue was recovered using manual methods. However, mechanical methods have dominated the biomass recovery operation where comminution processes occur (Cuchet, et al. 2004, Mitchell 2005). Comminution can be obtained by slash-bundling, grinding (Mitchell 2005) and chipping in the stand or by the roadside (Ghaffariyan 2010).

1.3 RESEARCH PROBLEM STATEMENT

The increasing demand for forest biomass as a bioenergy resource has encouraged the need to increase the efficiency of biomass collection methods. The lack of feasibility research and uncertainty on biomass supply system costs has restricted the participation by state owned enterprises and private entrepreneurs (Eker, et al. 2017). The collection of extracting residues is dependent on harvesting operations and how intensively the harvesting is carried out (McEwan, et al. 2020). Eker (2011) further explains that mechanised biomass collection can offer higher productivity but require higher investments, which local entrepreneurs in developing economies cannot access. When employing mechanised biomass collection, the entire harvesting system should be mechanised. Consequently, many other developing economies may suffer from the implementation of a complete system reform. In these conditions, manual biomass collection is advised and is readily practicable. Therefore, biomass recovery creates employment prospects for independent forest people in underdeveloped rural areas. Even when manual recovery is economically feasible, it certainly has technological constraints (McEwan, et al. 2020).

However, because of the uncertainty of the potential revenue, forestry companies and landowners appeared unwilling to establish the manual forest residue collection operation. (Tareen, et al. 2020). Moreover, factors such as lack of expertise, high investment costs and policies contributed to the slow uptake process (McEwan, et al. 2020). McEwan, et al. (2020) have indicated some of the harvesting machines and transport systems are used to collect biomass for energy generation. These systems include enlarge-space forwarders, compactor forwarders, bundlers and balers.

The application of manual forest residues collection from plantation forests is advantageous due to environmental quality improvement (reduces greenhouse gases by not using fossil fuels), sustaining future energy supplies and increasing economic opportunities (Zhang 2003). However, there are insufficient studies focusing on the manual biomass collection strategies. No scientific research exists regarding the quantification, productivity and costs of manual biomass collection. This research seeks to bring a better understanding of manual forest residues collection productivity and recovery after harvesting with a FT and TL harvesting system.

The following research questions can be derived from the problem statement above:

1. What is the amount of biomass available for extraction after mechanised full-tree (FT) and semi-mechanised tree length (TL) harvesting in *Pinus patula* stands?
2. What is the productivity (oven dry tons per hour) and cost (R/ODT) of various manually orientated forest residue collection methods, after mechanised FT and semi mechanised TL harvesting?
3. What are the factors affecting the productivity and costs of manually orientated residue collection after mechanised FT and semi mechanised TL harvesting?

1.4 AIMS AND OBJECTIVES OF THE RESEARCH

The following sections will discuss the aims, hypothesis and objectives of the research.

1.4.1 Aims

The research aims to quantify the woody biomass generated from a *Pinus patula* stands after mechanised FT and semi mechanised TL harvesting operations in Mpumalanga, South Africa. Furthermore, the research aims to determine the productivity and costs of the manually orientated residue collection method after the harvesting operation. Finally, the research will assess the FT and TL harvesting methods by looking at, biomass recoverability, recovery productivity and recovery cost, according to the research hypotheses listed below.

1.4.2 Research hypotheses

1. H₀: There is no significant difference in forest biomass recovery between the mechanised FT and semi-mechanised TL harvesting systems in *Pinus patula* stands.
H₁: There is a significant difference in the forest biomass recovery between the mechanised FT and semi-mechanised TL harvesting systems in *Pinus patula* stands.
2. H₀: There is no significant difference in productivity of woody biomass collection between the identified mechanised FT and semi-mechanised TL harvesting systems in *Pinus patula* stands.
H₁: There is a significant difference in productivity of woody biomass collection between the identified mechanised FT and semi-mechanised TL harvesting systems in *Pinus patula* stands.

3. H_0 : There is no significant difference in costs between the mechanised FT and semi-mechanised TL harvesting systems in *Pinus patula* stands.

H_1 : There is no significant difference in costs between the mechanised FT and semi-mechanised TL harvesting systems in *Pinus patula* stands.

1.4.3 Objectives

The following are the research goals:

- Quantifying *Pinus patula* biomass residues remaining in post FT and TL harvesting system operations. In particular, the study will determine the breakdown of total available biomass between utilisable timber, recoverable residues (woody-biomass) and unrecovered residues (branches, twigs, needles and cones) (Figure 1).
- Determining the productivity and cost of manually orientated residues collection method after a mechanised full tree (FT) and semi-mechanised tree length (TL) harvesting operation.

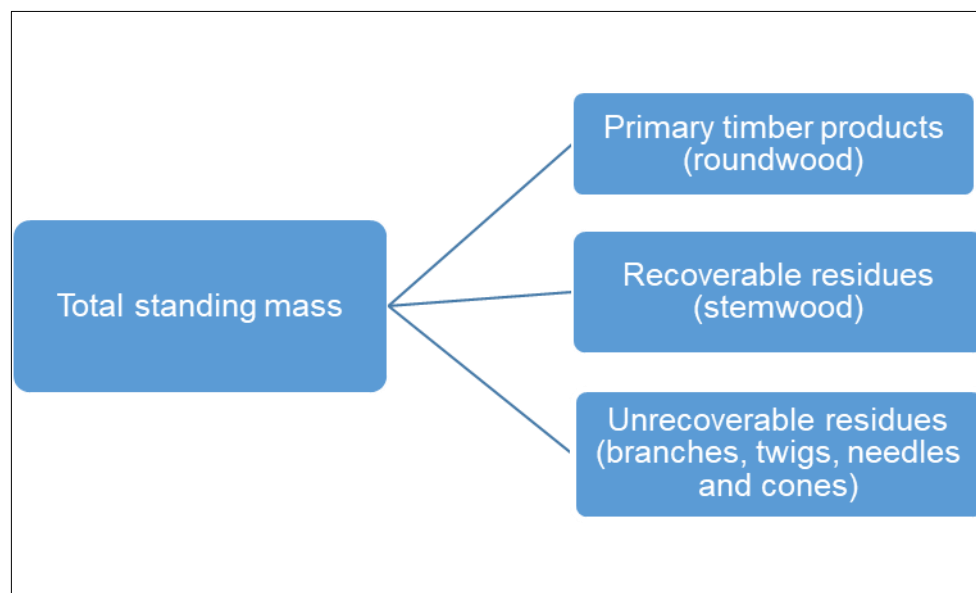


Figure 1: Breakdown of total standing mass

1.5 DATA COLLECTION

To achieve the required objectives, quantitative research was used. Between March 17 and March 20, 2020, a preliminary research visit selected the study locations and harvesting equipment. (see Chapter 4, Section 4.2 for details of pilot research). During the pilot study, the full tree and tree length harvesting systems that were in use in clear-felling operations were observed. To ensure that the selected data collection methods were appropriate and reliable for the study, a pilot study was carried out. Chapter 4 provides a comprehensive overview of the research methods.

1.5.1 Validity

Trees that were used in the research were marked and measured. The study required marking eight plots with approximately 200 trees each. Each tree in the research plot had its diameter and height measured and recorded. The diameters of each tree were measured using a tree diameter calliper at a breast height of 1.37 meters (Owen 2000). The heights of the trees were measured using a Vertex hypsometer. A tape measure was used to determine the diameter breast height of each tree measured for height. Each plot size area was measured by measuring the length and breadth of the plots in tandem with an area measuring App on a phone named the Area Measurement GPS Area Calculator.

After the harvesting operation performed in both the FT and TL harvesting systems, a time study was carried out to determine the required time to collect the woody biomass from each plot. The time study was conducted separately for each activity, namely: motor manual processing, manual extraction and manual loading. Additionally, a method for assessing harvesting residues was used to determine the weight of the unrecovered residues and to calculate the proportions of each component, such as stemwood, branches, needles, twigs, and cones (Ghaffariyan and Dupuis 2021).

Ghaffariyan, et al. (2012b) conducted a study where the unrecovered residues were categorised according to light, moderate and heavy density per area. About 50 sample points were marked to determine the proportion on each stratum. A slash calculator was then used to calculate the number of pre- and final-samples required for each stratum. A 0.68kg bucket and a handheld scale were used to weigh the unrecovered residues. Daily random readings were checked to ensure the portable scale readings

were accurate. The residues were measured in a 1 m x 1 m grid sample for each plot and recorded on the spreadsheet for the slash assessment.

Developing informed decisions and production predictions becomes difficult for foresters, contractors, or managers in the absence of any essentially valid information on the manual biomass collection process. According to predictions, South Africa will have a shortage of both electricity and jobs in the near future. (Tibane and Vermeulen 2014). Therefore, it is crucial to maximize all biomass recovery during harvesting operations in order to increase the supply of energy and improve employment prospects. Reduced unutilised timber waste from old plantations and log optimization is also necessary.

1.5.2 Reliability

The data collection method used for this study revealed good levels of reliability in the findings. The methods and equipment used to collect the data have been utilised in a number of studies in the past, and it has been determined that the outcomes would be accurate if the study were to be replicated. Moreover, previous researchers applied similar methods and equipment in other related studies (Ghaffariyan 2013, Ghaffariyan, et al. 2012b). For further descriptions, Chapter 4 contains the research methodology and data analysis details.

1.6 ORGANISATION OF THE RESEARCH

- **Chapter 1:** Introduction and research problem.

Provides a holistic view of the research topic and describes the background of the research problem. Moreover, it gives the research aims, objectives and the significance of the research.

- **Chapter 2:** Literature review

Provides comprehensive information related to the research topic. Generally, the literature focused more on explaining the value of bioenergy and the methods used to recover woody biomass during harvesting operations. It also offers information on variables influencing the efficiency of manual woody biomass collection. Moreover, drivers and barriers of the application on manual woody biomass collection are explained as they have an impact on this operation

- **Chapter 3:** Research site and harvesting systems

Focuses on the research sites, harvesting system matrix and methods used to conduct the research. In addition, terrain conditions and machine specifications information are detailed.

- **Chapter 4:** Experiment design and data analysis methodology

Explains the tools and methods applied to perform the research. The research methodology is focused on the methods used for data collecting and analysis and the study site

- **Chapter 5:** Results and discussion

Provides detailed results obtained from the research data collected from both the harvesting systems operations.

- **Chapter 6:** Conclusion and recommendations

It gives an overview of the key study findings. The significance of the research findings for the forestry industry is examined and related to the literature review.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

The information that is currently available on biomass recovery and biomass harvesting for forests is summarised in the chapter that follows. After information on the South African commercial forestry industry in the first section, a description of the *Pinus patula* species and a study of the harvesting techniques and systems follow. Thereafter, an overview of the state of bioenergy production globally and in South Africa, literature pertaining to biomass quantification is provided. The discussion concludes with information on the variables affecting the productivity of manual biomass collection.

2.1.1 Overview of commercial forestry globally

The world's total forest area was estimated to be 4 128 million ha in 1990, but due to population expansion, which increased food consumption and deforestation, this amount declined to 3 999 million ha in 2015. (MacDicken, et al. 2016). Roundwood is produced in two different forests namely indigenous forests and plantations (FAO 2018). Native forests were known to match timber demands, but this changed due to indigenous forests decreasing in size. It is predicted that plantation forests will make a significant contribution to meet future roundwood demands (Nilsson and Bull 2005). Roundwood supply is expected to increase by 46% in 2040, although the world currently has about 140 million ha planted areas for primary production purposes (Carle and Holmgren 2009). Irrespective of the available forests land, plantation forests contribute to the supply of diverse goods including timber, fibre, bioenergy, non-wood forest products, environmental services (rehabilitation of degraded lands, water, and soil protection, carbon sequestration and conservation) and social services (employment) (Carle and Holmgren 2009).

Between 1996 and 2005, more than 800 million hectares of the forests areas were destroyed by abiotic and biotic factors (FAO 2018). In this period, countries in South America and the Oceania region experienced severe losses of indigenous forests at a rate of 7 million ha per year (MacDicken, et al. 2016). According to FAO (2018), these losses can be attributed to climate change, pest and diseases, and deforestation impact.

2.1.2 Overview of commercial forestry in South Africa

In South Africa, plantation forests occupy an estimated of 1.2 million ha which is 1.2 % of the total land mass (Figure 2) (Godsmark and Oberholzer 2019).

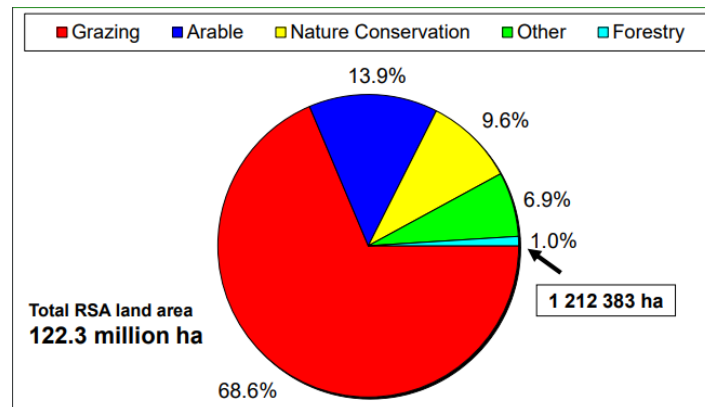


Figure 2: Land use in South Africa (Godsmark and Oberholzer 2019)

Although the plantation forests form a very small portion of the total land masses, these areas are highly productive, and growth is favourable. Plantation forestry in South Africa is supported by good practices of tree improvement and silviculture operations (Godsmark and Oberholzer 2019). These plantations are established in areas where rainfall exceeds 800 mm annually (Dlomo and Pitcher 2002). Mpumalanga province has the highest afforested area followed by KwaZulu Natal (Figure 3) (Godsmark and Oberholzer 2019).

These areas comprise of pine (50.6%), *eucalypts* (34.4%) and wattle with other species making up 15% such as poplar for match manufacturing (Godsmark and Oberholzer 2019).

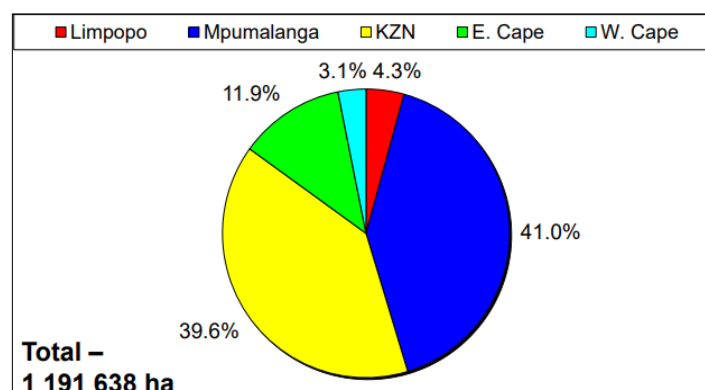


Figure 3: Plantation area of planted area by province (Godsmark and Oberholzer 2019)

The production of sawlogs (37,9%) is primarily under state-owned plantations whereas pulpwood (56,7%) plantations are privately owned (Forestry Economics Services 2019). Private timber companies - namely Sappi and Mondi - are the largest forestry landowners holding 51.4%, whereas state company (SAFCOL) owns 10.7%, with small private companies owning 14.8% and 3.8% owned by small growers (Godsmark and Oberholzer 2019). Some companies are currently FSC certified to ensure sustainable management (Forestry Economics Services 2019). Furthermore, South African plantations produce a total of 18.7 million m³ of roundwood annually (Forestry Economics Services 2019).

2.2 OVERVIEW OF *PINUS PATULA* IN SOUTH AFRICA

2.2.1 History

In 1907, *Pinus patula* was first introduced to South Africa from Mexico (Wormald 1975). Although other countries introduced *Pinus patula* early, South Africa had seed samples which were planted in 1877 because of its rapid growth and its seed accessibility from South African sources (Adams 1916, Lusweti, et al. 2011). *Pinus patula* became the preferred pine species of choice in east, central, and southern Africa (Wormald 1975).

African countries had already planted 424 000 ha of *Pinus patula* by 1970. On a commercial scale, the softwood plantations in Africa represented 50% of the global planted area while other countries including New Zealand, India, Argentina, Brazil, and Colombia established approximately 14 000 ha (Wormald 1975). Wormald (1975) further explained that between 1971 to 1972, 23% of *Pinus patula* plantations were grown for pulpwood and 77% for sawlogs. Approximately 50% of the sawlogs plantations were privately owned and the other half publicly owned, however, 70% of the pulpwood plantations were privately owned in South Africa (Wormald 1975). Today, plantation ownership is 82% private and 18% public (Godsmark and Oberholzer 2019).

2.2.2 Description of *Pinus patula*

Pinus patula is a slender tree, which grows up to 35–40 m in height with DBH up to 120 cm in diameter (Lusweti, et al. 2011). *Pinus patula* grows at altitudes between 1800 and 3000m above sea level in Mexico. It grows well in areas with high

precipitation ranging between 1000 to 2200 mm per year (Lusweti, et al. 2011, Wormald 1975). In South Africa, *Pinus patula* is the most commonly planted softwood species in the summer rainfall regions of Mpumalanga, Free State and KwaZulu Natal (Rolando and Little 2004). Although *Pinus patula* tend to be planted on sites considered highly productive (Rolando and Little 2004), it is particularly susceptible to a number of biotic (pests e.g. *Sirex noctilio*) and abiotic (chemicals) factors which increases mortality rates (Mitchell, et al. 2012).

The general biomass proportions for pines in South Africa are given as, 65% stemwood, 20% needles, 15% stump-root, 10% bark, 5% branchwood and 3% tops (Carlson and Allan 2001). *Pinus patula* like all other planted forest species is considered as a renewable source because of its ability to take up greenhouse gases (Praciak 2013).

2.3 OVERVIEW OF TIMBER HARVESTING IN SOUTH AFRICA

During the 1980s in South Africa, harvesting operations were primarily conducted using manual or semi-mechanised harvesting systems (Brink and Warkotsch 1990). Currently, the mechanisation of harvesting systems is increasing in significance due to the growing demands of timber and fibres (SA Forestry Online 2015). Harvesting system selection is dependent on economic, social and environmental conditions (Olivier 2009). These operations consist of timber harvesting, timber transport and road construction (Owen 2000). In South Africa, most timber is harvested using ground-based harvesting systems (Längin and Ackerman 2007). There is a huge emphasis on mechanisation in the South African forestry industry (Laengin, et al. 2010) due to factors such as the need to increase production, improving the working environment, safety concerns (Lindroos, et al. 2017), reduced operational costs and increasing machine efficiency (Alam, et al. 2012). These systems are utilized in clearfell and thinning operations. Harvesting comprises of various methods namely, cut-to-length (CTL), tree-length (TL) and full-tree (FT) methods (Brink and Warkotsch 1990, Längin and Ackerman 2007). Mathelele (2019) found that the CTL is the main harvesting method used for saw timber operations with 64%. Hardwood timber is harvested using CTL (41%), TL (15%) and FT (9%) methods (Laengin, et al. 2010).

The outcomes of timber harvesting operations are determined by the effectiveness of the planning, proper machine selection, quality of operations and ergonomics

(Laengin, et al. 2010). The operations are characterised by new developments and technologically advanced machines (Alam, et al. 2012). Hence, the use of mechanisation in the collection, processing and transportation of biomass is gaining momentum particularly for energy generating purposes (Ackerman, et al. 2013). Although mechanised systems are more efficient, manual biomass collection has the added benefit of fewer environmental impacts (less site disturbance) and is socially beneficial (e.g. employment) (Eker, et al. 2017, Miller, et al. 1987).

Harvesting methods and system used

Timber harvesting operations are carried out through harvesting systems and methods. A harvesting system is a collection of equipment and machinery vehicles used to harvest a stand of trees (Ngulube 2013). The systems can be categorised as being ground, cable or aerial based according to the method of extraction (McEwan, et al. 2013). Harvesting systems are established based on environmental, technological (safety and ergonomics) and socio-economic feasibility in relation to site factors (MacDonald 1999). In South Africa, systems differ from basic manual operations, motor-manual, semi-mechanised to fully mechanised operations (Längen and Ackerman 2007). Ground-based systems are preferred on accessible terrain because of the higher productivity and lower costs when compared to aerial systems and cable yarders (McEwan, et al. 2013). Ground-based harvesting is associated with site disturbance, residual stand damage and unfavourable aesthetics (Long 2003). However, the equipment and techniques in lower machine ground pressures and disturbances (Krieg, et al. 2010).

In any timber harvesting operation, various factors such as tree size (Greulich 1999), daily production requirements (MacDonald 1999), harvesting costs, terrain features and conditions (MacDonald 1999, McEwan, et al. 2013), environmental sensitivity (Horn, et al. 2007), slash handling capability, availability of equipment, and skill level of operators will influence and limit the choice of timber harvesting system to be selected (Greulich 1999).

The selection of systems for timber harvesting and forest residues collection in harvesting operations is influenced by transport requirements, system costs, and environmental implications (Kizha and Han 2015). Biomass can be collected from infield either as loose branches or as comminuted chips or chunks (Eker, et al. 2013,

Ghaffariyan, et al. 2014). Potential residues from forest harvesting includes branches, tops, offcuts (Han, et al. 2009) and unmerchantable stems (Das, et al. 2011). Different systems are available to collect and bundle loose branches such as bundlers and compactors. The comminution of biomass either with a mobile chipper (infield or roadside) or a stationary chipper at the processing plant is common practice (Eker, et al. 2013, Woo, et al. 2019).

2.4 HARVESTING SYSTEMS AND METHOD USED FOR *PINUS PATULA* IN SOUTH AFRICA

The ground-based harvesting systems practised in South Africa includes manual, motor-manual, semi-mechanised and fully mechanised. The harvesting methods include the tree length (TL), full tree (FT) and cut to length (CTL) method (Längin, et al. 2010a). These will be discussed in the following sections.

2.4.1 Harvesting systems

The harvesting system comprises of different tools and equipment applied to harvest a particular area (Längin, et al. 2010a). Harvesting systems are selected based on factors including environmental, technological and socio-economic feasibility in relation to the site conditions (Ngulube 2012). Various harvesting systems are used in South African forestry, depending on the application and market demands.

2.4.1.1 Manual system

Harvesting systems consist of basic technology focus on the use of manual labour and hand tools such as bow saws and axes to fell and optimise trees (debark, debranch and crosscut). The extraction process of the logs is performed by manual or by animal extraction (Längin, et al. 2010a). This system depends on personnel skills and requires higher capital input for equipment.

2.4.1.2 Semi mechanised

Semi-mechanised operations have been traditionally used for pine timber harvesting in South Africa (Eggers, et al. 2010). Semi mechanised systems consist of felling and processing (debranching and crosscutting) using chainsaws which is common in softwoods (Längin, et al. 2010a). Extraction is mostly conducted by cable and grapple skidders including agricultural tractors with winches (Längin and Ackerman 2007).

2.4.1.3 Mechanised harvesting

The most current system to be implemented in South Africa is the mechanised system. (Eggers, et al. 2010). All the operations including felling, processing and extraction are conducted by fully mechanical means (Krieg, et al. 2010). In CTL, the fully mechanised system employs harvesters which fell, debranch and cross-cut timber into commercial lengths at the stump site and forwarders that extract the logs to the roadside (Längin and Ackerman 2007, Längin, et al. 2010a). Whereas, in multiple stem operations, feller bunchers fell and bunch the trees, working together with grapple skidders and processors (Längin, et al. 2010a). Long (2003) indicated that although mechanisation has gained momentum in the past 25 years due to higher production figures while reducing the number of injuries, it poses a risk when it comes to site impacts (e.g., compaction).

2.4.2 Harvesting methods

A harvesting method describes systems based on the form of wood transported to the roadside (Längin, et al. 2010a).

2.4.2.1 Cut to length method

The cut to length method (CTL) comprises of felling and optimising (debranch, crosscut and topping) trees at the stump or at the landing (McEwan, et al. 2013). The mechanised CTL system, which consists of a harvester and a forwarder, is considered the most advanced harvesting and extraction system, it continues to improve as a more innovative solution when implemented (Längin, et al. 2010a). This system is advantage because it has low traffic in the compartment due to fewer machines used. The machines include forwarder since they carry large payload (Gellerstedt & Dahlin, 1999). Moreover, the logs have less soil contamination and stem breakages due to logs carried off the ground. The CTL method is referred to as the most environmentally friendly, versatile and safe method that provides end products of higher quality and consistency (Nurminen, et al. 2006).

2.4.2.2 Tree length method

The tree length method (TL) is the second most commonly used method in South Africa (Mathelele 2019). In the tree length methods, felling, debranching and topping are carried out at the stump site, where the stem is extracted to the roadside for

optimisation (Längin, et al. 2006, McEwan, et al. 2013, Pulkki 1997). The semi mechanised TL method usually combines motor manual felling and extraction with a cable or grapple skidder (Längin, et al. 2010a). Although the TL method has a higher timber contamination with stem breakages because of logs dragged on the ground. The remaining tops provide collectable residues after harvesting (Spinelli, et al. 2009).

2.4.2.3 Full tree method

The full tree method (FT) involves felling trees either by motor manual or mechanical means. All above-ground biomass (branches and tops) are extracted to the roadside by a grapple skidder (Eggers, et al. 2010, Längin, et al. 2010a). Therefore, large volumes of forest residues are accumulated at the landing area (Krieg, et al. 2010). Moreover, remaining residues infield during harvesting (breakage during dragging) may increase the availability of forest biomass (Warkotsch 1988, Zamora-Cristales and Sessions 2016). The residues at the roadside can be used as material for energy generation and creating extra income (Pierre, et al. 2013). However, the biomass accumulated at the landing poses environmental challenges to the harvested stand such as soil exposure and the reduction of soil nutrient values (soil exposed reducing nutrients) (Zamora-Cristales and Sessions 2016).

2.5 OVERVIEW OF BIOMASS

Organic material derived from plants and animals is known as biomass (Houghton, et al. 2009). In the specific case of trees, biomass includes both the above and below-ground components such as leaves, twigs, branches, merchantable stem, stump, and roots (Vasco and Costa 2009). Biomass covers a wide variety of different products that are used as a source of energy, either for power, heat production, and as a feedstock for biofuel production (Skrifvars, et al. 1996). These products include wood from natural forests, forestry plantations, forestry residues, and agricultural residues (Bain, et al. 2003). Around the world, biomass from forestry and agricultural crops may produce between 4.3 billion and 9.4 billion tonnes (high estimate) for energy annually (World Bioenergy Association 2019). The size of the forestland and the potential for producing other forest products like wood fuel are significant factors affecting the amount of biomass generated (World Bioenergy Association 2019). Plantations supply biomass in the form of forestry residues, damaged stands (by insects, diseases or fire) and deadwood (Bain, et al. 2003).

Forestry residues (Figure 4) are produced by operations such as thinning, clear-felling, and extraction of trees when conventional products such as pulpwood and sawn timber are optimised. When thinning operations occur, tops and branches usable for biomass energy are produced (Bain, et al. 2003). Standard harvesting operations remove 25% to 50% of the timber volume, leaving residues available as biomass for energy production (Bain, et al. 2003).



Figure 4: Forestry residues after clear-felling operation (Elbein 2019)

Biomass can be scarce and costly unless produced sustainably (Becker 2001). If biomass is recovered unsustainably, it could result in significant negative environmental and socio-economic impacts such as greenhouse emissions, loss of biodiversity, land use degradation, and low water availability. Additionally, biomass fuels typically do not compare favourably to fossil fuels on an economic basis since they are less dense, have lower energy contents, and are harder to manage (Preto 2011).

2.6 BIOMASS PRODUCTION FOR ENERGY

In the next century, biomass has the potential to become the worldwide primary energy source. (Berndes, et al. 2003). Bioenergy is categorised into traditional biomass and modern bioenergy, based on the efficiency and sustainability in production and use. Modernised bioenergy systems will play a critical role in the development of sustainable energy sources and sustainable economies in developed and developing countries (Berndes, et al. 2003).

Due to climate change, the sustainable supply of energy has become an important global challenge that requires urgent intervention (Lynd, et al. 2015). There is an

opportunity to expand the use of biomass to supply future energy demands in a sustainable manner (Lynd, et al. 2015) by using natural resources and reducing waste in plantations. The reliable supplies and the high cost of biomass resources are some of the main barriers to bioenergy developments on a global scale (McKendry 2002). In 2005, the contribution of forestry residues and wood supply was estimated at 163 million m³ per year. Thus, it was expected to have a negative impact on timber supply to the forestry industry globally (Nilsson and Bull 2005).

The expansion of bioenergy requires high capital investment. Challenges such as uncertainties of biomass availability, quality, procurement costs and lack of information on historical performance hinders investments into the industry (McKendry 2002). However, various industries have been finding innovative ways to improve recovery and efficiency of bioenergy systems (Glance 2014). The method of energy conversion and the necessary energy form mostly define the type of biomass that is needed (Berndes, et al. 2003). Power produced from wind turbines, solar panels, geothermal plants, biomass, and hydropower plants is referred to as renewable energy (Figure 5) (Tareen, et al. 2020). Thus, biomass is directly converted into energy by burning or gasification. Burning biomass fuels like wood produces power or local heating for residences and workplaces (Brito-Cruz, et al. 2015).

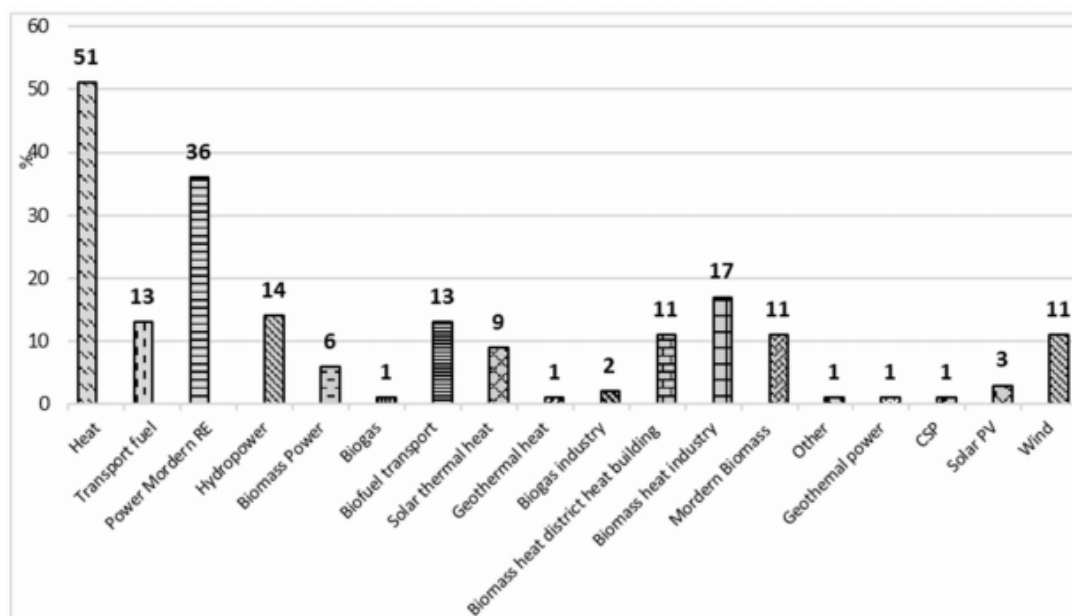


Figure 5: Different forms of renewable energy sources with the consumption rate globally (Tareen, et al. 2020).

2.6.1 Traditional bioenergy

Traditional biomass is the common energy source in various developing countries because it is inexpensive, and does not require processing before use (Goldemberg and Coelho 2004). Characteristics of traditional bioenergy use is dependent on the energy source either firewood, charcoal, agricultural residues or dung for cooking, drying and or charcoal production (Karekezi, et al. 2004). According to Karekezi, et al. (2004), in Africa 73% of the population relies on bioenergy for household use, hence the rule states, the poorer the country, the greater the reliance on traditional biomass resources. Hoffmann (2016) reported that 2 million tonnes of biomass fuel is consumed for cooking purposes daily and 4.1 million tonnes per day are used as fuel globally. Traditional biomass is produced in an unsustainable manner, which results in deforestation on both a small-scale home level and a large-scale industrial level (Goldemberg and Coelho 2004, Woods, et al. 2015).

Moreover, it has a direct negative impact on society of which, women and children are the most vulnerable group and suffer serious indoor air pollution impacts (Shukla 1997). In addition, traditional bioenergy remains the major provider to energy supply in developing countries, where it meets most of the needs of households. Cleaner cooking stoves and fuels made from biomass are potential improvements in human health and environmental effects. These have some success (Sagar and Kartha 2007). Although traditional bioenergy is associated with challenges, it provides vital energy services in the day to day lives of developing countries (Woods, et al. 2015).

2.6.2 Modern bioenergy

Modern bioenergy is referred to as the source of electricity as well as liquid and gaseous fuels (like ethanol and methanol) (Thrän 2015). The use of modern bioenergy has the potential of providing cleaner, more efficient energy services (heat and power generation) to support local developments, promote environmental protections and improved domestic fuel usage (Karekezi, et al. 2004). Not only will it be an energy supplier, but modern bioenergy is a very important attraction for developing countries faced with high unemployment rates (Woods, et al. 2015).

On the other hand, several challenges can pose a threat on implementing modern biomass resources including, the practice of high input mono cropping (loss of

biodiversity), land degradation (use of fertilizers) and increasing competition for land between food production and biomass resources (Goldemberg and Coelho 2004). Karekezi, et al. (2004) illustrates that one of the main challenges of using modern biomass is the competing costs and reliability when compared to conventional fossil fuels on both transportation and electricity supply. However, it was fully proven that modern large scale biomass energy systems on both economic and technical ground will be implemented.

2.7 BRIEF HISTORY AND CURRENT STATUS OF BIOENERGY

More than half of the world's use of renewable energy comes from bioenergy, which accounts for three-quarters of all such usage. In 2015, the usage of bioenergy made up 1.9% of the world's power production and 10% of all final energy consumption (IRENA). In 1994 bioenergy represented a large potential of the available energy which was under-utilised. The energy from forestry residues could provide 7% of the world's energy needs. The energy content of forestry residues could provide 7% of the world's energy (Hall and Rosillo-Calle 1999). Hall and Rosillo-Calle (1999) claim that the lack of expansion was not because of the low availability of biomass but concerns about management, sustainability and acceptable cost.

The potential of bioenergy to produce energy sources including electricity, gases, and transportation fuels has grown, while maintaining the ability to use biomass for its traditional use (Hall and Rosillo-Calle 1999). In 2012, bioenergy and traditional bioenergy represented 10.1% and 5.7% of the total energy demand globally, respectively (Brito-Cruz, et al. 2015).

High growth in modern and sustainable bioenergy is more concentrated in developed countries such as China, USA and Sweden (Brito-Cruz, et al. 2015). Perea-Moreno, et al. (2019) specified that 67.3% of the world's electricity was produced by the combustion of fuels in 2018 whilst Tareen, et al. (2020) stated that bioenergy provided 10% of the world primary energy supply. Three regions including Africa, The Caribbean and Asia are developing affordable and reliable sources of electricity generation in order to reduce climate change effects, and provide renewal techniques (Tareen, et al. 2020). Therefore, the renewable industries are constantly improving to modernise in order to increase the dependability of the current facilities.

In 2001, Fischer and Schrattenholzer predicted that bioenergy would play a vital role in the future global energy systems, but that the rapid bioenergy developments could exacerbate challenges rather than becoming a viable a solution, if not developed sustainably. According to Perea-Moreno, et al. (2019), it is expected that by 2040 bioenergy will provide the world's energy demand (Figure 6).

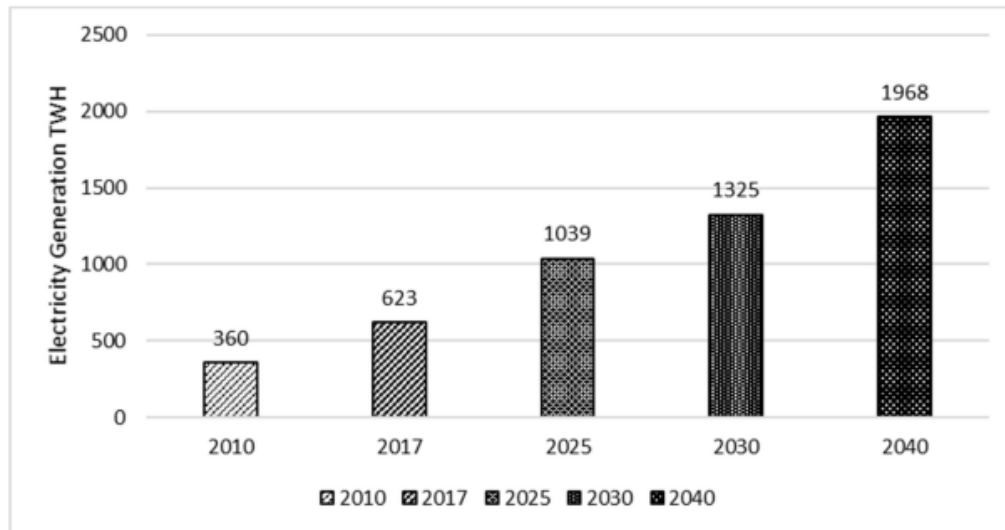


Figure 6: Bioenergy for electricity generation worldwide (Tareen, et al. 2020).

By 2020, 20% of energy will be produced from renewable sources, including bioenergy, according to the European Union (EU). In 2010, biomass accounted for over 64% of Europe's renewable energy sources, although only accounting for 8.2% of the EU's 27 member states' total energy consumption (Woo, et al. 2019).

In South Africa, the primary energy resource is coal. The world's electrical production uses 36% of the entire amount of fuel consumed as coal (Tibane and Vermeulen 2014). The Department of Energy identified alternative sources to promote the use of renewable energy in South Africa. The White Paper on Renewable Energy had targeted 10 000 Gigawatts hours (GWh) of energy to be produced from biomass by 2013. However, the lack of improvement and implementation of renewable energy sources has hindered bioenergy production (Tibane and Vermeulen 2014). In 2016, renewable electricity contributed 3.1% of the total electricity production in South Africa. Only 0.1% was produced from biomass sources with wind and solar collectively representing 2.7% of the electricity production (World Bioenergy Association 2019).

2.8 CHARACTERISTICS OF BIOMASS PRODUCTION

The method of conversion and the form in which the energy is needed define the kind of biomass to use for energy production (McKendry 2002). The chemical and physical properties of biomass are influenced by the value of the biomass (Preto 2011). These characteristics include high production of dry matter per ha, low energy input, low costs, low contamination, and low nutrient requirements. One important factor is identifying suitable biomass species, which can produce high energy outputs and substitute conventional fossil fuels (Kauriinoja and Huuhtanen 2010).

Biomass material properties differ depending on the type of biomass, such as harvesting residues (wood, bark, and residues) (Table 1). The following properties are crucial to be taken into consideration (Kauriinoja and Huuhtanen 2010):

- Moisture content
- Calorific value
- Proportions of fixed carbon and volatiles
- Ash/residue content
- Alkali metal content
- Cellulose/lignin ratio
- Carbohydrate/sugar content
- Lipid/fat content
- Protein content
- PH

While the first and last features are of primary significance for wet biomass conversion processes, the first five properties are of interest for dry biomass conversion processes.

Table 1: Average properties of wood, bark and leaves (Pierre, et al. 2013)

Property	Wood	Bark	Leaves
Basic density [kg/m ³]	Acacia: 300-600 Euc.: 350-550 Pine: 250-550	Acacia: 350-450 Euc.: 250-300 Pine: 260-300	
Ash [%]	Acacia: 0.5-1.5 Euc.: 0.8-1.2 Pine: 0.8-1.2	Acacia: 2.5-3.9 Euc.: 3.5-4.4 Pine: 2.5-4.9	Euc.: 3.5-5.5
Volatile matter [%]	Acacia: > 90 Euc.: >85 Pine: > 86	Acacia: 80-85 Euc.: 85-87 Pine: 82-87	Euc.: 83-86
CV [MJ/kg]	Acacia: 19.6-19.9 Euc.: 19.7-20.1 Pine: 19.7-20.5	Acacia: 19.1-20.1 Euc.: 17.8-19.5 Pine: 19.5-20.5	Euc.: 19.5-20.2

2.9 DRIVERS AND CHALLENGES OF BIOENERGY IN SOUTH AFRICA

South Africa is currently experiencing a major problem in electricity generation on a national scale. Eskom, the entrusted company to supply electricity, has over the years been predominantly generating power through burning coal (Arndt, et al. 2019).

2.9.1 Challenges of bioenergy in South Africa

Bioenergy is connected and related to emissions into the environment through their development processes as conventional fuels. Trees absorb carbon dioxide that is emitted into the environment reducing greenhouse gases.

Tareen, et al. (2020) compiled a list of challenges South Africa is experiencing regarding the expansion of bioenergy:

- Policymaking (ownership models, operation risk management, cost analysis of resources and cash flow)
- Production-based incentives (protection against political risk, reduce import duties on the facility, guaranteed purchase of all available renewable the energy)
- Lack of access to the local renewable resource
- Marketing (categories different zones to ensure biomass availability)
- Access to finance (monetary incentive, mandatory use of renewable projects in the public, trade effectiveness, competitive tariffs) (Arndt, et al. 2019)

2.9.2 Drivers of bioenergy

The vision and long-term objectives of the renewable energy roadmap must be developed, and a crucial step is to determine the drivers for establishing bioenergy technologies. The factors and their respective relevance for implementing bioenergy differs significantly among nations (Tareen, et al. 2020). In South Africa, there are three main groups of bioenergy drivers (Landolina and Maltsoğlu 2017):

- Economic development and employment (create jobs, increase energy access)
- Energy security (diversify energy supply mix)
- Reduction of pollution and greenhouse gas emissions (improve air quality and mitigate environmental pollution).

The collection of forest residues has represented the most common strategy to match the new market demands for renewable energy generation (Spinelli, et al. 2019). Biomass components are obtained from lower value or non-merchantable stand components (Ghaffariyan, et al. 2012a, Ghaffariyan, et al. 2017, Spinelli, et al. 2019, Tolosana, et al. 2014). According to Wolf, et al. (2014), several positive factors on residue recovery includes:

- Increasing revenue
- Increase accessibility for site preparation
- Reduce the risk of insect and fire outbreaks

2.10 BIOMASS RECOVERY AND QUANTIFICATION

This section provides an existing literature on biomass recovery and quantification as well as the derivation of productivity.

2.10.1 Biomass quantification

Quantification of biomass is essential for process optimisation (Giebner, et al. 2015). The systems for collecting and processing of logging residues are based on information on quantity and quality. Biomass can be established using direct or indirect sampling methods (Karpachev, et al. 2017). In direct method, the actual residues in the quadrants are measured, weighed, or estimated. The foundation of indirect method is the development of a relationship between the tree weight and the parameters, such

as the height and diameter of the trunk, that are then measured (Bonham 2013). Geographic information systems (GIS), remote sensing, and yield growth models are preferred for biomass estimation at the state and national levels (Karpachev, et al. 2017). The use of remote sensing is important because of the continuous and repetitive digital data input from the same area with different spatial resolutions. The system covers a large area, reducing time and financial costs (Woo, et al. 2019).

The types of vegetation, observer abilities, sample size requirements, time and budgetary constraints, as well as other factors, define the most effective approach to calculate biomass in an inventory or monitoring program (Ghaffariyan 2013, Ghaffariyan, et al. 2017). Forest residues are parts of felled trees which usually remain on the forest site when conventional harvesting occurs (Ghaffariyan 2013, Ghaffariyan, et al. 2017). The rate of removal varies among forests depending on the end product and cost effectiveness of harvesting (Eker and Spinelli 2018). One of the main principles of sustainable forest management is to maintain ecosystem services in the forest biomes (Kizha and Han 2015). An estimation of the potential forest residues available is important when planning the biomass supply chain, assessing financial viability, calculating potential revenue, and determining the possible energy production (Woo, et al. 2019).

Residues can remain infield or broadcasted on the site for soil fertilisation and the protection of biodiversity (Ranius, et al. 2018). Biomass recovery is determined by the type of forests operations (clear-fell or thinning), and the profitability of removing the biomass (Ghaffariyan, et al. 2011). The quantification of the available harvesting residues are influenced by the annual roundwood production rate, rate of felling extraction, and percentage of residues that are already used (Hoyne and Thomas 2001).

2.10.2 Biomass extraction (manual and mechanised)

The collection of forestry residues from sustainable forest operations are recoverable as a source of biomass fuel for renewable energy generation (Eker, et al. 2017, Ghaffariyan 2013). Conventional harvesting focuses on extracting timber efficiently and cost-effectively (Eker, et al. 2017, Ghaffariyan 2013, Laengin, et al. 2010). However, residues are considered a by-product (Zamora-Cristales and Sessions 2016) of commercial roundwood production (Ackerman, et al. 2013). Forest residues

are produced through harvesting operations such as reduction thinning, salvage logging, and pre-commercial thinning. About 75% of harvestable residues are from clear-fell operations and 45% from thinning operations (Baker, et al. 2010). Biomass extraction, processing, and transportation are major challenges which can directly affect the economic viability of residue utilisation operations (Spinelli, et al. 2019).

Zamora-Cristales and Sessions (2016) state that residues can typically be used to produce sustainable energy if desired. During the harvesting process, a significant amount of residue that does not reach the landing, which could increase the availability of forest biomass. Thus, collection costs, which are a function of the distance from infield to landing method used, have an impact on the amount of recoverable residues (Zamora-Cristales and Sessions 2016), terrain conditions, collection methods, and system productivity (Webb, et al. 2008). Webb, et al. (2008) emphasised that the further the distance collection, the higher the biomass cost will be. Thus, equipment balancing is important to avoid affecting the productivity of the whole collection operation (Webb, et al. 2008).

Forest residues can be harvested with timber in a two-pass (non-integrated) or a one-pass, integrated system (Ackerman, et al. 2013). In the one-pass system, round wood and residues are harvested simultaneously and forwarded to the primary landing at the same time (Ackerman, et al. 2013, Miller, et al. 1987). This system is considered the most cost-effective biomass collection method when using equipment such as feller-bunchers and skidders (Miller, et al. 1987). This is due to slash accumulating at the landing sites (Webb, et al. 2008), as they harvest all products in a single operation (Stokes, et al. 1985) while avoiding the addition of other machines (Miller, et al. 1987). The one-pass system simplifies the residue collection process, but the residues usually have a higher moisture content. Thus, biomass is often broadcasted back to the site in order to clear space (Ackerman, et al. 2013). However, a two-pass approach is preferable due to factors such as the importance of drying biomass in the forest (Webb, et al. 2008).

The two-pass system recovers roundwood and biomass separately (Figure 7) (Stokes, et al. 1985). The biomass is piled next to the landing sites for later collection when the timber is extracted. Miller, et al. (1987) reported that this system is less popular and has not proven to be as cost-effective as the one-pass system. Although the two-pass

system can place the operators at a disadvantage, it provides opportunities for smaller, specialized biomass harvesting contractors to operate if timber harvesting contractors do not utilise the biomass (Miller, et al. 1987). Furthermore, it allows residues to dry before collection and ensures a better distribution of the remaining residues (Ackerman, et al. 2013).



Figure 7: A loaded forwarder traveling to the landing with residues (Zamora-Cristales and Sessions 2016).

Ranius, et al. (2018) mentions that whenever residues are broadcasted infield, soil productivity increases. Forest residues remain in the ground and then supply the soil with vital nutrients. These systems will not eliminate nutrients but will certainly reduce it (Ranius, et al. 2018). The collection of forest residues from poor sites should be avoided in all cases because this would aggravate the availability of the nutrients (Ghaffariyan 2010).

2.10.3 Different methods used for biomass quantification

In order to predict the biomass supply and possible revenue production, practical biomass planning requires a quantitative estimate of the amount of collecting residue that is accessible (Wells, et al. 2016). In biomass pre-feasibility research, a number of collecting residue quantification techniques have been investigated and deployed (Carrasco-Diaz, et al. 2019). The following methods have been used with various kinds of forests (Lu 2006, Shi and Liu 2017):

- Allometric equation
- Mean biomass density

- Biomass expansion factor
- Geostatistics
- Remote sensing

2.10.4 Advantages and disadvantages of methods used for biomass quantification

The advantage and disadvantage of biomass quantification (Table 2).

Table 2: Advantages and disadvantages of biomass quantification methods (Shi and Liu 2017).

Method	Disadvantages	Advantages	Improvement practices
Allometric equation	Varying frequently with species, terrain, temperature, and rainfall. Less sampling trees	Can be reused by others and make comparable.	Incorporating these factors into allometric coefficients; combine with LIDAR
Mean biomass density	Easily leading to an overestimation	It produces biomass estimates without having to make volume estimates	Randomly set more plots
Biomass expansion factor	Varying frequently with species, terrain, temperature, and rainfall	Biomass factors are easier to use than biomass equations	Incorporating these into conversion factor
Remote sensing	Saturation and reflectance of surface features	More accurate and less time consuming	Higher spatiotemporal resolution, advanced algorithm and technology
Geostatistics	More field data	More accurate and less time consuming	Constructing the biomass database

2.11 FACTORS INFLUENCING BIOMASS RECOVERY

Ghaffariyan (2013) showed that the quantity of residues on sites after commercial timber recovery depends on various parameters pertaining to the harvesting method. There is very little information available regarding the impact of each harvesting method with regards to the amount of remaining residues infield (Ghaffariyan, et al. 2017). Although there are a lot of residues type, it is difficult to predict their nature, quantity, and quality before each harvesting process. The year-round accessibility of forest sites, weather, the availability of preprocessing technologies, haulage contracting methods, and plant distance are among the aspects that are not well known (Woo, et al. 2019), which should promote further study.

CHAPTER 3: RESEARCH SITES AND HARVESTING SYSTEM

3.1 INTRODUCTION

This chapter provides a comprehensive breakdown involving the research sites and descriptions of the harvesting methods. The research was based on two harvesting systems namely fully mechanised and semi mechanised in *Pinus patula*.

3.2 LOCATION

This section provides a description of the research sites (the plantation and compartments).

3.2.1 Description of the research site plantation area

The study was conducted at the Sappi (South African Pulp and Paper Industries limited) plantations situated in the Ngodwana area of Mpumalanga, South Africa (Figure 8). Ngodwana is located along the N4 national road in the Elands Valley, 50 km from Mbombela, the capital of Mpumalanga province. Sappi is a producer of paper, paper packaging, dissolving pulp, and growing commercial timber. Sappi forests have access to 534 000 ha of plantations, of which 394 000 ha are owned and approximately 140 000 ha are contracted supply (Sappi 2019). The study trial areas were laid out in *Pinus patula* plantations in Helvetia and Houtboschoek.

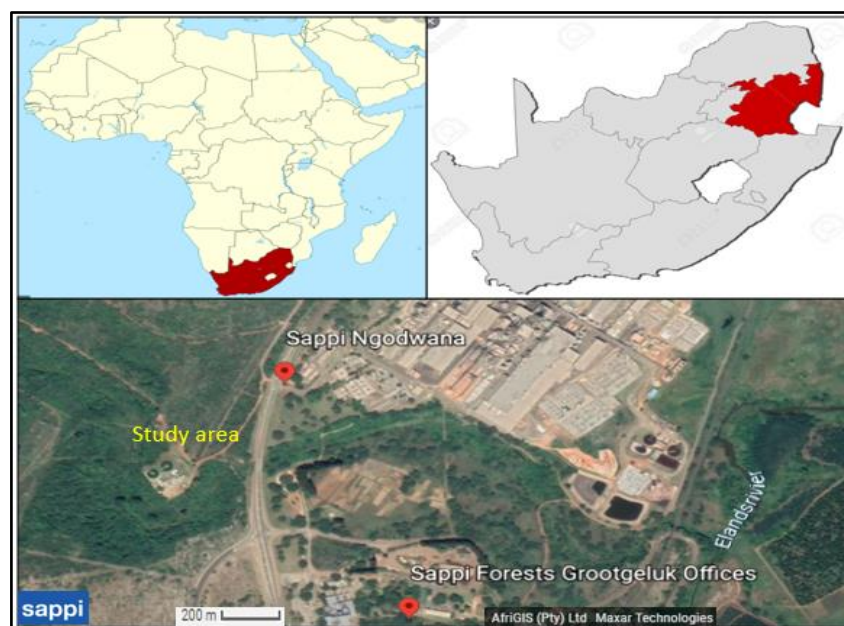


Figure 8: Study location indicated on map in Mpumalanga, South Africa.

3.2.2 Description of research compartments

Two identified harvesting systems namely, semi-mechanised tree-length (TL) and fully mechanised full-tree (FT) were observed. Both harvesting systems worked on different sites (Table 3) (gentle to level slope conditions) but with the same species (*Pinus patula*). The two compartments were namely C35a (25°32'18.558" S; 30°22'45.24" E) and E32 (25°28'32.485" S; 30°34'45.502" E). The field work was carried out from the 7th of October to the 14th of November 2020 for the FT system and the 30th of November to the 18th of December 2020 for the TL system. Fifty-one research days were spent in both the compartments collecting data. The total research area of the plots was 2.23ha.

Table 3: Study site information

Compartments	C35a	E32
Systems	FT	TL
Species planted	<i>P. patula</i>	<i>P. patula</i>
Area (ha)	50.75	25.71
Date planted	2004	1998
Planting espacement	3 x 2	2.9 x 2
Age (years)	17.2	22.2
Average DBH (cm)	24.7	20.1
Average height (m)	24.9	21.9
Average tree volume (tons)	0.75	0.33
Trees per hectare	832	1342
Tons/ha (p=wbv)	325	294
Total compartment tons (p=wbv)	16493	7570

3.3 TERRAIN CONDITIONS

The terrain condition information was evaluated using the South African National Terrain Classification System (Erasmus 1994) of the research sites. The terrain conditions (ground conditions, slope, and ground roughness) (Table 4) for both

compartments were different, hence the high variability in the data. In compartment C35a, the terrain research site was on a gentle slope (11% to <21%), while compartment E32 was on a moderate (20% to <30%) to steep slope 1 (30% to < 35%) with a smooth surface and good ground condition (Table 5). The slope was enough to be considered a potential factor affecting the productivity.

Table 4: South African National Terrain Classification categories (Erasmus 1994).

Ground Conditions	Ground Roughness	Slope (%)
1= Very Good	1= Smooth	1= Level (< 11)
2= Good	2= Slightly uneven	2= Gentle (11 to <21)
3= Moderate	3= Uneven	3= Moderate (20 to <30)
4= Poor	4= Rough	4= Steep 1 (30 to <35)
5= Very Poor	5= Very Rough	5= Steep 2 (35 to <40)
		6= Steep 3 (40 to <50)
		7= Very steep (>= 50)

Table 5: Study compartment terrain conditions

Compartments	Ground Conditions	Ground Roughness	Slope (%)	Aspect
C35a	Good -Very Good	Smooth	Gentle (11 to < 21) to level (< 11)	South East
E32	Good	Smooth	Moderate (20 to < 30) to steep 1 (30 < 35)	South East

3.4 HARVESTING SYSTEMS

This section provides a detailed description of the harvesting systems used in the research. Two harvesting method comprising of harvesting systems were used in a clear-felled operation in *P patula* compartments. In the context of this research and in the remainder of the dissertation, the harvesting system associated with the tree length harvesting method which comprised of a chainsaw for felling, cable skidder for

extraction, chainsaw for processing and logger for bunching, sorting and stacking will be referred to as the tree length system. The harvesting system associated with the full tree harvesting method which comprised of a feller buncher for felling, grapple skidder for extraction and roadside processor for processing will be referred to as the full tree system. The machines and equipment utilised for harvesting and extracting was operated by two contractors namely Imphisi Harvesting Contractors (semi-mechanised TL system) and Imishini Contracting Services (fully mechanised CTL system). The loading operation from the roadside to the depot was performed by a different contractor. The log assortments were counted, tagged and sold at the landing (Table 6). Once at the roadside, the client would collect the logs to their respective mills. The log assortments were optimised to meet the Sappi Ngodwana specifications.

Table 6: Products produced and their dimensions.

Products	Client	Diameter (cm)		Length (m)	
		Min	Max	Min	Max
New sprint (NP)	Sappi (Ngodwana mill)	12	38	2.25	2.40
Chemical pulp (CP)	Sappi (Ngodwana mill)	11	5	1.8	2.40

3.4.1 General overview of semi mechanised tree length system

The semi-mechanised tree length system comprised of a chainsaw for felling and processing (debranching and topping), and a cable skidder for extraction (Figure 9). Other chainsaws were available at the landing to optimise tree lengths according to the specifications of the markets. After optimisation, a three-wheeled logger would stack logs into separate piles for each client, thereafter removing debris along the roadside.





Locality Activity	Stand	Extraction route	Roadside landing
Felling & debranch: Chainsaw			
Extraction: Cable Skidder			
Cross-cutting & topping: Chainsaw			
Bunching, sorting & stacking			

Figure 9: Tree length harvesting system matrix.

1) Husqvarna 61 chainsaw

The Husqvarna 61 chainsaw was used infield for felling, debranching and topping, whilst another chainsaw was used at the landing for optimisation (Figure 10). Log scalers were used to mark the logs into various assortments at the landing. Thereafter, a chainsaw operator would follow behind the log scaler and crosscut the logs according to the marked specifications. This operator was also responsible for quality control of the logs. Quality control involved removing excess branches that would have been missed infield and fibre tear-offs on the logs.



Figure 10: Husqvarna chainsaw 61

Below are detailed chainsaw specifications (Table 7). The weight of the machine does not include fuel, bar and chain.

Table 7: Husqvarna chainsaw specifications (Husqvarna 2018)

Chainsaw	Specifications
Saw chain (cm)	38
Displacement (cm ³)	61.5
Power output (kW)	2.9
Weight (excluding cutting equipment kg)	6.2
Recommended guide bar length (cm)	28 in

2) Extraction: John Deere 648 H

A John Deere 648H cable skidder was used to extract trees from the compartment to the landing (Figure 11). The Cable skidder specifications are provided in Table 8.



Figure 11: Cable skidder John Deree 648H

Table 8: Cable skidder specifications (Deere 2021a)

Cable skidder	Specifications
Make	John Deere
Model	648H
Aspiration	Turbocharged, air to air intercooled
Engine type	6.8 L (415 cu.in.)
Power	128 kw (172p)
Winch control	Mechanical
Slope operation, maximum angle	45%
Machine hours	25548

3) Pre-bunching and stacking: Bell 225A three-wheeled logger

A Bell 225A three-wheeled logger (Figure 12) performed several tasks including bunching trees, removing residues at the roadside, sorting and stacking logs. These included pre-bunching stems infield and sorting stems at the roadside for ease of optimisation and crosscutting. Other tasks involved were sorting and stacking of log assortments according to dimensions and client specifications and removing residues from the roadside back to infield.



Figure 12: A three wheeled logger bunching, sorting, stacking and clearing residues

3.4.2 General overview of fully mechanised full tree system

The fully mechanised FT system comprised of three machines: a feller buncher to fell and bunch the trees. A grapple skidder to extract the tree bunches to the roadside and a processor to debranch and crosscut the trees into commercial assortments (Figure 13).




<div>Locality</div> <div>Activity</div>	Stand	Extraction route	Roadside landing
			
Extraction; Grapple Skidder			
Debranch & cross-cutting; Processor			

Figure 13: Full tree harvesting system matrix

1) Felling: John Deere 859m feller buncher

The John Deere 859m tracked wheel feller buncher was used to fell and accumulate multiple trees before laying them down in bunches (Figure 14). The specifications of the feller buncher are presented in Table 9.



Figure 14: A feller buncher John Deere 859m

Table 9: Feller buncher specifications (Deere 2021b)

Feller buncher	Specifications
Make	John Deere
Model	859M
Weight	36 060kg
Engine type	John Deere Power Tech PSS 9.0L
Power @ 2000rpm	213 kw (286hp)
Number on cylinders	6
Track chain	215.9 mm (8.5 in)
Year of manufacture	2018
Machine hours	3488

2) Extraction: CAT 525 C grapple skidder

A dual arch grapple skidder was used to extract the trees prepared by the feller buncher from infield to the roadside (Figure 15). The specifications of the grapple skidder are presented in Table 10.



Figure 15: CAT 525 C grapple skidder

Table 10: Grapple skidder specifications (RitchieSpecs 2018)

Grapple Skidder	Specifications
Make	CAT
Model	525C
Operating weight	17 711kg
Engine type	Cat C7 ACERT
Number of cylinders	6
Gross power	146 Kw
Gross torque	896Nm at 1.400rpm
Grapple Boom	Dual Arch
Max grapple capacity	1.16m ²
Fuel tank standard	315 Litres
Machine hours	14676

3) Processing and optimising: CAT 320D processor

The CAT 320D tracked processor performed the tasks of debranching and cross cutting (Figure 16). The specifications of the processor are presented in Table 11.



Figure 16: CAT 320D roadside processor used for processing trees on roadside

Table 11: Excavator processor specifications (CAT 2015)

Processor	Specifications
Carrier band	CAT
Carrier	320D series 2
Operating weight	27 330kg
Engine type	Cat C7.1 ACERT
Cylinders	4
Engine net power	118kW
Undercarriage length	0.8m
Machine hours	14 774

3.4.3 Equipment operators

All the operators were trained by an accredited and experienced training provider for mechanised harvesting machines and equipment. Their work skills and techniques were acceptable. The Imphisi Harvesting Contractors (semi-mechanised TL system) operators were working for nine hours (shift length) from Monday to Saturday. The

Imishini Contracting Services operators worked eight hours (shift length) a day from Monday to Sunday. See Table 12 for details regarding the experience of the operators.

Table 12: Experience of the operators

Operator	Contractor name	Experience as operator (years)
Chainsaw operators	Imphisi Harvesting Contractors	15,13,10
Cable skidder operator	Imphisi Harvesting Contractors	9
Logger operator	Imphisi Harvesting Contractors	12
Feller buncher operator	Imishini Contracting Services	6
Grapple skidder operator	Imishini Contracting Services	22
Processor operator	Imishini Contracting Services	4

CHAPTER 4: RESEARCH AND DATA ANALYSIS METHODOLOGY

4.1 INTRODUCTION

This chapter describes the general research methodology (material and methods), as well as the pilot study information used to test the data collection methods. The research methods section includes the description of instruments used for taking measurements, data collection techniques and data capturing processes. Furthermore, in-depth, procedures used for the analysis of sample trees, quantifying tree biomass components and statistical analysis are also discussed.

4.2 PILOT RESEARCH

A pilot research study was performed before the actual research occurred. Pilot research is a preliminary study using a small sample of the larger study area (Singh 2012). The purpose of the pilot research is to determine and test the adequacy of the research operation, and assess the feasibility of the full research (Singh 2012). The pilot research was conducted from the 17th to the 20th of March 2020. During this period, the researcher identified the full tree and tree length harvesting systems compartments in Helvetia compartment C35a and in the Houtboschoek compartment E32. The research areas were selected from a compartment list of the 2021 clear-fell annual plan of operations (APO). Thereafter, the sites were visited to assess their suitability (e.g., terrain conditions) for the research. The total clearfell area of each system was sufficient to produce plots for a valid experiment. Each site was deemed suitable to produce the planned eight plots, with each plot measuring an average size of 19 318 m². The initial plan was to collect all branches when collecting the remaining biomass, but after the pilot study observations, it was decided to only collect the residues with a diameter of 8 cm and above, because this would be easier using manual collection methods. Moreover, a chainsaw was needed to crosscut woody residues into 1m to 1.5m lengths in both operations.

4.3 RESEARCH METHODOLOGY

This section describes the measuring instruments, fieldwork practice, data collection process (Figure 17) and data capturing methods used during the research period. The following variables were measured:

- Plot surface
- Total mass per plot (commercial volume)
- Recovered residues per plot
- Remaining residues per plot
- Biomass collection productivity

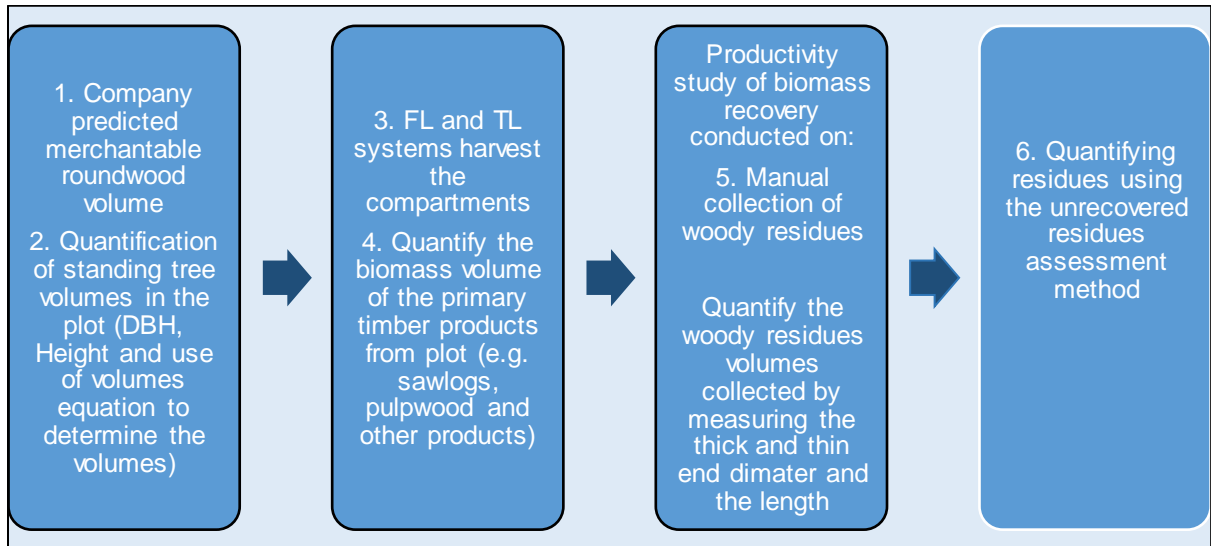


Figure 17: The process of biomass collection

4.3.1 Measuring tools for productivity operation

The following instruments were used to measure key variables including commercial volumes, biomass quantification and productivity operations (motor manual processing, manual extraction, manual loading).

For productivity measurement, tools were used to conduct the time study and to quantify the output. These tools and their functions are described in Table 13. There were certain time elements required for both harvesting systems. The data was collected by recording the time taken to complete each element. When the time studies were completed, the information on the spreadsheet was transferred into a Microsoft Excel spreadsheet. The spreadsheets contained the following information (see Annexure 1: Time study form).

- Date and time of the study
- Plot number
- Starting and ending time

- Tally
- Element
- Terrain conditions
- Observer name
- Person observed
- Notes
- Delays times

Table 13: Measuring tools and their functions

Measuring and capturing tools	data Description	Output Assessed	quantified/
Stopwatch	To record time taken to complete activities in each sample plot	Activity sampling	
Digital camera	To capture pictures that will prove what was observed during the study	Site conditions	
Tape measure	To measure DBH and length	Biomass log volume	
Clip board and pen	Recording tree measurements	Tree volume and activity sampling data	

The time taken for each operation including motor manual processing, manual extraction, and manual loading was assessed to determine the productivity level. The volume was quantified by measuring individual logs after the collection of the woody biomass. The length and diameter of the logs from each plot was measured to determine the volume output of each harvesting system. For measuring productivity, the labourer's operations were split into specific elements.

4.3.1.1 Tree volume determination

Estimation of tree volume of the entire area was determined based on the data collected from each sample. SAPPI provided detailed information for each compartment including average DBH, average height, compartment age and species. The sampled area for each harvesting system was set ahead of the harvesting operation. Tools and equipment were used to collect and record the data (Table 1).

Table 14: Measuring tools and their functions

Measuring tools	Description	Output Assessed	quantified/
Calliper	For measuring tree DBH	Tree volume	
Vertex	For measuring tree height	Tree volume	
Paint and paint brush	For marking and numbering the trees	Tree identification	
Digital camera	To capture pictures that will prove what was observed during the study	Site and stand conditions	
Diameter tape	To measure exact DBH	Tree volume	
Clip board and pen	Recording tree measurements	Tree volume	
Area measurement app	Length and breadth of the plots	Plot area	
Tape measure	To measure the length and diameter of logs	Tree volume	

The trees were measured their diameters over the bark using a calliper at standard breast height of 1.37 m used in South Africa in each plot (Owen 2000). All measured DBHs and heights were recorded in the form (see Annexures 2: Standing volumes DBH and height) and numbered with a visible white paint (Figure 18).



Figure 18:Trees to be harvested marked with white paint

Each sample area consisted of 1600 trees with 8 plots of +/-200 trees. For each plot, an average of 20 tree heights were measured relative to the diameter distribution within the plot using a Vertex hypsometer with a transponder. The diameter and heights of the selected trees were used to estimate a DBH-height curve, which was used to determine the heights for the other trees in the sample (Owen 2000). To increase and optimize the measuring accuracy, the Vertex was recalibrated at the beginning of each day regularly. Diameter and height measurements were used to determine tree volume by using the equation based on the Schumacher and Hall model (Bredenkamp 2012). The standard equation and descriptions of the equation were as follows:

Schumacher and Hall's model: $\ln V = b_0 + b_1 \ln (dbh + f) + b_2 \ln H$, where:

- \ln = natural logarithm to base e
- V = stem volume (m^3 , under bark up to 50mm)
- dbh = diameter at breast height (measure in centimeters, over bark)
- f = correction factor
- H = tree height

The volume of individual trees was determined using *Pinus patula* coefficients. Tree volumes were calculated up to a 5 cm top diameter. *Pinus patula* coefficients used within the equation were:

$$\ln V = -13.47 + 2.44 \ln (dbh + 8) + 1.325 \ln H$$

4.3.1.2 Motor manual processing

A Husqvarna 61 chainsaw was used to process (debranch and crosscut) the woody biomass (Figure 19). See Chapter 3.4.1 for a comprehensive description of the chainsaw specifications. The utilised chainsaw operator in the field research study was with a working experience of 10 years (detailed information on the operators is provided in Chapter 3). The operator was given instructions on how to process the woody biomass in all the plots. The researcher and assistant followed the operator to

ensure the quality produced was of a sufficient quality while capturing activity time study data using a stopwatch.

The assistant was a forestry student completing his experiential training who was trained in collecting and recording data. Thereafter, the researcher recorded and followed the tasks performed by the operator on a data collection form. The operator would walk to a specific log, move the log for proper positioning, and then debranch and crosscut the log (Table 15). The operator performed several additional activities such as refuelling, equipment inspections and so forth. Activities that caused delays were also recorded. These activities included break times and equipment changes. The length of the woody biomass in both harvesting systems was between 0.95m to 1.5m. The specific task performed by the operator was recorded at 30 seconds intervals, along with the total time taken to complete the work. The proportions of each task were computed to determine the productivity of the various elements for the duration of the study.

Table 15: Motor manual processing elements for both systems

Elements	Description
Walk	Begins when the operator starts to move and ends when the operator reaches logs
Crosscut	Starts when the operator crosscuts the log and ends when the crosscutting finishes.
Move log	Starts when the operator stops the machine and moves residues or logs preventing him from crosscutting the logs safely.
Debranch	Begins when the operator starts to cut the top and branches and ends when all branches on the log have been removed
Move to/from refuel	Starts when the operator moves to/from refuel at the designated area and ends when the operator reaches the designated area
Refuel	Starts when the operator reaches the designated area to refuels and ends when the operator stops to refuelling.
Inspect	Beings when the operator had breaks related to failure in tools including the tearing of chain of chainsaw and ends when finishing to inspect
Delays	Any interruption during working time including personal (rest and personal breaks) and mechanical (broken chain)



Figure 19: Motor manual processing of biomass

4.3.1.3 Manual extraction

The manual extraction operation was conducted by four skilled workers who had 5-10 years of work experience (Figure 20). These were all adult males, aged between 26 and 42 years.



Figure 20: Manual extraction of woody biomass

The same crew was used for biomass collection at both harvesting sites. The workers were considered representative of the workers in the region. The performance of the worker's during observation was very similar. The manual extraction method was

divided into working elements and data was collected based on the described elements. Four elements were described, namely, walking (not carrying anything), picking up stemwood infield, carrying stemwood to the roadside, and stacking of stemwood at the roadside (Table 16).

Table 16: Manual extraction elements for both systems.

Activity	Description
Walking	Begins when the worker starts walking towards the stemwood to be moved and ends when the worker reached the stemwood.
Picking up	Begins when the worker reaches the stemwood and proceeds to bend down to lift the stemwood from the ground to the shoulder and ends when the worker is in a standing position carrying the log.
Carrying	Begins when the worker is in a standing position and starts to walk with the stemwood or drag the stemwood and ends when the worker stops at the roadside landing area.
Stacking	Begins when the worker stops at the roadside landing area and proceeds to drop the log down or move the stemwood by hand and ends when the worker starts walking back to collect stemwood.

The specifications of recoverable stemwood were a minimum diameter of 5 cm and a minimum length of 0.95m. The total extraction distance for the FT system was 100m and for the TL system was 195m. A plot level time study was conducted using a stopwatch whilst observing the four workers extracting stemwood that matched the collection specifications. The starting time and ending time for each plot was recorded in a data collection sheet. Activity sampling was conducted whereby all workers were observed every 1 minute. The specific activity observed was noted with the proportions of all activities tallied when the extraction was completed for each plot. The proportions of each activity were computed to determine the productivity of the various activities for the duration of the research. The volume of usable stemwood biomass collected, by the team, was calculated based on the Smalian's formula where the thin and thick end diameters and lengths are measured (Bredenkamp 2012). The standard equation and descriptions of the equation variables were as follows:

Smalian's formula: Volume: $\pi D^2/40\,000 + \pi d^2/40\,000 /2 \times h$, where:

- π = the ratio of the circumference of a circle to its diameter (3.1416)
- D = diameter at thick end in cm
- d = diameter at thin end in cm
- h = log length in m

A sample of usable residues extracted from stemwood was taken for moisture content determination. Two wood samples from each plot were taken in the form of chips using a Milwaukee wood drill coupled with a wood boring drill bit (Figure 21). The chips were placed in a white plastic container (500ml) and immediately placed in sealed plastic bags to be weighed. The chips were oven dried and weighed to determine the moisture content of each sample on the same day. The details (harvesting system, date, plot number) associated with each sample were recorded on each bag. The moisture content of the stemwood coming from different plots differed because of the different harvesting operation starting dates (Figure 22 & 23).



Figure 21: The Milwaukee wood drill and chips collected for moisture content determination



Figure 22: The moisture content transition for the FT system



Figure 23: The moisture content transition for the TL system

4.3.1.4 Manual loading

All the workers were informed of the objectives and methods. In the field, manual loading was carried out by four adult workers. The time data for loading was collected only in the FT harvesting system. A tipper truck (Quester UD trucks CWE 370) tipper truck was employed to transport the stemwood to the Ngodwana Mill Weighbridge. Table 17 displays the specifications of the tipper truck.

Table 17: Tipper truck specifications

Tipper truck	Specifications
Make	UD Trucks
Model	Quester CWE370
Configuration	6x4 dump
Engine type	GH11E
Tare weight	8 380
Payload allowance (kg)	17 320
Power output	278 @1 900
Max body length	7 475
Gross vehicle mass (tons)	28,5-31
Machine hours	7571

The bin of the tipper truck had a total length of 4.29 m, a width of 2.26 m and a height of 1.24 m. The loading activity included four elements namely, walking, picking up a log, handing over a log, stacking a log and standing (Table 18). During the operation, two workers were responsible for picking up the stemwood, which had been stacked along the roadside, and handing it over to the other two workers inside the truck bin (Figure 24).



Figure 24: Manual loading of woody biomass

The two workers inside the truck bin were responsible for stacking the stemwood inside the truck platform. Two full loads were completed during the loading operation. The stem wood loaded came from four plots from the FT harvesting system. Once loaded the stem wood was transported to the Ngodwana mill for weighing. The loading start and end times for each plot was recorded in a data collection sheet. An activity sampling time study was conducted whereby each worker was observed every minute during the loading operation. The specific activity that the observed worker was performing during that 1-minute interval was noted and the proportions of all activities were tallied when the loading was complete for each plot. The proportions of each activity combined with the stemwood output was recorded to determine the productivity of the loading activity.

Table 18: Description of manual woody biomass loading elements

Activity	Description
Walking	Begins when the worker who is on the floor and start walking towards the stemwood to be loaded and ends when the worker reached the woody biomass.
Picking up	Begins when the worker reaches the woody biomass and ends when the worker bends down to lift the woody biomass from the ground and when the worker is in standing position.
Handing over	Begins when the worker is in standing position starts handing over the woody biomass and ends when the worker holds the woody biomass
Stacking	Begins when the worker drops the woody biomass on the truck platform or move the woody biomass by hand and ends when the worker stop sorting the woody biomass.
Standing	Begins when the worker starts waiting for the handover and ends when the worker reaches towards the woody biomass handed over

4.3.2 Measuring tools for biomass quantification

Woody biomass has been estimated at forest harvesting sites in the past. After the harvesting of primary products (pulpwood) was completed, the sites were assessed to determine the uniformity of distribution of the harvest residues. The residues were classified based on the residue distribution pattern and type of materials. The Cooperative Research Centre (CRC) for Forestry in Australia developed a harvesting residues assessment method using plots and line transects (Ghaffariyan and Apolit 2015, Ghaffariyan and Dupuis 2021, Ghaffariyan, et al. 2016). This method was applied to calculate the quantity of unrecoverable residue and to estimate the components including stemwood, branches, needles and cones. Woo, et al. (2019) adds that the harvesting residues assessment method is classified as a direct method because of the high accuracy rate. For quantifying residues, various tools were used (Table 19).



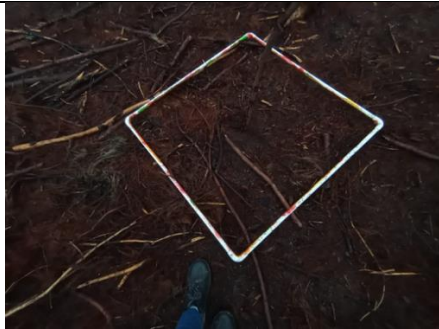
Table 19: Tools and their functions

Tools and equipment	Description	Output Assessed	quantified/
Digital camera	To capture pictures that will prove what was observed during the research	Site conditions	
Clip board and pen	Recording tree measurements and biomass weights	Tree volume, activity sampling data and biomass quantification	
Portable scale and bucket	To measure the mass of biomass (branches, woody debris, fine twigs, needles and cones)	Biomass quantification	
Tape measure	To measure slash depth	Stemwood volumes biomass quantification	
Spray paint	To mark the square meter for cutting the unrecovered residues	Biomass quantification	
1m x 1m grid	To mark off an exact area of 1m x 1m for identifying and collecting the unrecovered residues	Biomass quantification	
Pegs	To mark the sample points per stratum	Biomass quantification	
Handsaw	To manually cut pieces within the square sample plot area	Biomass quantification	
Chainsaw	To cut large and long stemwood pieces	Biomass quantification	
Computer with the AFORA spreadsheet for sample determination	To determine the number of pre-samples required per stratum	Biomass quantification	
Valmet MR Moisture Analyzer	To determine the moisture content of the wood samples	Biomass moisture determination	
Wood boring drill	To drill holes in the stemwood and collect wood samples for moisture content determination	Biomass moisture determination	

4.3.2.1 Determining number of plots for each stratum

A residue assessment method was used to estimate unrecovered residue quantities by using the stratum technique. Ghaffariyan, et al. (2017) defines stratum as grouping the forest residues into similar features, depending on the condition of the forest mass and the fraction of forest covered. After accessing the types of unrecovered residues on each research site, three visible strata were classified, namely high density (stratum 1), moderate density (stratum 2) and low density (stratum 3) (Table 20). Strata are selected in a specific manner so that they do not overlap.

Table 20: Types of the residues stratum

Stratums	Description	Image
1. High density	All the above residues with a height ranging from 1m to 1.5m.	
2. Moderate density	All the above residues with a maximum height of 0.5m	
3. Low density	All the above residues with sparse lying residues	

The proposed residue assessment method was conducted in each plot with a sample area of 1m x 1m. The assessment method was conducted according to the following steps:

Step 1: After a brief investigation of the two sites, three visually identifiable strata were defined

Step 2: A set of representative transects were created at each study site to provide about 50 sample points (where the spacing between the samples on each transect was 10m). The samples were visually assessed for which stratum the point represented, this was in order to produce a stratum map containing the various points

(pegs were used to marked on the ground so they could easily be found for detailed sampling) and to determine the proportion of each stratum

Step 3: Based on the transects the number of points identified per stratum were entered into a sample calculator to determine the number of pre-samples required per stratum (total number of pre samples were 9-11) (Figure 25). Using the transect points, the required pre-sample of 1m X 1m grid samples (Figure 26) were randomly done within each stratum (on 25% of the samples or every third point per stratum, researchers collected the fractional detail). For each plot the slash depth was measured and recorded (the middle of the 1m X 1m plot and each of the 4 corners).

Step 4: The plot samples were used to compute the number of samples for each stratum. Absolute error was adjusted for so that the number of required plots was about 20 per hectare. If the error (as a percentage) of the mean was greater than 15%, then additional 1m × 1m grid samples were randomly collected within each stratum, while ensuring pre-sample points were not repeated (every third point per stratum were collect the fractional detail).

Inputs	Stratum 1	Stratum 2	Stratum 3	Stratum 4	Stratum 5	Sum
	1	2	3	4	5	
# transect points per stratum						0
Plot 1						
Plot 2						
Plot 3						
Plot 4						
Plot 5						
Plot 6						
Plot 7						
Plot 8						
Plot 9						
stratum mean	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	
std. error of stratum	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	
# plots stratum (pre-sampling)	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
# plots required (final sampling)	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Overall mean	#DIV/0!					
	E =	10	abs. value			
	E =	#DIV/0!	% of mean	(min up to 20 plots but do not exceed 15%)		
	n =	#DIV/0!		(target 20 provided E%<15%)		
	n(optimal) =	#DIV/0!				

Figure 25: Sample size calculator for forest residues (Ghaffariyan, et al. 2012b)



Figure 26: The 1m x 1m sample grid

The green weight of stemwood, needles, cones and branches with diameter larger than 3cm was recorded in each sample on the slash assessment form (see Annexures 3: The unrecovered slash assessment). The green weight samples were measured with a portable digital scale weighing tool and a bucket weighing 0.68kg, which was accounted for (Figure 27). The moisture content of the samples was not evaluated in this study.



Figure 27: Weighing unrecovered residues

CHAPTER 5: RESULTS AND DISCUSSION

5.1 INTRODUCTION

This chapter presents the findings from the data collection methods used for the full tree (FT) and tree length (TL) harvesting systems. The biomass quantification, woody residues collection productivity, and cost results for the two harvesting systems are provided. Figures and tables are used to illustrate the findings of the research.

5.2 BIOMASS QUANTIFICATION RESULTS

The following section represents the results for the FT and TL harvesting systems, namely:

- standing trees volume
- harvested commercial volumes
- recovered residues (oven dry tons)
- unrecovered residues (oven dry tons)

Descriptive statistics were used in order to determine the mean values for each variable (Table 21).

Table 21: Variables and their functions

Variables	Description	
Odt/ha (recovered)	The total amount of oven dried material in tons per hectare of woody residues (mainly stemwood and offcuts)	
Odt/ha (unrecovered)	The total amount of oven dried material in tons per hectare of branches, twigs, needles and cones	
Odt/ha (total)	The total amount of oven dried material in tons per hectare of stemwood, branches, twigs, needles and cones	
Recovery ratio	The percentage of woody residues from the oven dried material in tons	
% nearer (stemwood)	The percentage of stemwood recovered from the 100m (FT) and 95m (TL) distance at the roadside	
Standing trees m ³ /ha	The volume of standing trees in cubes per hectare before harvesting.	
Log volumes m ³ /ha	The total volume of harvested timber in cubes per hectare, after harvesting.	
Commercial wood (m ³ /ha)	The volume per hectare of commercial wood i.e. logs supplied to the timber markets such as sawlogs and pulpwood	

5.2.1 Full tree harvesting system results

In the following section, the FT harvesting system results in relation to the variables that were determined, consisting of standing tree volumes, commercial volumes, biomass recovery and unrecovered residues will be presented.

5.2.1.1 Standing trees volume

For the FT harvesting system, descriptive statistics and Mann Whitney tests based on different variables for standing trees volumes were used. These were conducted to determine the standing tree volumes ($\text{m}^3 \text{ ha}^{-1}$) and log volumes ($\text{m}^3 \text{ ha}^{-1}$) before and after harvesting operation.

Table 22 shows the descriptive statistical values utilised for the study. The FT harvesting site primarily contained trees with a mean DBH of 24.7 cm. This resulted in a mean standing volume of $91.5 \text{ m}^3 \text{ ha}^{-1}$. Thus, log recovery was $73.6 \text{ m}^3 / \text{ha}^{-1}$. The mean DBH can be directly related to the log volume recovery from the harvested trees.

Table 22: Site characteristic for the FT harvesting system (See Annexure 4)

Variables System	Standing volume m^3/ha		Log volume m^3/ha	
	Mean	Standard deviation	Mean	Standard deviation
FT	91.5	5.1	73.6	9.1

5.2.1.2 Commercial volumes and biomass recovery

The results for commercial volumes, log volume recovery, biomass recovery and unrecovered residues were determined using the descriptive statistics and Mann Whitney tests. The results show that from the standing volumes, the FT harvesting system produced 85% of commercial timber (logs supplied to the timber markets e.g. sawlogs and pulpwood) with 15% error (Figure 28). From the results, it was discovered that the FT harvesting system could produce a potential target of 4% for the biomass recovery and 11% for unrecovered residues.

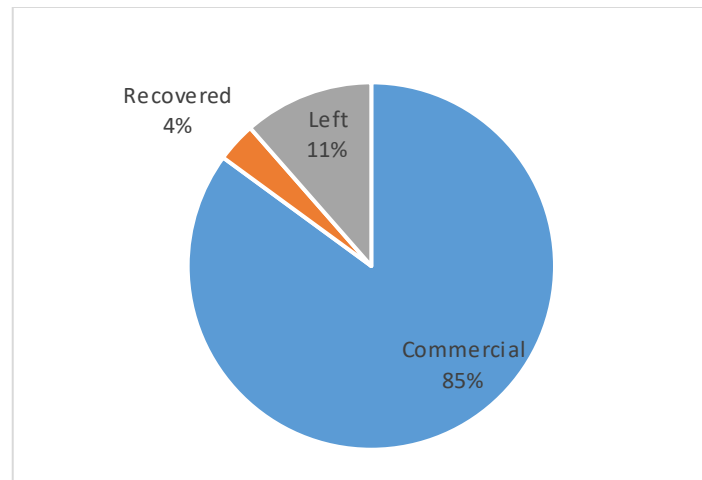


Figure 28: Estimation of wood production and biomass production

5.2.1.3 Recoverable and unrecovered residues

During the observation of harvested stands, it was discovered that forest residue produced by the FT harvesting system were more concentrated nearer to the roadside (Figure 29). The descriptive statistical values indicated that the FT harvesting system recovered a mean value of 5.2 odt/ha of woody biomass (Table 23). Moreover, the woody biomass recovered varied between a minimum and maximum of 4.3 odt/ha and 8 odt/ha respectively. An average of 26.6% moisture content was used to determine the oven dry tons of the woody biomass.



Figure 29: Biomass along roadside after FT harvesting operation

Table 23: Recoverable residues for FT system (see Annexure 5)

Variables	Recoverable stemwood (odt/ha)			
System	Mean	Standard deviation	Minimum	Maximum
FT	5.2	1.735	4.3	8.0

The unrecovered residues were determined after the recovered biomass odt was calculated. For unrecovered residues, the FT harvesting system showed a mean of 17.1odt/ha (Table 24), with minimum and maximum values of 12.5 and 23, respectively.

Table 24: Unrecovered residues for FT systems (see Annexure 5)

Variables	Unrecovered residues (odt/ha)			
System	Mean	Standard deviation	Minimum	Maximum
FT	17.1	3.989	12.5	23.0

A breakdown of unrecovered residue components was conducted to determine the percentage from the FT harvesting system operation. The unrecovered residues components comprised of stemwood, branches, twigs, needles and cones. The volume of unrecovered residues was dominated by twigs and needles, which accounted for 56% of the total volume. Conversely, the volume of unrecovered residues from cones was the lowest at 5% (Figure 30).

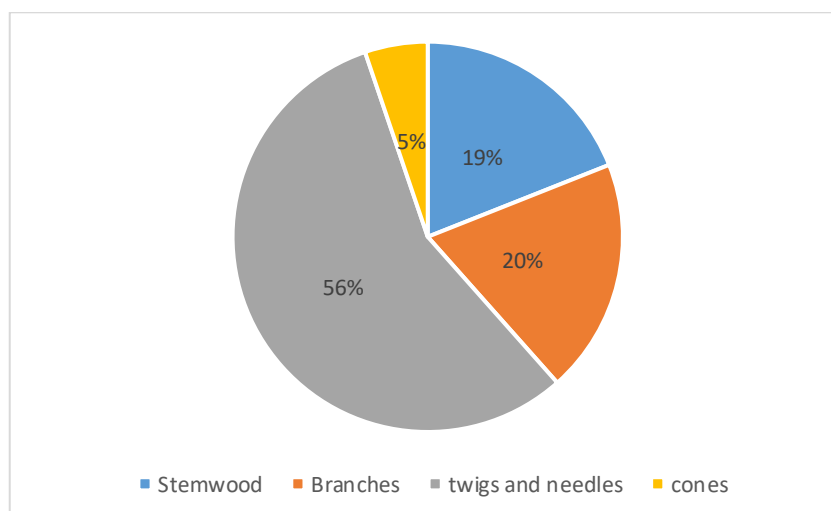


Figure 30: Composition of unrecovered residues from the FT harvesting system

5.2.2 Tree length harvesting system results

The standing tree volume, commercial volume, biomass recovery, and unrecovered residues are the variables that were identified using descriptive statistics tests. The results from the tree length system will be presented in relation to each of these variables in the section that follows. The individual results of each variable are discussed.

5.2.2.1 Standing trees volume

For the TL harvesting system, descriptive statistical values were derived for the standing trees (m^3/ha) and commercial wood quantities (m^3/ha).

The data collected from the stand was utilised to compile the descriptive statistical results (Table 25). The average DBH of the trees at the TL harvesting research site was 20.1 cm. As a result, a log volume recovery mean of $50.2 \text{ m}^3/\text{ha}$ was obtained. The standing trees mean volume was discovered to be $61.5 \text{ m}^3/\text{ha}$.

Table 25: Site characteristic for the TL harvesting system (see Annexure 4)

Variables	Standing trees m^3/ha		Log volumes m^3/ha	
System	Mean	Standard deviation	Mean	Standard deviation
TL	61.5	4.3	50.2	4.0

5.2.2.2 Commercial volumes and biomass recovery

A determination was made regarding the commercial volumes, biomass recovery, and unrecovered residues. With a 7% error, the data showed that the TL harvesting system produced 93% of the commercial timber (Figure 31). Based on these findings, the TL harvesting system could potentially yield 4% of biomass recovery and 3% of unrecovered residues.

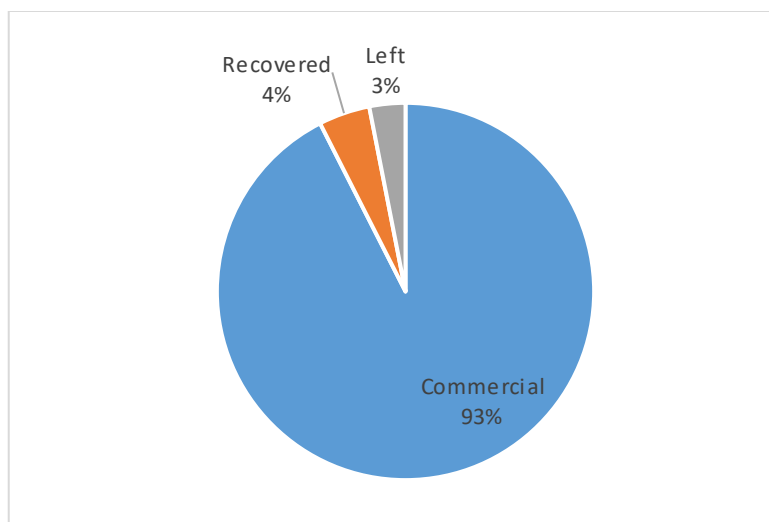


Figure 31: Estimation of wood production and biomass production

5.2.2.3 Recovered and unrecovered residues

Forest residues produced by the TL harvesting system were evenly spread across the site (Figure 32). According to the descriptive statistical tests, the TL harvesting system recovered woody biomass on average at a rate of 9.1 odt/ha (Table 26). Due to inaccurate length measurement for the log recovery, the log processing operation did result in a loss of log value. Additionally, the woody biomass recovered from the TL system varied greatly, with a minimum of 5.4 and a maximum of 15.6. The oven dry tons of the woody biomass were calculated using an average moisture content of 27.2%.



Figure 32: Biomass distributed in field after TL harvesting operation.

Table 26: Recoverable residues for TL harvesting system (see Annexure 5)

Variables	Recoverable stemwood (odt/ha)			
System	Mean	Standard deviation	Minimum	Maximum
TL	9.1	3.539	5.4	15.6

The results from the TL harvesting system showed that the mean value of unrecovered residues was 12.7 odt/ha (Table 27). A minimum of 10.3 and a maximum of 17.7 were found in the unrecovered residues variation from the TL harvesting system.

Table 27: Unrecovered residues for TL harvesting systems (see Annexure 5)

Variables	Unrecovered residues (odt/ha)			
System	Mean	Standard deviation	Minimum	Maximum
TL	12.7	2.518	10.3	17.7

The percentage of unrecovered residues in the TL harvesting system was calculated. Among the components of the unrecovered residues were stemwood, branches, twigs, needles, and cones. The largest (53%) of the biomass material was made up of twigs and needles, whereas 6% of it was made up of tree cones (Figure 33).

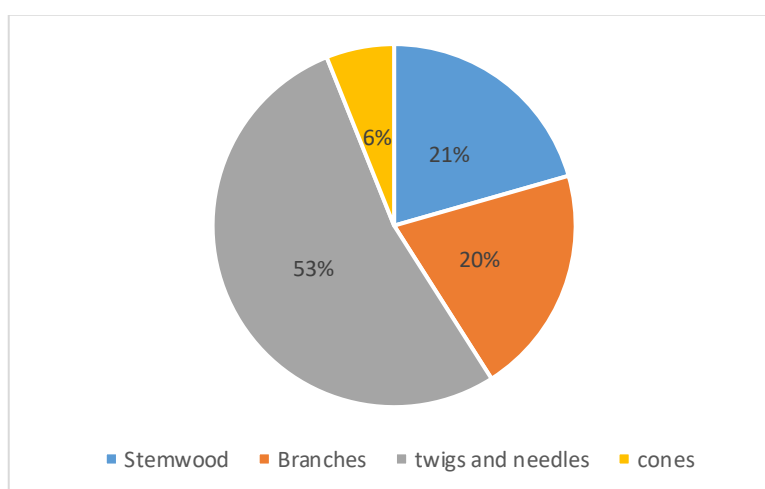


Figure 33: Composition of unrecovered residues from the TL harvesting system

5.3 BIOMASS COLLECTION PRODUCTIVITY

The following section presents the productivity results of the manual biomass recovery processes as conducted after FT and TL harvesting system operations. This process consists of:

- motor manual processing
- manual extraction
- manual loading

For both harvesting systems, a descriptive statistical test was used to determine the mean values of each variable (Table 28).

Table 28: Description of variables evaluated

Tools	Description
Processing h/ha	The mean total time taken to process woody biomass measured in hours per ha
Manual extraction h/ha	The mean total time taken to extract woody biomass from the designated distance point to the roadside measured in hours per ha
Manual loading h/ha	The mean total time taken to load woody biomass measured in hours per ha
Processing h/odt	The mean total time taken to process woody biomass measured in hours per odt
Manual extraction h/odt	The mean total time taken to extract woody biomass from the designated distance point to the roadside measured in hours per odt
Manual loading h/odt	The mean total time taken to load woody biomass measured in hours per odt
ZAR/ha	The total amount cost average in rands per ha
ZAR/odt	The total amount cost average in rands per odt

5.3.1 Full tree harvesting system results

Descriptive statistics were conducted based on different operations including motor manual processing, manual extraction, and manual loading.

5.3.1.1 Motor manual processing of residues operation

After harvesting the commercial wood, motor manual processing of residues occurred, but not immediately, as residues had to dry (five weeks) before they could be processed. The woody biomass was debranched and crosscut using a chainsaw to improve handling (Figure 34).



Figure 34: Chainsaw processing of residues operation .

The descriptive statistical results showed that the chainsaw operator required 2.7h per hectare to process the forest residues from the FT harvesting system operation (Table 29). A total of 1 180 pieces of woody biomass were produced by the chainsaw operator (lengths ranging between 1m to 1.5m).

Table 29: Motor manual processing productivity hours/per ha (see Annexures 7)

Variables	Processing = 1 Chainsaw operator (h/ha)			
System	Mean	Standard deviation	Minimum	Maximum
FT (100m)	2.7	0.584	1.8	3.6

A breakdown of the motor-manual processing operation was conducted in order to determine the most time-consuming element. The subtasks comprised of crosscutting, log movement, debranching, the time taken to move from their work site to the refuelling area, the process of refuelling, inspections and delays. The most time-consuming element was crosscutting with 33% of the total time being dedicated to this process (Figure 35).

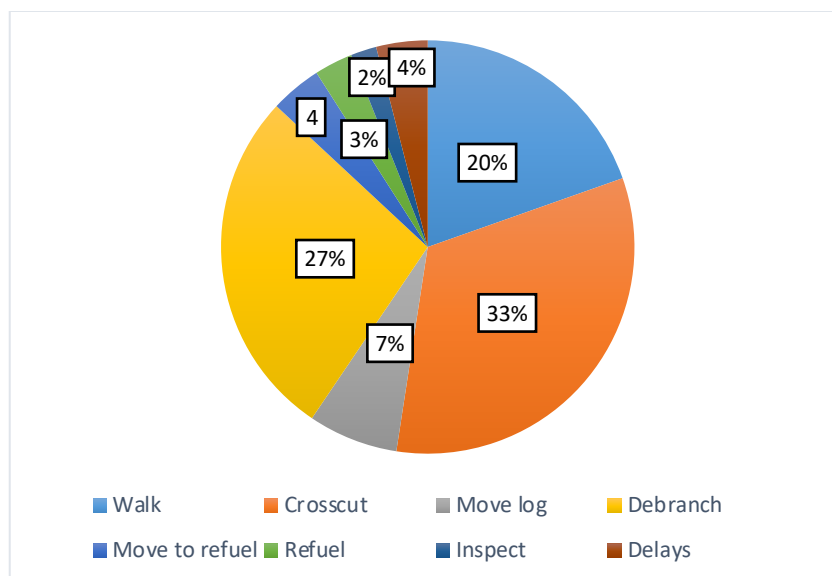


Figure 35: Composition of motor manual processing elements

5.3.1.2 Manual extraction of woody biomass

The manual extraction of the woody biomass was performed after the motor manual processing operation (Figure 36). The manual extraction operation elements were divided into walking, picking up the logs, carrying the logs, and finally stacking the logs. The extraction distance was used to divide the data into two sections. The first involved manually extracting woody biomass from the portion of the plot nearest to the road (FT system=50m) in the first half. The second subset included the manual extraction from the end of the plot to the roadside (FT system=100m).



Figure 36: Manual extraction stemwood operation.

a. *Time study for FT harvesting system*

The most time-consuming element of the FT harvesting system was the walking without the woody biomass (31%), whilst the least time consuming was the stacking of the logs (13%) (Figure 37). For the 100m manual extraction distance, the most time-consuming element was carrying the logs (34%), while stacking still took the least time (11%) (Figure 38).

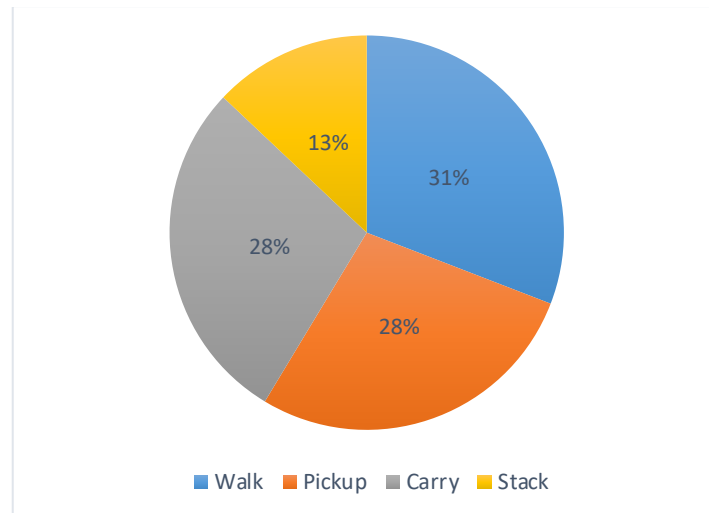


Figure 37: Time composition per element for manual extraction for the 50m FT harvesting system

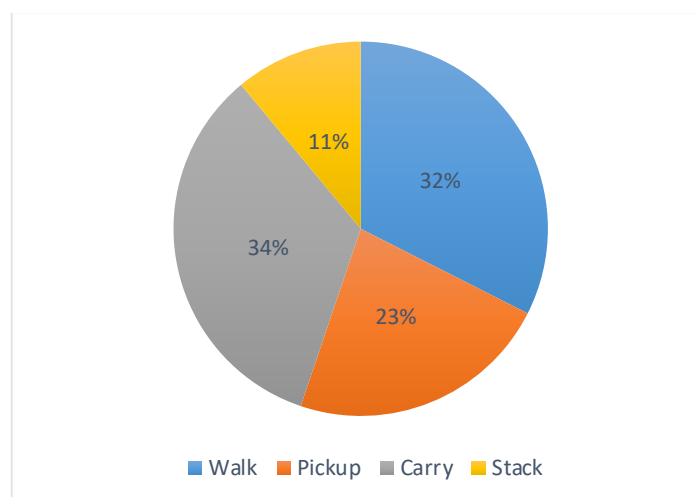


Figure 38: Time composition per element for manual extraction for the 100m FT harvesting system.

b. The effect of distance on manual stemwood extraction

The FT harvesting system extraction operation took place over two lengths, a short distance (50m), and a long distance (100m), as indicated in section 5.3.2.1. As 100m is the average distance between most harvesting sites and the extraction point, the long distance was utilised to determine the time required to collect woody biomass from the site to the roadside. According to descriptive statistics, it will take four workers 9.9 h to manually extract the 1,180 pieces of woody biomass pieces in the 100m extraction distance (Table 30).

Table 30: FT harvesting system productivity for the long distance (100m) (see Annexures 7)

Variables	Extraction = 4 labourers (h/ha)			
	Mean	Standard Deviation	Minimum	Maximum
FT (100m)	9.9	2.005	7.2	13.3

5.3.1.3 Manual woody biomass loading operation

The manual loading of the woody biomass operation was conducted only on the FT harvesting system. The stacking of the logs on roadside in preparation for loading was the same for both harvesting systems. The manual loading operation comprised of different elements, namely, walking, picking up of the woody biomass, the handover, stacking woody biomass and standing (Figure 39).



Figure 39: Stemwood manual loading operation.

Four sample plots of woody biomass were loaded on a tipper truck in order to determine the time taken for manual loading. The manual loading operation took 5.6h on average to load 455 woody biomass pieces (Table 31).

Table 31: Manual loading productivity for FT harvesting system (see Annexures 7)

Variables	Loading = 4 labourers (h)			
	Mean	Standard deviation	Minimum	Maximum
FT	5.6	1.9	3.6	8.6

After examining the productivity data, a breakdown of the various elements was compiled to determine the most and least time-consuming component. It was discovered that the log handover, which consumed 54% of the overall time, was the most time-consuming component. The least time-consuming elements were standing (5%) and walking (6%) (Figure 40). This might be as a result of the truck being stationed by the roadside, which made loading easier and the short walking distance.

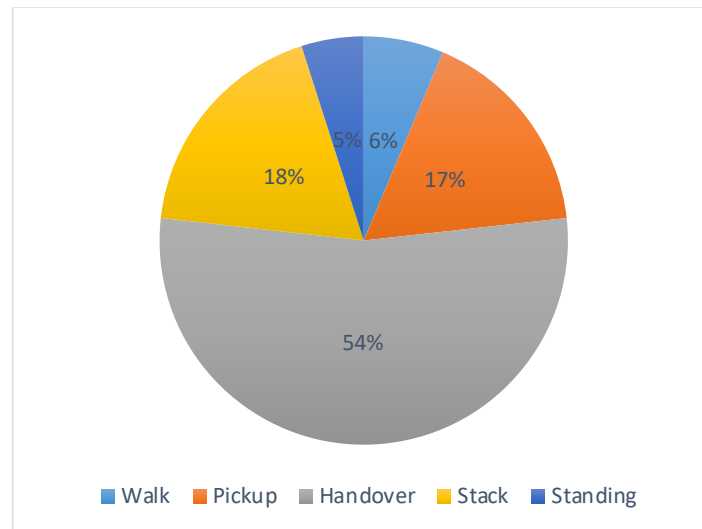


Figure 40: Time composition of manual loading elements for FT harvesting system

5.3.1.4 Biomass collection costs

For all the operations, the rand/ha and rand/odt were calculated once more using descriptive statistical analysis (motor-manual processing, manual extraction, and manual loading). The total costs/ha were calculated using an hourly rate for each operation. Costs associated with all operations for the FT harvesting system were 373.3 ZAR/ha and 75.6 ZAR/odt (Table 32). To calculate the overall expenses of the operations, the following equation was used:

Total ZAR/ha= [(motor manual processing h/ha x 19) + (manual extraction h/ha x 20) + (manual loading h/ha x 19)].

Table 32: Cost/ha for stemwood collection after FT harvesting (see Annexures 7)

Variables	ZAR/ha		ZAR/odt	
	Mean	Standard deviation	Mean	Standard deviation
FT (100m)	378.3	81.330	75.6	11.928

5.3.2 Tree length harvesting system results

The descriptive statistics tests were conducted for the TL harvesting system to determine the motor manual processing, manual extraction and manual loading results.

5.3.2.1 Motor manual processing of residues operation

During the observations of the motor manual processing, a chainsaw operator was employed to process (debranched and crosscut) the forest residues. This was done to improve handling of the woody biomass after harvesting commercial wood. A waiting period of four weeks was implemented to allow the forest residues to dry to reduce the weight (moisture content). According to the descriptive statistics results, it was discovered that the chainsaw operator took 7.2 h to process and produce 1 590 woody biomass pieces from the TL harvesting system (Table 33).

Table 33: Motor manual processing productivity for the total area (see Annexures 7)

Variables	Processing = 1 Chainsaw operator (h)			
System	Mean	Standard deviation	Minimum	Maximum
TL (195m)	7.2	2.898	4.0	12.0

A breakdown of the motor-manual processing operation was conducted in order to determine the most consuming element for the TL harvesting system. The subtasks comprised of crosscutting, log movement, debranching, to move to and from the refuelling stations, refuelling, and inspections and delays. According to the results, cross-cutting took the most time (33%), and refuelling took the least time (3%) (Figure 41).

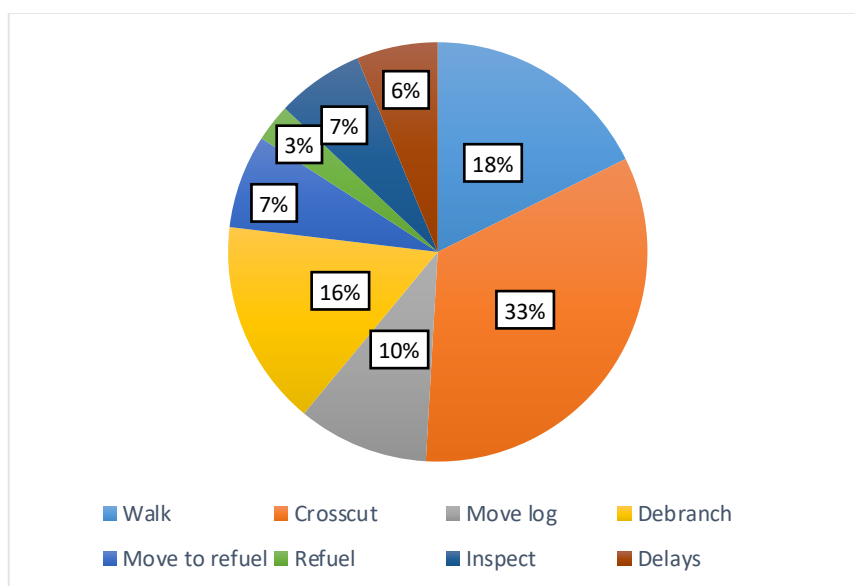


Figure 41: Composition of motor manual processing elements

5.3.2.2 Manual extraction of woody biomass

The manual extraction of the woody biomass was performed after the motor manual processing operation. This operation data was divided into two subsets, based on the extraction distance. The first subset included the manual extraction of woody biomass from the first half of the plots, nearest to the roadside (TL harvesting system= 95m). The second subset included manual extraction from the end of the plots to the roadside (TL system=195m).

a. Activity sampling time study for TL harvesting systems

A breakdown of the manual extraction operation component was conducted to determine the most and least time-consuming element for the TL harvesting system. The results indicated that the most time-consuming element was the log pickup, which took 27% of the total time for the 95m extraction distance (Figure 42). This was due to a higher quantity of woody biomass distributed over the shorter distance. This was because of the log optimisation at the roadside as well as the skidder dragging some residues to roadside during extraction (Figure 43).

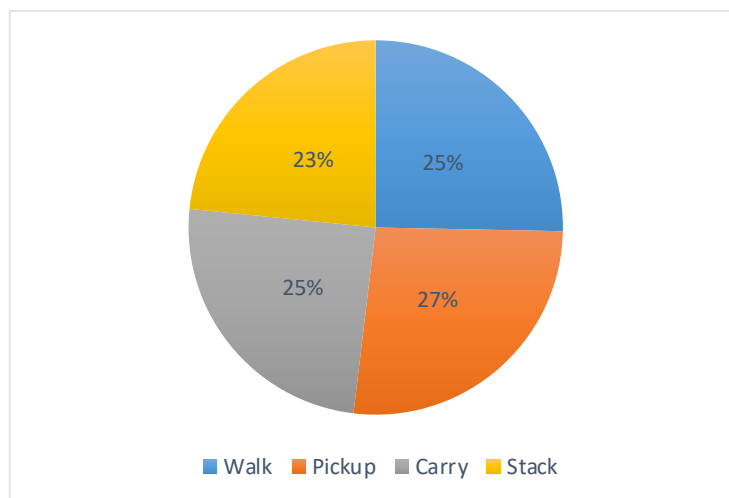


Figure 42: Composition of manual extraction for the 95m TL system

Over the 195m extraction distance, the most time-consuming element during the TL harvesting system was walking, which took 32% of the total time, whilst the least was stacking with 16% (Figure 44). This resulted from longer distances and the woody residues distributed across the sample plots.

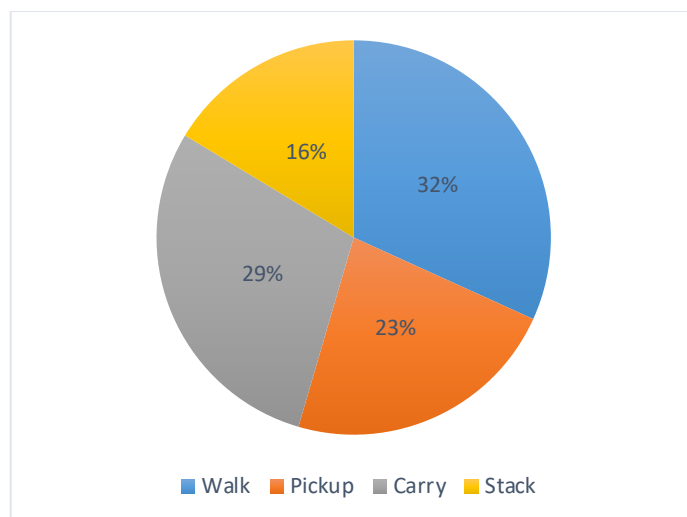


Figure 43: Composition of manual extraction for the 195m TL system

b. The effect of extraction distance on manual stemwood extraction

As described in section 5.3.2.1, the extraction operation occurred in two instances: short (95m) and longer distances(195m). In order to be similar to the FT system extraction distance for any future assessments, the TL harvesting system distances were separated in this approach. According to the extraction of woody biomass throughout the full distance, the TL harvesting system took 33.9 h/ha (Table 34). In the TL harvesting system, 1,590 pieces of woody biomass were extracted. As a result, the dispersed distribution of the woody biomass influenced time consumption.

Table 34: Manual extraction productivity for the total area (see Annexures 7)

Variables	Extraction = 4 labourers (h/ha)			
	Mean	Standard Deviation	Minimum	Maximum
TL (195m)	33.9	11.072	24.4	58.2

After equalising the extraction distance by considering only half of the extraction distance for the TL harvesting system, manual extraction still required more time, taking 23.5 h/ha (Table 35).

Table 35: Manual extraction productivity for the equalised distance 95m. (see Annexures 9)

Variables	Extraction = 4 labourers (h/ha)			
System	Mean	Standard Deviation	Minimum	Maximum
TL (95m)	23.5	8.658	12.7	36.5

5.3.2.3 Manual woody biomass loading operation

As discussed in 5.1.1.4, manual loading was conducted only on the FT harvesting system. The layout of the logs on the roadside in preparation for loading was the same from both harvesting systems. Therefore, manual loading productivity inferences can be made for the TL system based on the results from the FT system manual loading data. According to the results, the TL system manual loading required an average of 9.9h/ha (Table 36). As mentioned above in 5.3.2.2, because there was more woody biomass, the TL system harvesting operation took longer.

Table 36: TL system loading productivity (see Annexures 7)

Variables	Loading = 4 labourers (h/ha)			
System	Mean	Standard deviation	Minimum	Maximum
TL	9.9	3.8	5.9	16.3

5.3.2.4 Biomass collection total cost

Cost calculations were made to determine the expenses of the biomass collection operation. A descriptive statistical test was conducted to determine the rand/ha and rand/odt on average for all operations (motor-manual processing, manual extraction, and manual loading). A rate per hour was determined for each operation to calculate the costs/ha. The costs were divided according to the manual extraction for both the full and half distances. For the full extraction distance, it was discovered that it will costs 1 024.4 ZAR/ha and 119.4 ZAR/odt to complete the operation (Table 37). After equalising the extractions distance, the results indicated that the TL harvesting system

will cost 827.9 ZAR/ha and 95.9 ZAR/odt (Table 38). The following equation was utilised to determine the total costs for the operations:

$$\text{Total ZAR/ha} = [(\text{motor manual processing h/ha} \times 19) + (\text{manual extraction h/ha} \times 20) + (\text{manual loading h/ha} \times 19)].$$

Table 37: Full extraction distance costs/ha for woody biomass collection (see Annexures 7)

Variables	ZAR/ha		ZAR/odt	
	Mean	Standard deviation	Mean	Standard deviation
TL (195m)	1024.4	252.726	119.4	25.730

Table 38: Equalised distance costs/ha for woody biomass collection (see Annexures 9)

Variables	ZAR/ha		ZAR/odt	
	Mean	Standard deviation	Mean	Standard deviation
TL (95m)	827.9	252.726	95.9	25.730

5.3.3 Illustrating the equalised distance for the operations

The equalised distance results showed that the manual extraction on both systems was significantly different with a p-value of 0.0831 whilst the manual processing and manual loading was not significantly different. The results revealed that the manual extraction will require 2h/odt and 2.8h/odt for FT system and TL system, respectively. Both systems require 1.1 h/odt for manual loading while the motor manual processing requires 0.6 h/odt for the FT system and 0.8 h/odt for the TL system (Table 39)

Table 39: Biomass collection recovery productivity in h/odt (see Annexures 11)

Variables	Extraction h/odt		Processing h/odt		Loading h/odt	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
FT (100m)	2.0	0.529	0.6	0.144	1.1	0.000
TL (95m)	2.8	0.577	0.8	0.345	1.1	0.000

5.4 BIOMASS RELATIONSHIP COMPARISONS

The scatterplots visualise the relationship between three variables namely recovered (woody biomass), unrecovered (stemwood, needles, branches, twigs and cones) and the total biomass (woody biomass, stemwood, needles, branches, twigs and cones) for both harvesting systems. Figure 44 represents the relationship between the biomass recovered versus the total biomass quantity. The total biomass (odt/ha) serves as the dependant variable with the biomass recovered (odt/ha) serving as the independent variable.

Figure 45 represents the relationship between the unrecovered biomass and the total biomass, with the unrecovered biomass(odt/ha) serving as the dependant variable and the total biomass (odt/ha) serving as the independent variable. In Figure 44, the relationship between the two variables shows that the regression line is weak due to the high variability in the data (although highly significant and quite logical), shown by the $r^2 = 0.21$.

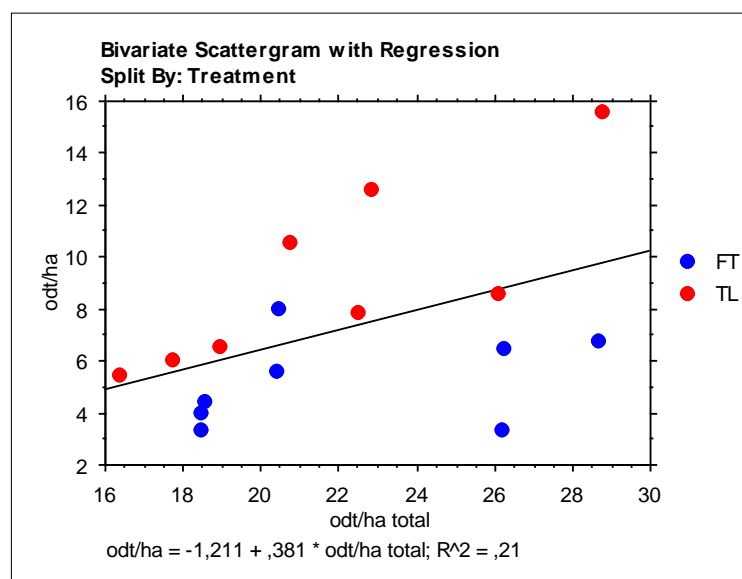


Figure 44: Relationship between biomass recovered and total biomass

The scatterplot in Figure 45 indicates that the relationship between the two variables (unrecovered biomass and total biomass), regression is weak due to the high variability in the data with an r^2 of 0.411.

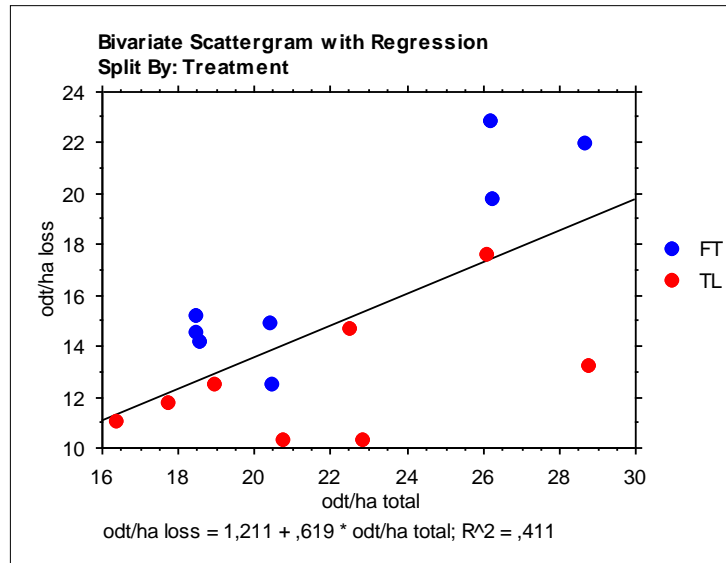


Figure 45: Relationship between unrecovered biomass and total biomass

Both graphs indicates that the amounts of recovered and unrecovered biomass increase with the total biomass available for collection. This actively demonstrates that the more available biomass on the ground, the higher the possibility to recover some portion of it, especially if the timber has been harvested according to the TL harvesting system. In contrast, the recovery ratio is less dependent on the overall amount of residues available when the timber has been harvested using the FT harvesting system.

5.5 COMPARISON OF TERRAIN CONDITIONS

In this section a comparison is conducted between stand system combinations, whereby larger trees on flat terrain are harvested by the FT system and smaller trees on steep terrain are harvested using the TL system. The focus is not comparing equivalent harvesting systems in order to select the best system, but rather to produce a benchmark for productivity and biomass recovery for each system within these specific conditions. This is in order to assist in biomass recovery plans. Therefore, the benchmarks are estimated as a function of prevalent site conditions within the range of variation of each individual case.

The FT harvesting system terrain condition was on a gentle (11% to <21%) slope, and the TL harvesting system was on moderate (20% to <30%) to steep 1 (30% to < 35%) slope. This comparison will include all the processes that were determined using the descriptive statistics. The flat and steep terrain conditions were used to determine the

productivity and biomass recovery differences. The standing trees and log volumes for both terrain conditions were further analysed for both harvesting systems. For both harvesting systems, the significant differences between the flat (FT) and steep (TL) terrain was tested with nonparametric assumptions by using the Mann Whitney U test.

5.5.1 Comparison of biomass quantification

The standing tree volumes on flat (FT) and steep (TL) terrain was of 91.5 m³/ha and 61.5 m³/ha, respectively. Whilst log volumes on flat (FT) and steep (TL) was on average 73.6 m³/ha and 50.2 m³/ha, respectively. The Mann Whitney U test indicated that this difference was significant on standing trees and log volumes (p-value 0.0028 and 0.0323).

The biomass quantification and biomass recovery differences between the terrain conditions were determined using descriptive statistical analysis. The results show that on flat (FT) and steep (TL) terrain, the biomass recovery produced 5.2 odt/ha and 9.1 odt/ha with a p-value of 0.0239. For the unrecovered biomass, the flat terrain conditions yielded 17.1 odt/ha while the steep terrain condition yielded 12.7 odt/ha, with a significantly different p value of 0.0207.

A percentage nearer (volume of recovered biomass) by the roadside indicated that on flat terrains the average produced 0.7% and on steep terrain it was 0.5%. This showed that there is significant difference between the terrain conditions with a p-value of 0.0039. However, the total biomass (recovered and unrecovered) averages were found as 22.3 odt/ha and 21.9 odt/ha, respectively. Hence, there was no significant difference between the flat and steep terrain conditions with p-value of 0.9581. Moreover, the recovery ratio was determined between both terrain conditions. On average flat terrain produced 0.2 recovery ratio and on steep terrain it was 0.4 recovery ratio. This was significant difference (p-value 0.0054) as this indicate the relationship of recovery ratio on both terrain conditions.

5.5.2 Biomass collection productivity comparisons

Comparisons were conducted to determine if there were differences in manual biomass collection on flat and steep terrain conditions. Motor manual processing operations were studied on both terrain conditions which showed that flat terrain produced 2.7 h/ha and steep terrain produced 7.2 h/ha. Statistically, it was found that

there was a significant difference (p-value 0.0009) between motor manual processing productivity on the flat and steeper terrain.

For the manual extraction distances, as mentioned above, was divided into two distances, half and full distance. On the full extraction distance for flat and steep terrain, the averages were found to be 10 h/ha to extract 1 180 woody biomass pieces and 33.9 h/ha to extract 1 590 pieces of woody-biomass, respectively. Thus, there was a significant difference (p-value 0.0009) in the extraction productivity conducted on flat and steep terrain. After equalising the distance, it was found that on flat terrain the woody biomass was extracted at 10 h/ha and steep terrain was at 23.9 h/ha. This indicated that there is a significant difference because of a p-value of 0.0014 between the terrain conditions for the equalised extraction distance. Moreover, the manual loading productivity averages were determined for terrain conditions. It was found that 455 woody-biomass pieces were loaded in 5.6 h/ha on the flat terrain condition. For the steep terrain, productivity results were based on the flat terrain results as manual loading was only performed on flat terrain. It was discovered that it will take 9.9 h/ha to load woody biomass on steep terrain. Therefore, this is statistically different with a p-value of 0.0239 between the two terrains on loading woody biomass.

5.5.3 Biomass recovery costs comparisons

Biomass collections costs were determined in both terrain conditions for all the operations (Table 40). The cost determination was separated into two variables, ZAR/ha and ZAR/odt. The averages for each variable were determined in both terrain conditions. On the full extraction distance, the flat terrain will cost R378.3/ha and R75.6/odt. On steep terrain full extractions will cost R1024.4/ha and R119.4/odt, with a p-value of 0.0074 between the two variables on steep full extraction. After equalising the extraction distances, it was found that on the steep terrain it will cost R827.9/ha and R95.9/odt, however the cost remains the same on flat terrain due to the extraction being slightly different from the steep terrain. There was significant difference (p-value 0.1278) between the equalised extraction distances on both terrain conditions.

Table 40: Significant difference between the two systems (Annexure 6, 8 and 10)

		Variables	Terrain	Systems	P-value	Mann whitney U test
Biomass quantification						
Extraction distance (m)		Standing trees (m³/ha)	Gentle	FT	0.0028	Significant difference
			Steep 1			
		Log volume (m³/ha)	Gentle	FT	0.0428	Significant difference
			Steep 1	TL		
		Recovered (odt/ha)	Gentle	FT	0.0239	Significant difference
			Steep 1	TL		
		Unrecovered (odt/ha)	Gentle	FT	0.0207	Significant difference
			Steep 1	TL		
		Odt/ha (recovered & unrecovered)	Gentle	FT	0.9581	No significant difference
			Steep 1	TL		
		% nearer (volume of stemwood)	Gentle	FT	0.0039	Significant difference
			Steep 1	TL		
		Recovery ratio	Gentle	FT	0.0054	Significant difference
			Steep 1	TL		
Biomass collection productivity						
		Motor manual processing (h/ha)	Gentle	FT	0.0009	Significant difference
			Steep 1	TL		
100m			Gentle	FT	0.0009	Significant difference
195m			Steep 1	TL		
		Manual extraction (h/ha)	Gentle	FT	0.0014	Significant difference
100m			Steep 1	TL		
95m			Gentle	FT	0.0239	Significant difference
			Steep 1	TL		
		Manual loading (h/ha)	Gentle	FT	0.0239	Significant difference
			Steep 1	TL		

Extraction distance (m)	100m	Motor manual processing (h/odt)	Gentle	FT	0.1278	No significant difference
			Steep 1	TL		
	95m	Manual extraction (h/odt)	Gentle	FT	0.0.831	Significant difference
			Steep 1	TL		
		Manual loading (h/odt)	Gentle	FT	0.3815	No significant difference
			Steep 1	TL		
Biomass collection costs						
Extraction distance (m)	100m	ZAR/ha	Gentle	FT	0.0009	Significant difference
			Steep 1	TL		
	195m	ZAR/odt	Gentle	FT	0.0074	Significant difference
			Steep 1	TL		
	100m	ZAR/ha	Gentle	FT	0.0009	Significant difference
			Steep 1	TL		
	95m	ZAR/odt	Gentle	FT	0.1278	No significant difference
			Steep 1	TL		

5.6 SUMMARY RESULTS

In this chapter, the research findings and discussions of biomass recovery, productivity and costs for FT and TL harvesting systems in manual biomass collection were discussed. A data analysis of biomass recovery, biomass collection productivity, assessment of costs and comparison on both terrain conditions results were provided. In this section, the manual biomass collection productivity, biomass recovery and costs were determined. These results can be applied to determine the productivity and biomass recovery results to post harvesting systems. The next chapter will give a conclusion and recommendations of this research. The key findings of the research will be outlined with linkages to existing literature.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

This concluding chapter provides a summary of the research findings and aims to address the objectives of the research stated in Chapter 1. The benefits of the research to the forestry industry are deliberated and recommendations for future research are drawn.

6.2 SUMMARY AND DISCUSSIONS OF KEY FINDINGS

A summary of the research problem and methodology is discussed. This is followed by an outline of the key findings of the biomass quantification and recovery, manual biomass collection productivity and costs.

6.2.1 Summary of research findings and research methodology applied

Biomass collection operations have increased because of the use of biomass harvesting machines and systems. Nowadays, the processing of biomass can be carried out by chipping and grinding machines infield (McEwan, et al. 2020). Miller, et al. (1987) states that biomass is commonly extracted using machines, although manual methods are still applied where labour costs are affordable, and employment generation is a priority social goal. The research was conducted to address the lack of scientific information relating to manual biomass collection in South Africa. The research focussed on the quantification, productivity, and costs of manual biomass extraction for *Pinus patula* species. The research aimed at determining the biomass recovery and productivity for two distinct harvesting systems.

In this research, the FT and TL harvesting systems were evaluated during clear fell operations in two different compartments with different site conditions (terrain, tree size and age). In both compartments, the same manual biomass collection method was applied. The two harvesting systems could not be compared directly because of the significantly different conditions in which they worked; however, comparisons were derived relative to the terrain conditions on which the two systems are known to operate in.

The questions outlined in Chapter One were answered with the following results:

- The biomass recovery for each harvesting system was determined. The results indicated that in both harvesting systems there was a difference of 3.9 odt/ha in woody biomass recovered and a difference of 4.4 odt/ha in unrecovered residues (details produced under 6.2.2).
- The productivity of both harvesting systems was determined. According to the results, it will take 10h to manually extract 0.51 odt/h of woody biomass, 2.7 h to manually process 1.90 odt/h, and 5.6 h to manually load 0.92 odt/h for the FT system. Moreover, the results indicated that the manual extraction would take 2h/odt. The results for the TL system showed that manual extraction would require 23.5 h to yield 1.27 odt/h, while manual motor processing and manual would require 7.2 h and 9.9 h, respectively, to produce 0.39 odt/h, 1.27 odt/h, and 0.92 odt/h.
- The costs of the operation were determined. It was determined that the FT system will cost R75.6/odt to perform all operations, whereas the TL system will cost R95.9/odt (including motor manual processing, manual extraction and manual loading).
- Additional factors that may affect productivity included distance, weather and distribution of biomass, but those could not be measured in this study.

6.2.2 Key findings of biomass quantification results and discussion

The amounts of recovered and unrecovered biomass were determined for both harvesting systems. The relationship between the total biomass, recovered and unrecovered biomass was examined.

- The FT system had an average woody biomass recovery rate of 5.2 odt/ha, while the TL system had an average recovery rate of 9.1odt/ha – resulting in a difference of 3.9 odt/ha. This difference was possibly due to the availability and distribution of the biomass for each system.
- When quantifying the unrecovered biomass, the results showed a distribution of 17.1 odt/ha for the FT system and a distribution of 12.7odt/ha for the TL system produced.
- The relationship between the variables (total biomass and recovered biomass) was weak due to a low r^2 value of 0.2, while the total biomass and unrecovered residues had an r^2 value of 0.4, illustrating this difference. Thus, the availability (total odt/ha)

of the biomass does not result in higher or lower production rates but is instead influenced by the total volume available. Hence a conclusion is not based on the relationship of these variables.

6.2.3 Key findings and discussion of productivity of manual biomass collections results

The productivity of manual biomass collection was determined separately for motor manual processing, manual extraction and manual loading. After determining the productivity in h/ha, the productivity in odt/ha was determined when the extraction distance was equalised between the two extraction areas.

The main productivity findings for the FT and TL harvesting systems were as follows:

- For the FT system, the motor manual processing operation took 2.7h/ha to process and produce 1 180 odt pieces of woody biomass. The most time-consuming element was crosscutting while the least time-consuming task was refuelling
- The TL harvesting system took 7.2 h/ha to process and produce 1 590 odt pieces of woody biomass material, but productivity was influenced by the steep terrain. Residue distribution, debris accumulation and the larger quantity of woody biomass material also affected the completion time. The distribution of the residues increased the processing time spent in the TL system as the operator had to remove debris to work properly. The time consumed was due to larger quantity of woody biomass remaining on site.
- Moreover, the most time-consuming task was crosscutting with 33%, while the least time-consuming task was refuelling with 3%.
- The productivity results of the manual extraction operation indicated that the FT system will spend 10 h/ha and TL system would take 33.9 h/ha on average to extract 1 180 odt pieces and 1 590 odt pieces of woody biomass in full distance, respectively. After equalising the extraction distance, the TL system will spend 23.5 h/ha whilst the FT system remains the same. In this operation the distance was the main factor that influenced the results. The most time-consuming component on the equalised distance was walking (33%) and log pickup (27%) for FT and TL system, respectively. The log pickup element percentage on TL system was because of high quantity of biomass distributed by the roadside. Over the full distance, the walking component accounted for 32% of the total time consumption

under the TL treatment whilst under the FT treatment, carrying was the dominant task and accounted for 34% of the total time consumption.

- Manual loading of the woody biomass was conducted only on the FT harvesting system. The productivity results showed that the FT system will spend 5.6 h/ha and the TL system 9.9 h/ha on average to load 455 odt pieces of woody-biomass. Moreover, the most time-consuming element in the FT system was handing over of the woody biomass pieces which accounted for 54% of the overall time.

6.2.4 Key findings and discussion of costs of the operation results

The costs of the manual biomass collection operation to quantify recovered residues in FT and TL harvesting system were determined and discussed.

- When biomass collection is conducted after FT harvesting, manual biomass recovery will cost R 378/ha or R75.6/odt. Whilst after the TL system, it will cost R827.9/ha and 95.9/odt.

6.3 RELATION OF RESEARCH RESULTS TO THE LITERATURE

The literature showed that there is no existing scientific information on the manual collection of woody biomass in *Pinus patula* stands, which is why this research was vital for the forestry industry as a whole. No conclusion was drawn as to whether these findings agree or disagree with previous studies as this research was exploratory in nature. In searching for relevant literature, it was taken into consideration that the current study did not duplicate any previous studies completed in the past. However, the gap identified indicated a need to investigate the quantity of residues and determine the productivity rates of collecting woody biomass manually after a harvesting operations using the FT and TL system.

Most existing studies on the subject, focused on mechanised systems where biomass is collected in the form of bundlers and communiton is performed by chippers and grinders. However, Eker, et al. (2017) investigated three options for manual biomass recovery after the motor-manual harvesting of Turkish pine (*Pinus brutia*). The extraction of woody biomass was similar to the CTL motor manual system because the woody biomass was carried uphill. Eker, et al. (2017) reports that the recovered woody biomass amounted to 11.9 t/ha and took 8.75h/ha to complete, with another

14.8 h/ha dedicated to manual processing and woody biomass extraction. That corresponded to a productivity of 0.72t/h and 0.79 t/h, respectively.

Additional studies performed by (Eker 2011) offer similar results: recovered woody biomass was 6.6 t/ha and the productivity of manual collection was 0.22 t/h. The productivity rate of manual loading was 2.4 t/ha which will cost R70.98/odt. Both previous studies focused on two workers, not four workers as this study did. The fact that relatively similar results are obtained from different studies with different quantities of workers may indicate that team size has little effect on the productivity of labour intensive operations, at least in the cases of small woody biomass processing operations (Eker 2011). Spinelli, et al. (2012) adds that smaller quantities of woody biomass units are known to produce a very low rate of productivity for a recovery operation.

In addition, a study conducted by (Ghaffariyan 2013, Ghaffariyan and Apolit 2015) in a CTL and FT method showed, when quantifying a proportion of unrecovered residues, the largest parts were found to be the stemwood and branches. There is little information available on the impact of the harvesting methods and its relationship to the amount of remaining slash distributed over the site. However, Ghaffariyan, et al. (2012b) found that the minimum diameter requirements for the industry and cost of biomass extraction are the key factors affecting the amount of biomass available. In terms of the available literature on this research, the comparative results cannot be used because the studies were too different. There was no literature focusing on biomass recovery in *Pinus patula* in South Africa.

6.4 VALUE OF RESEARCH RESULTS TO THE FORESTRY RESEARCH

The results and information presented in this study have the potential to assist foresters, contractors, decision makers and many other forestry stakeholders, locally and internationally, by providing:

- Recovered and unrecovered biomass estimates for mechanised FT and semi-mechanised TL systems in the clear felling of *P patula*
- Productivity and cost estimates of motor manual processing, manual collection and extraction and loading of recoverable biomass after mechanised FT and semi mechanised TL harvesting in *P patula* stands.

- Factors influencing woody biomass recovery after mechanised FT and semi mechanised TL harvesting in *P patula* stands
- A guide for grower companies who want to integrate local communities into their business model, by providing financial and productivity estimates.

6.5 RECOMMENDATIONS

The results of this research responded to the main questions described in Chapter 1. The research only considered two harvesting methods however, various other harvesting systems can potentially be investigated, and more valuable information can be gathered on the factors influencing biomass recovery and manual collection productivity in South Africa. In particular, the CTL harvesting system was not included in this study; hence it is recommended that future research focuses on CTL to assess and compare with the current result on biomass recovery.

The research only considered the two current systems available and the present terrain conditions for manual biomass recovery. It is recommended that future research focus on other harvesting systems operating in similar conditions to allow for comparative analysis

The research did not comprehensively explore the manual loading activity. It is recommended that future studies focus on the factors influencing the productivity of people loading woody biomass manually and on the impact of biomass characteristics on secondary timber transport payloads and overall efficiency. In addition, the research did not investigate environmental impacts such as soil disturbance, reduction of soil nutrients and other possible environmental concerns associated with biomass harvesting. Future research can focus on understanding the environmental impacts posed by the collection of biomass residues on harvested stands.

Manual biomass recovery has specific wood size and distance limits, because workers cannot handle loads heavier than 20 kg on a regular basis, nor can they move these loads over distances exceeding 100 m (Eker, et al. 2017). Therefore, use of the systems described in this study requires that a dense forest road network is available, or that additional implements (e.g. carts) are introduced. In any case, heavy manual work is taxing and inherently dangerous. Therefore, the systems described in this study should be analysed further for additional risks. The scope of this research

focused on collecting biomass manually only, however, future studies can consider alternative semi-mechanised options.

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Annexures 1: Standing tree DBH and height

[illegible]

Annexures 2: Time study form

[illegible]

Annexures 3: Unrecovered slash assessment

Forest:				Assessors:				
Location:								
Date:								
Plot	Weight	Vessel weight	Nett weight	Stemwood	Branches (>30mm)	Branches (<30mm)	Twigs and leaves	Cones

Annexure 4: Standing trees and log recovery volumes descriptive statistics

Variable	Aggregate Results Descriptive Statistics (Spreadsheet in Total distance)									
	Treatment	Valid N	Mean	Median	Minimum	Maximum	Quartile Range	Std.Dev.	Coef.Var.	Standard Error
Standing trees (m3)	FT	8	91.45825	90.73400	73.56000	119.6540	16.06400	14.43944	15.78801	5.105113
Utilisable (m3)	FT	7	73.59300	72.68100	45.44100	98.6760	41.57900	19.90488	27.04724	7.523336
Standing trees (m3)	TL	8	61.50975	62.39950	45.74200	84.26400	16.35550	12.28559	19.97341	4.343613
Utilisable (m3)	TL	8	50.28613	48.13100	35.71300	65.91200	15.57900	10.71573	21.30951	3.788582

Annexure 5: Objective One: Biomass quantification descriptive statistics

Variable	Aggregate Results Descriptive Statistics (Spreadsheet in Data results 2)									
	Treatment	Valid N	Mean	Median	Minimum	Maximum	Quartile	Std.Dev.	Coef.Var.	Standard
odt/ha (Stemwood)	FT	8	5.20898	4.97245	3.28961	7.99350	2.936642	1.735969	33.32648	0.613758
% nearer (volume of stemwood located FT 50m/ TL 95m)	FT	8	0.72231	0.74950	0.44191	0.89459	0.068927	0.130327	18.04325	0.046078
odt/ha loss (Remaining branches, bark and needles)	FT	8	17.09393	15.12900	12.54600	23.02560	6.605100	3.989286	23.33745	1.410425
odt/ha total (Stemwood and bark, branches and needles and cones)	FT	8	22.30290	20.52773	18.56621	28.85509	7.736949	4.195151	18.80989	1.483210
Recovery ratio (Ratio of collected stemwood to total residues remaining)	FT	8	0.23614	0.23457	0.12586	0.38918	0.061645	0.076322	32.32027	0.026984
odt/ha (Stemwood)	TL	8	9.13152	8.19659	5.41262	15.58512	5.269684	3.539032	38.75620	1.251237
% nearer (volume of stemwood located FT 50m/ TL 95m)	TL	8	0.46841	0.44703	0.34725	0.64333	0.168123	0.107319	22.91133	0.037943
odt/ha loss (Remaining branches, bark and needles)	TL	8	12.73050	12.17700	10.33200	17.71200	3.321000	2.518176	19.78066	0.890310
odt/ha total (Stemwood and bark, branches and needles and cones)	TL	8	21.86202	21.73522	16.48262	28.86912	6.122057	4.206618	19.24167	1.487264
Recovery ratio (Ratio of collected stemwood to total residues remaining)	TL	8	0.40935	0.34487	0.32499	0.54920	0.188759	0.101884	24.88913	0.036022

Annexures 6: Objective One: Biomass quantification Mann Whitney

Mann-Whitney U Test (w/ continuity correction) (Sheet1 in Data results 2)										
By variable Treatment										
Marked tests are significant at p < .05000										
variable	Rank Sum FT	Rank Sum TL	U	Z	p-value	Z adjusted	p-value	Valid N FT	Valid N TL	2*1sided exact p
odt/ha (Stemwood)	46.00000	90.00000	10.00000	-2.25795	0.023949	-2.25795	0.023949	8	8	0.020668
% nearer (volume of stemwc	96.00000	40.00000	4.00000	2.88808	0.003876	2.88808	0.003876	8	8	0.001865
odt/ha loss (Remaining bran	90.50000	45.50000	9.50000	2.31046	0.020863	2.31387	0.020676	8	8	0.014763
odt/ha total (Stemwood and	69.00000	67.00000	31.00000	0.05251	0.958122	0.05251	0.958122	8	8	0.959130
Recovery ratio (Ratio of c	41.00000	95.00000	5.00000	-2.78306	0.005385	-2.78306	0.005385	8	8	0.002953

Annexures 7: Objective Two: Productivity of manual biomass collection descriptive statistic (100m and 195m)

Variable	Aggregate Results Descriptive Statistics (Spreadsheet in Data results 2)									
	Treatment	Valid N	Mean	Median	Minimum	Maximum	Quartile Range	Std.Dev.	Coef.Var.	Standard Error
Extraction h/ha	FT	8	9.8991	10.2083	7.2000	13.3333	2.7835	2.00514	20.25587	0.70892
Chainsaw h/ha	FT	8	2.7325	2.8177	1.8296	3.5803	0.7715	0.58371	21.36153	0.20637
Load h/ha	FT	8	5.6257	5.3702	3.5528	8.6330	3.1716	1.87485	33.32648	0.66286
ZAR/ha	FT	8	378.3087	350.8443	286.4475	490.8457	146.5075	81.33010	21.49834	28.75453
ZAR/odt	FT	8	75.5726	75.5941	61.1535	90.7043	23.2674	11.92812	15.78366	4.21723
Extraction h/ha	TL	8	33.872	31.3492	24.4328	58.245	10.4572	11.0727	32.68932	3.91478
Chainsaw h/ha	TL	8	7.159	6.0915	4.0367	11.991	4.6850	2.8984	40.48624	1.02473
Load h/ha	TL	8	9.862	8.8523	5.8456	16.832	5.6913	3.8222	38.75620	1.35134
ZAR/ha	TL	8	1024.425	969.0602	717.1192	1584.561	312.7764	275.3171	26.87529	97.33931
ZAR/odt	TL	8	119.378	124.2246	63.7632	150.641	29.6139	27.7402	23.23730	9.80763

Annexures 8: Objective Two: Productivity and costs of manual biomass collection Mann Whitney (100m and 195m)

Mann-Whitney U Test (w/ continuity correction) (Sheet1 in Data results 2)										
By variable Treatment										
Marked tests are significant at p <,05000										
variable	Rank Sum FT	Rank Sum TL	U	Z	p-value	Z adjusted	p-value	Valid N FT	Valid N TL	2*1sided exact p
Extraction h/ha	36,00000	100,0000	0,00000	-3,30816	0,000939	-3,30816	0,000939	8	8	0,000155
Chainsaw h/ha	36,00000	100,0000	0,00000	-3,30816	0,000939	-3,30816	0,000939	8	8	0,000155
Load h/ha	46,00000	90,0000	10,00000	-2,25795	0,023949	-2,25795	0,023949	8	8	0,020668
ZAR/ha	36,00000	100,0000	0,00000	-3,30816	0,000939	-3,30816	0,000939	8	8	0,000155
ZAR/odt	42,00000	94,0000	6,00000	-2,67804	0,007406	-2,67804	0,007406	8	8	0,004662

Annexures 9: Objective Two: Productivity and costs of manual biomass collection
descriptive statistic (100m and 95m)

Variable	Aggregate Results Descriptive Statistics (Spreadsheet in phozisa)										
	Treatment	Valid N	Mean	Median	Minimum	Maximum	Quartile Range	Std.Dev.	Coef.Var.	Standard Error	
Extraction h/ha Edit	Full tree method	8	9.8991	10.2083	7.2000	13.3333	2.7835	2.00514	20.25587	0.70892	
ZAR/ha Edit	Full tree method	8	378.3087	350.8443	286.4475	490.8457	146.5075	81.33010	21.49834	28.75453	
ZAR/odt Edit	Full tree method	8	75.5726	75.5941	61.1535	90.7043	23.2674	11.92812	15.78366	4.21723	
Chainsaw h/ha	Full tree method	8	2.7325	2.8177	1.8296	3.5803	0.7715	0.58371	21.36153	0.20637	
Load h/ha	Full tree method	8	5.6288	5.3732	3.5547	8.6377	3.1733	1.87587	33.32648	0.66322	
Extraction h/ha Edit	Tree length	8	23.5317	20.5520	12.6891	36.508	14.5577	8.6577	36.79166	3.06096	
ZAR/ha Edit	Tree length	8	827.9507	758.4626	526.5425	1261.082	357.8862	252.7260	30.52428	89.35213	
ZAR/odt Edit	Tree length	8	95.9836	102.6391	58.4471	128.035	44.8346	25.7297	26.80637	9.09683	
Chainsaw h/ha	Tree length	8	7.1589	6.0915	4.0367	11.991	4.6850	2.8984	40.48624	1.02473	
Load h/ha	Tree length	8	9.8675	8.8572	5.8488	16.841	5.6944	3.8242	38.75620	1.35208	

Annexures 10: Objective Two: Productivity and costs of manual biomass collection
Mann Whitney (100m and 95m)

variable	By variable Treatment Marked tests are significant at p <,05000									
	Rank Sum Full tree method	Rank Sum Tree length	U	Z	p-value	Z adjusted	p-value	Valid N Full tree method	Valid N Tree length	2*1sided exact p
Extraction h/ha Edit	37.00000	99.0000	1.00000	-3.20314	0.001360	-3.20314	0.001360	8	8	0.000311
ZAR/ha Edit	36.00000	100.0000	0.00000	-3.30816	0.000939	-3.30816	0.000939	8	8	0.000155
ZAR/odt Edit	53.00000	83.0000	17.00000	-1.52280	0.127809	-1.52280	0.127809	8	8	0.130381
Chainsaw h/ha	36.00000	100.0000	0.00000	-3.30816	0.000939	-3.30816	0.000939	8	8	0.000155
Load h/ha	46.00000	90.0000	10.00000	-2.25795	0.023949	-2.25795	0.023949	8	8	0.020668

Annexures 11: Objective Two: Productivity and costs of manual biomass collection
descriptive statistic (100m and 95) (odt/ha)

Variable	Aggregate Results Descriptive Statistics (Spreadsheet in Oven dry tons)					
	Treatment	Valid N	Mean	Minimum	Maximum	Std.Dev.
Extraction h/odt	FT	8	2.025656	1.300915	2.638734	0.528935
Chainsaw h/odt	FT	8	0.554956	0.410664	0.782662	0.144042
Load h/odt	FT	8	1.080000	1.080000	1.080000	0.000000
Extraction h/odt	TL	8	1.400965	0.643877	2.335657	0.577306
Chainsaw h/odt	TL	8	0.838609	0.399220	1.491051	0.345583
Load h/odt	TL	8	1.080000	1.080000	1.080000	0.000000

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OF TREATISE/DISSERTATION/THESIS TO THE EXAMINATION OFFICE

Please type or complete in black ink

FACULTY: Science

SCHOOL/DEPARTMENT: Cluster for Natural Resource Science & Management

I, (surname and initials of supervisor) Ramantswana, MM

and (surname and initials of co-supervisor) Spinelli, R ; McEwan, AM

the supervisor and co-supervisor respectively for (surname and initials of
candidate) _____

(student number) 216413311 a candidate for the (full description of qualification)

Thandekile Hazel Ncongwane

with a treatise/dissertation/thesis entitled (full title of treatise/dissertation/thesis):

The quantification of Pinus patula recovery and productivity of manually orientated biomass collection
in post mechanised full tree and semi mechanised tree length harvesting operations

It is hereby certified that the proposed amendments to the treatise/dissertation/thesis have been effected and that **permission is granted to the candidate to submit** the final bound copies of his/her treatise/dissertation/thesis to the examination office.



SUPERVISOR

07/12/2022

DATE

And



CO-SUPERVISOR

03/01/2023

DATE