Harvesting of Invasive Woody Vegetation (Eucalyptus *lehmanii, Leptospermum laevigatum, Acacia Cyclops*) as Energy Feedstock in the Cape Agulhas Plain of South Africa

by
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DECLARATION

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Abstract

This study is aimed at testing the possibility of using woody biomass from three invasive woody vegetation types (Spider Gum, Myrtle and Acacia) for production of bioenergy in the Cape Agulhas Plain. Physical recoverability of the woody biomass was studied by means of a semi-mechanized harvesting system to evaluate potential productivity, operational costs and the estimated yield energy gain.

The system consisted of five components: manual harvesting, motor-manual harvesting, extraction, chipping and road transport. Data on the system productivity was obtained using activity sampling and time study techniques. Activity sampling was applied on manual and motor-manual harvesting in order to record harvesting time and standard time study techniques were used to obtain time data for extraction, chipping and road transport operations.

Findings revealed benefits associated with the utilisation of invasive woody vegetation as energy feedstock. Therefore, the problem of exotic tree species can be dealt with by transforming them into energy feedstock, thus minimising the effect of invasive plants. At the same time essential biomass energy can be produced, while some of the cost of production could be offset by the benefits accruing from the biomass energy.

The Acacia site, characterized by larger mature dense trees, had the highest amount of harvested biomass compared to the rest of the vegetation types (i.e. Myrtle and Spider Gum).

The overall system productivity was found to be significantly influenced by a low equipment utilisation rate, estimated at 50%. This resulted in low production rates in general. The low supply rate of material to the chipper by the three-wheeled loader (1.5 – 5.3 oven-dry tonne per production machine hour) was found to be a major constraint in the chipping process, especially when considering that the chipper is potentially capable of chipping 4 – 9.4 ODT PMH^{-1} at the harvesting sites. This resulted in a significant energy balance of 463 GJ between output and input energy of the system. The overall total supply chain system costs based various road transport distances of species ranged from R 322.77 ODT^{-1} to R 689.76 ODT^{-1} with an average of R 509 ODT^{-1}. This was found to be costly compare to the case where high machine utilisation rate and optimal productivity are used (average of R 410 ODT^{-1}), biomass recoverability in this field trial had a higher total system cost due to low productivity, resulting from the low equipment utilisation rate applied.

Key words: Invasive tree species, energy feedstock, productivity, biomass recoverability, operational cost, man-day, energy balance

Uittreksel

Hierdie studie was gemik daarop om die moontlikheid van die gebruik van houtagtige biomassa, afkomstig van uitheemse plantegroei (Bloekom, Mirte en Akasias) op die Agulhasvlakte vir bio-energie te ondersoek. Potensiële produktiwiteit, bedryfskostes en die geskatte energie opbrengs toename is gebruik, om die fisiese opbrengs van houtagtige biomassa van ʼn semi-gemeganiseerde ontginningstelsel te evalueer.

Die stelsel het uit vyf komponente bestaan: Handontginning, motor-handontginning, uitsleep, verspandering en padvervoer. Data oor die stelselproduktiwiteit is uit tydstudie en aktiwiteit steekproewe verkry. Aktiwiteit steekproewe is toegepas op hand- en motor-handontgining om ontginingstyd te verkry, terwyl tydstudie standaardtegnieke gebruik is om tyd data vir uitsleep, verspandering en padvervoer werksaamhede te verkry.

Bevindings het die voordele met bettrekking tot die gebruik van uitheemse plantegroei as energiebron bevestig. Die uitdaging rondom die verspreiding van uitheemse plantegroei kan dus aangespreek word deur dit as energiebron te benut. Die produksiekoste vir die toegang tot die bruikbare biomassa kan moontlik voorsien word uit die voordele van die gebruik van die energie wat uit die benutting van die biomassa verkry word.

Die groter meer volwasse en digte Akasia opstand het die meeste ontginde biomassa gelewer vergeleke met die ander opstande in die studie (d.i. Mirte en Bloekom).

Die stelselproduktiwiteit is beduidend beïnvloed deur die lae toerustinggebruik wat minder as 50% beloop het. Dit het ook laer produksievermoë in die algemeen tot gevolg gehad. In die verspandering werksaamheid blyk die lae invoer tempo (1.5 – 5.3 oonddroog ton per produktiewe masjienuur) van die driewiellaaier die beperking op die proses te wees, veral as in ag geneem word dat die verspandering teen 4-9.4 ODT PMH^{-1} kan geskied. Die resultaat was ʼn beduidende energie balans van 463 GJ tussen uitset- en invoerenergie van die stelsel. Die totale toevoerketting kostes gegrond op verskeie padvervoer afstande van die spesies was tussen R 322.77 ODT^{-1} tot R 689.76 ODT^{-1}, met ʼn gemiddelde rondom R 509 ODT^{-1}. Die resultaat is duur gevind in vergeleke met gevalle waar hoë masjiengebruik en optimale produktiwiteit (gemiddeld van R 410 ODT^{-1}), moontlik was. Die biomassaherwinning in die studie het ’n hoer totale stelselkoste gehad veroorsaak deur lae produktiwiteit, wat verwant is aan die laer toerusting gebruikstempo wat verkry is.

Sleutelwoorde: Uitheemse plantegroei, energiebron, produktiwiteit, biomassaherwinning, bedryfskoste, mandag, energiebalans.

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List of Abbreviations and Acronyms

ODT:	Oven-Dry Tonne
Lndist:	Natural logarithm of the distance
Lnprod:	Natural logarithm of the productivity
Lncycle time:	Natural logarithm of the cycle time
WfW:	Working for Water
SRWC:	Short-Rotation Woody Crop
R: Rand:	(South African currency)
DME:	Department of Minerals and Energy
SRWC:	Short Rotation Woody Crops
USDA:	U.S. Department of Agriculture
DOE:	U.S. Department of Energy
FFRI:	Finnish Forest Research Institute
FAO:	Food and Agriculture Organization of the United Nations
GWh:	Giga Watt Hours
VAT:	Value Added Tax
RFA:	Road Freight Association
SVF:	Solid Volume Factor
RSB:	Roundtable on Sustainable Biofuels
IEA:	International Energy Agency
ANOVA:	Analysis of Variance
PMHo:	Productive Machine Hours (no delays)
HHV:	Higher Heating Value
LHV:	Lower Heating Value
DWAF:	Department of Water, Agriculture and Forestry

1. Introduction

1.1 Background and justification

Since the acceptance of the Kyoto protocol in 1997, interest in replacing fossil fuels with renewable alternatives has continued to increase. Reports and predictions of climate change and global warming have resulted in the recognition of the societal benefit of using alternative energy sources that are environmentally and socio-economically friendly. In recent years, South Africa has committed itself to the target of producing 10 000 GWh of electricity from renewable energy by 2013 (Department of Minerals and Energy, 2003). In order to reach this goal, many studies in the development and production of renewable energy are currently underway. Although South Africa has limited land potential for bioenergy production from woody biomass resources, it is playing a leading role as a technology developer in this field in Africa. One remarkable example for biomass utilisation is within the sugarcane industry, which is considered the most efficient bio-ethanol source in South Africa.

Several investigations have already been undertaken for various biomass types, including agricultural crops and wood harvesting residue. However, little attention has been paid to invasive vegetation as energy feedstock, creating the need to focus research on this widely unknown biomass resource.

Invasive vegetation in South Africa, as in other parts of the world, is becoming increasingly widespread (Richardson and Van Wilgen, 2004). A government program known as Working for Water (WfW) monitors the spread of invasive vegetation, but despite the efforts of WfW, invasive vegetation continues to spread and threaten the South African plant biodiversity and water resources. It is estimated that invasive vegetation occupies 8% of the South African land area (Marais *et al.,* 2001; Richardson and Van Wilgen, 2004).

Clearing invasive vegetation in South Africa is a large and complex problem, with high harvesting cost and low efficiency (Theron *et al.,* 2004), as indicated by the R800 million spent from 1995 to 2001 on the clearing of invading alien vegetation (Marais *et al.,* 2001). The return on investment in terms of biomass energy production has not been satisfactorily established and benefits that can accrue from harvested invasive plants are yet to be investigated.

An important consideration in the exploitation of invasive woody vegetation for energy production is the selection of the most efficient harvesting and transportation systems. This will ensure efficient and low-cost methods of harvesting and delivering biomass material from selected areas to processing plants. Fundamental factors to be considered in selecting a harvesting system are productivity, operational costs and net energy gain. These factors are crucial for the production of energy from invasive plants, since no managed plantation setup facilitating the harvesting and transport can be presumed.

This study was conducted in the Fynbos ecosystem of the Cape Agulhas Plains. A semi-mechanized harvesting system operated by a WfW team was used as a pilot study. The species harvested from the study area for energy feedstock included *Acacia Cyclops*, *Leptospermum laevigatum* (Myrtle) and *Eucalyptus lehmanii* (Spider Gum). Data from the harvesting operation was generated using activity sampling and time study techniques. The South African harvesting and transport costing model was applied to evaluate operational performance and costs.

1.2 Objective

The main objective of the study was to test the feasibility of using invasive woody vegetation for bioenergy generation, based on an example in the Agulhas Plain on the southern coast of South Africa. Net energy gains, harvesting productivity, and operational cost will be used as the key indicators.

Sub-objectives were to:

- quantify recoverable biomass per hectare under prevailing conditions;
- determine the productivity of the applied harvesting system;
- determine the production costs of the applied system and
- determine the potential net energy output and input.

1.3 Research Hypothesis

Possible cost of harvesting wood from invasive vegetation as a source of raw material for biomass production is hypothesised. The validity of the following alternative hypotheses will be tested:

H_A1: It is possible to identify variables that significantly affect the productivity of biomass extraction for the three prevailing tree species.

H_A2: Productivity of biomass extraction with the three-wheeled loader differs between the three prevailing tree species.

H_A3: The total cycle time of biomass extraction with the three-wheeled loader differs between the three prevailing tree species.

H_A4: The chipper productivity differs between the three prevailing tree species.

H_A5: The total cycle time for chipping differs between the three prevailing tree species.

H_A6: The waiting time of the chipper differs between the three prevailing tree species.

H_A7*:* The chipper feeding time differs between the three prevailing tree species.

1.4 Study limitations

The study focused only on the biomass production in the field. It does not cover the quantification of the potentially available biomass in the area, but is restricted to the recoverable biomass from a given site. Harvesting technology was restricted to current systems (WfW teams), and available equipment and technology.This study does not consider marketing, trade of the bioenergy products or the conversion of biomass into actual energy (e.g. electricity or thermal energy) following the harvesting process. It also does not provide the life cycle analysis of the invasive biomass as a bioenergy system and the relationship between capital investments and the financing are not part of this investigation.

2. Literature review

This review covers essential theory applicable to the harvesting of invasive woody vegetation as an energy feedstock. The key issue in evaluating the energy potential of exotic tree species is understanding its role as an alternative energy source. This research also considers existing harvesting system options, which have been investigated for wood fuel. Cost factors impacting on the harvesting of woody biomass and the feedstock properties are also discussed.

2.1 Woody biomass as bioenergy feedstock

Woody biomass refers to merchantable and un-merchantable trees, small diameter trees, tops, needles, leaves, limbs, stump and logging slash produced from mechanical thinning and conventional saw-timber harvesting with the potential of producing energy (Norton *et al*., 2003; Han *et al.,* 2004; Stampfer and Kanzian, 2006; Marinescu and Bush, 2009; Jackson *et al.,* 2010). As stated by the International Energy Agency (2002a), forest biomass is a source of energy for industrial, commercial and domestic use.

In the renewable energy context, woody biomass is regarded as one of the resources with important energy content which could be profitable as agricultural and industrial biomass sources such as untreated wood residues (IEA, 2002; Zafar, 2008). Beckert and Jakle (2008) reported that over 25 million British Thermal Units (Btu's) could be produced per woody biomass tonne. According to IEA (2002), about 11% of the world's primary energy was supplied by woody biomass. In developing countries, 55% of the 4 billion m^3 of wood used annually, is used directly as fuel wood or charcoal in order to meet daily energy needs of cooking and heating.

2.2 Current potential woody biomass sources

2.2.1 Short rotation wood crops (SRWC)

One of the sources of the rand woody biomass for energy is energy crops (Zafar, 2008), also known as short-rotation wood crops (SRWC).These include fast-growing species such as hardwoods: *Alnus, Platanus, Eucalyptus spp.,* hybrid poplars, willows, and specifically some perennial grasses used as energy feedstock (Ashton, 2010). Short-rotation energy plantations refer to a new type of agroforestry practice such as fast-growing trees with significant potential for providing woody biomass (Rauscher, 2008; Fege *et al.,* 1979; Bain and Overend, 2002). Several clones have been identified through crop improvement processes, with species selected for their rapid growth, ease of establishment and regeneration, tolerance to major pests and diseases and matching to site as well as to soil conditions (IEA, 2002b; Zafar, 2008). Economically, SRWC show promise in producing a sustainable supply of woody biomass. Zafar (2008) stated that 10-15 t ha^{-1} of energy crops are harvested annually in the northern hemisphere while Ashton (2010) reported that establishment costs are low as compared to conventional processes. This shows a positive indicator for the short rotation trees.

2.2.2 Logging residues

This biomass category caters for non-commercial trees, for conventional products of pulp or lumber and paper and small understory trees, as well as tops, limbs, dead trees and cull material(i.e. inferior quality) left over from forest harvesting operations (Smith, 1982). Logging residues, also known as forest residues, result from cutting during silvicultural management, such as the thinning of live to dead material in the standing forest (Andersen, 1999; Enters, 2001; Rauscher, 2008; Ashton, 2010). Logging residues represent an important share of the total biomass present in the forest (Zafar, 2008). After mill residues, logging residues are the most significant source of woody biomass and a readily available energy fibre (Spinelli *et al.,* 2007). Adams (1995), cited by Koopmans and Koppejan (1997), reported that recovery rates vary considerably and depend on local conditions. The disadvantage of using logging residues is that the collection and transportation costs are often greater than the market value of the materials (Withycombe, 1982).

2.2.3 Mill residues

Mill residues are the by-products of processing operations (USDA, 2005), which according to Rauscher (2008), are also one of the most readily available biomass sources as compared to other feedstock supplies. The potential of mill residues has been well demonstrated in the USA where about 97 percent of this resource has been utilized (USDA, 2005). Categories of available mill residues are: waste of lumber production, veneer and plywood, pulp and paper, bark and others e.g. black liquor, bark and sawdust (Enters, 2001; Walsh, 2007). Residues from sawmills, veneer and plywood mills and furniture manufacturing, as well as a number of other forest product industries are in a usable form for pulp or board manufacture. So the structural use competes with the use as fuel to generate energy in the form of heat and power. The advantage of processing residue is that it tends to be clean, uniform, concentrated, of low moisture content and easily transportable. The cost of wood pellet manufacturing could be confined if the competition for mill residue does not exist (Bergman and Zerbe, 2008).

2.2.4 Invasive vegetations

Woody biomass of the invasive vegetation can be integrated into different biomass conversion routes as suggested by Frombo *et al.* (2008) (Figure 1).

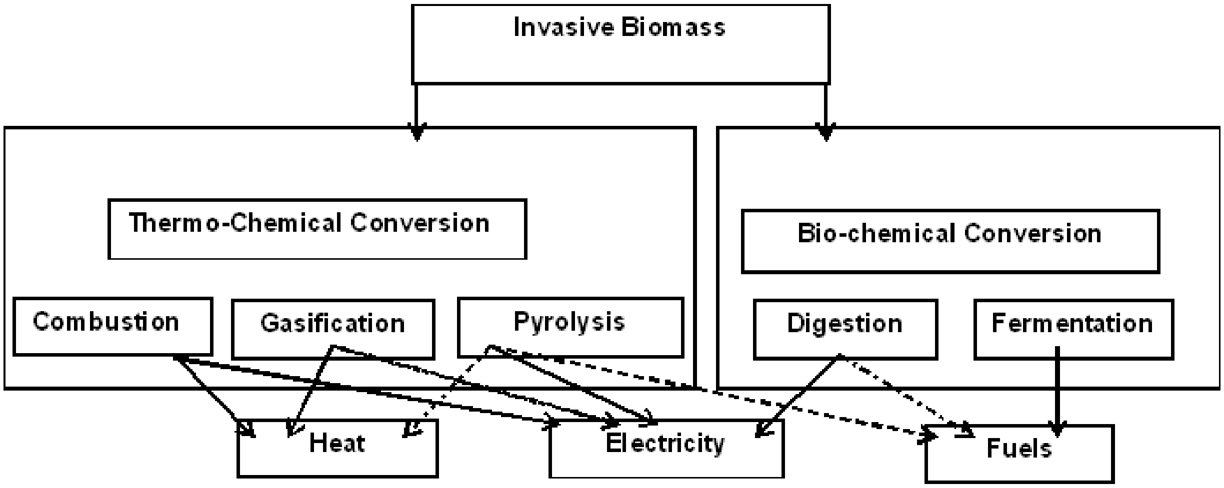

Figure 1: Biomass conversion routes (Adapted from Frombo *et al.*2008).

As any other woody biomass types, invasive vegetations can aid in meeting policy goals of rural development and environmental improvement (Leinonen, 2007). Recent studies conducted in Namibia have shown examples of the use of invasive plants to produce energy. It was found that wood from invasive vegetation has some potential for supplying power plants and charcoal-briquette production in that country. The Namibian examples have, shown conclusively that bush encroachment biomass offers many economic and energy benefits (Leinonen, 2007). Invasive vegetation has also been used as biofuel feedstock in the USA and Brazil. *Prosopis juliflora* species, a small tree from Central America, is considered as invasive vegetation in the USA which is nowadays used as feedstock for second generation biofuels production. Another case concerns the African oil palm, considered an invader in Brazil and therefore used for biofuel production (Howard and Ziller, 2008). The *Prosopis* species use as biofuel feedstock in Africa can only be feasible with strict adherence to the criteria and principles for sustainable biofuel production established by the Roundtable on Sustainable Biofuels (RSB, 2010). These criteria and principles are built on the optimisation of economic, social and environmental benefits.

Many exotic tree species in South Africa have been identified to be invasive as they are responsible for the modification of the ecosystem composition, structure and processes where they occur (Noss, 1990). The *Prosopis* species have, for example, radically changed bird habitats by replacing native Acacia-dominated communities (Dean *et al.,* 2002). According to the Agulhas National Park, many invasive tree species currently occupy the region, where about 142 672 ha (66% of the total area) is invaded by exotic trees (Figure 2) on the Agulhas Plain (Krug *et al.,* 2010).

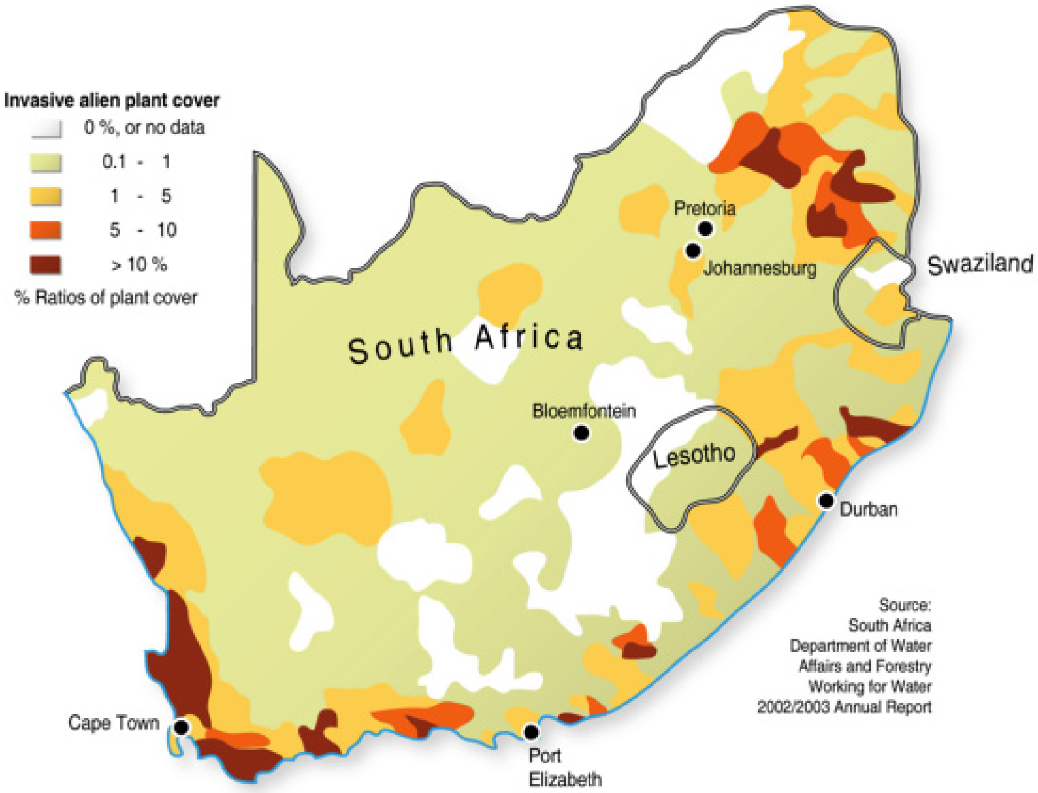

Figure 2: Distribution of alien invasive vegetations in South Africa (DWAF, 2003).

2.3 Feedstock supply chain

The supply chain focuses on everything occurring from the harvest to end use. In general, two main steps characterise the production of wood and biomass from the forest: the primary (biological) and the secondary (technical) production phases. Primary production refers to the growth of trees and secondary production to harvesting operations including felling, pre-processing and the transport of the resource. One of the main aspects of the technical production is the synchronization of all activities within the woody biomass supply chain. In this context, three major elements have to be considered when planning for woody biomass harvesting: 1) the harvesting methods; 2) the harvesting system and 3) the biomass processing stages (Allen *et al.,* 1998).

The harvesting method refers to the form in which wood is delivered to the logging access road and depends on the amount of processing (e.g. delimbing, bucking, barking, chipping) which occurs in the cut-over. Harvesting methods are: full tree method, tree-length method and cut-to-length method (Pulkki, 2001). The harvesting system includes the combination of tools, equipment and machines used to harvest wood, and vary depending on the specific terrain, work object and labour availability (Hall, 2005). In certain cases individual components of the system can be changed without changing the entire harvesting system, while components can be used for different harvesting systems. The one-grip harvester, for example, fells, delimbs and cross-cuts in the stump area, and can be used in the typical mechanised cut-to-length logging system. A forwarder can carry the product to roadside. Motor-manual felling, delimbing and topping, tree-length skidding to roadside and roadside slashing can be included in the tree-length method. For a typical harvesting system used in whole-tree harvesting, the system can include a feller buncher, grapple skidder, stroke delimber and slasher (Tsoumis, 1992). Biomass processing considers all the phases involved in the transformation of the raw material into the final product (Allen *et al.,* 1998).

According to Hall (2005), four factors can influence a successful harvesting operation: 1) the amount of available and recoverable wood fuel; 2) management constraints and site or location; 3) the harvesting system and 4) the extraction equipment selection. These factors must be considered in order to ensure that the woody biomass is supplied to the plant in time, at the right quality and right quantity (Alakangas and Virkkunen, 2007). The most important point is to optimise the supply chain, depending on cost and environmental considerations (Schaberg *et al.,* 2005). Figure 3 shows the example of the woody biomass feedstock supply chain.

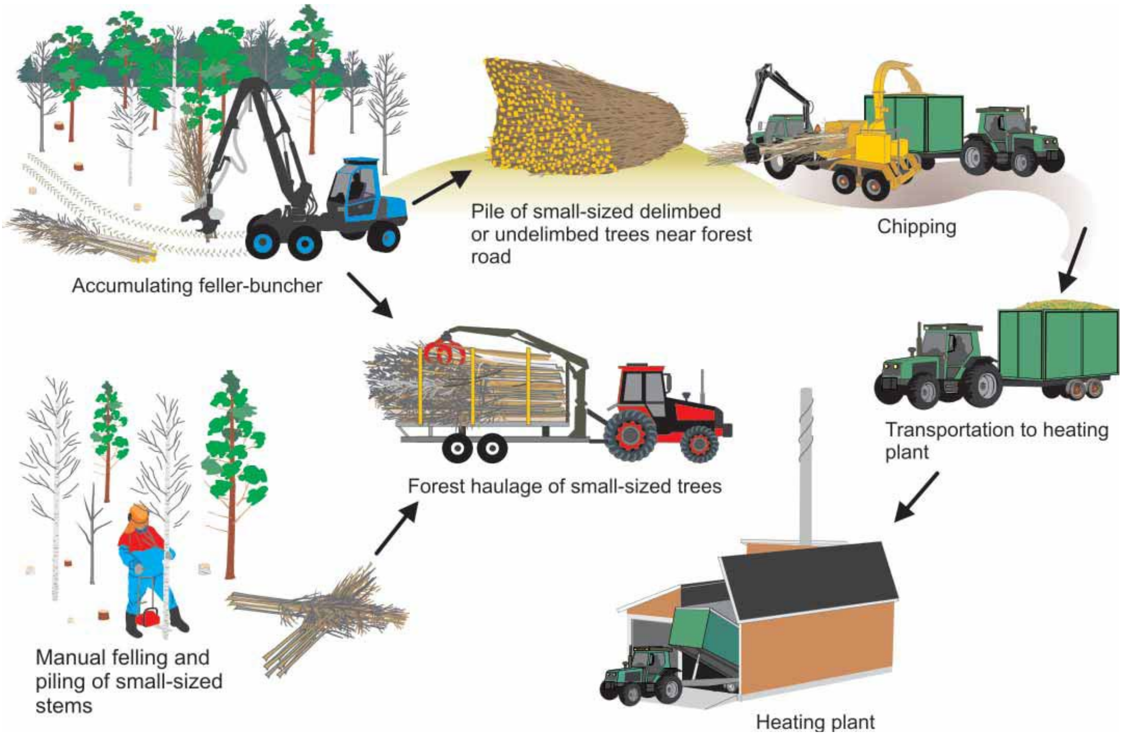

Figure 3: Biomass feedstock supply chain (Alakangas and Virkkunen, 2007).

2.3.1 Supply Chain Components

A woody biomass supply chain must consider three main levels of planning (Richardson *et al.,* 2002): the stump site, the harvesting process and the biomass plant. All actions required for cutting the forest biomass and bringing it to the consumption facilities to be manufactured in final wood products are included in the harvesting process. Figure 4 shows the supply chain components.

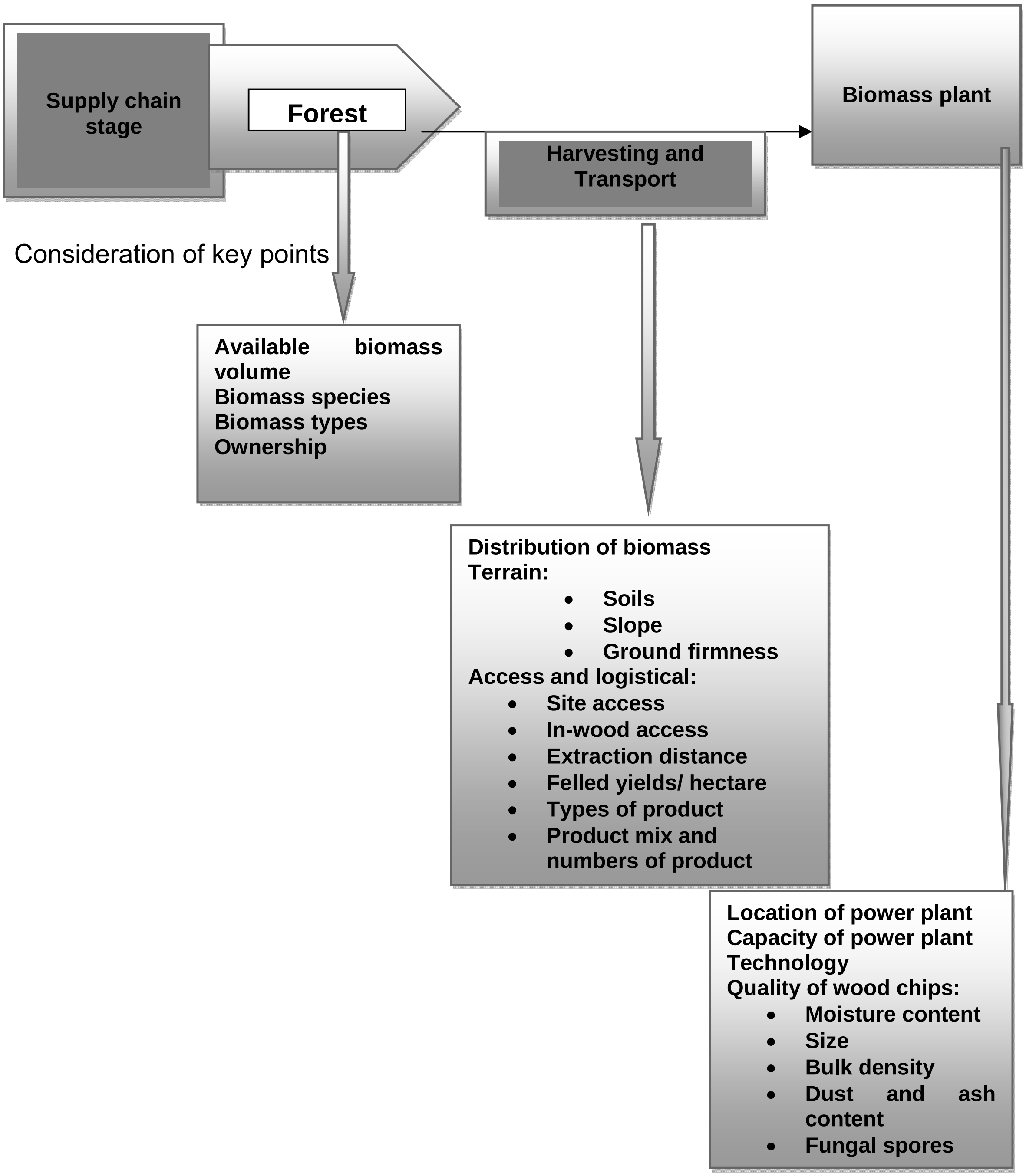

Figure 4: Supply chain components (adapted from Richardson *et al.,* 2002).

In a supply chain felling, extraction, chipping and transport operations of wood fuel are arranged in series in order to allow processing from the stand to the end-use point in a logical and sequential manner. Mechanized operations rely on consistent cycle times for scheduled production and allocated labour (Richardson *et al.*, 2002).

2.3.2 Harvesting options in wood fuel

Several harvesting options can be applied according to the extracted form of the product (Stampfer and Kanzian, 2006), the most significant consideration being the conversion of biomass into a form that can be transported cost-effectively to the end use. In this chain of events, the chipping of biomass seems to be dominant over other harvesting methods since the location of chipping operations within the production chain can play a major role in distinguishing various production options (Jackson *et al.,* 2010). Some production options are presented in Figure 5.

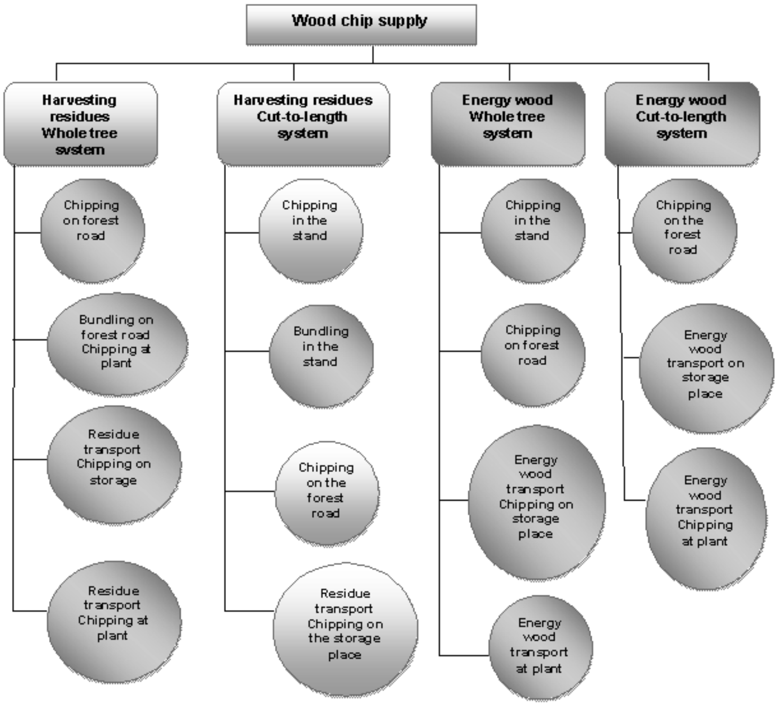

Figure 5: Woody biomass production systems based on sources, location of chipping, and type of biomass (Stampfer and Kanzian, 2006).

Harvesting systems can be either mechanical or semi-mechanical. When mechanical, all operations (felling, extraction, chipping and road transport) are executed by appropriate machines operated by trained operators. Semi-mechanized systems employ both manual labour and machines as is the case when felling is done motor-manually (Grobbelaar, 2000).

2.4 Cost factors affecting the harvesting of woody biomass

For biomass harvesting to be cost-effective, cost factors must be clearly defined and understood (Richardson, 2002). In order to make a significant profit, the optimisation of the harvesting system is required (Talbot and Raae, 2007).

2.4.1 Factors affecting harvesting and transport costs

By definition, cost factors in forestry are variables associated with equipment investment, terrain circumstances, operators, organisations, products and silviculture affecting the costs of production (Richardson *et al.,* 2002). Ashton and Cassidy (2007) reported that harvesting costs can also depend on the types of machines used as well as the season. The transport of woody biomass is furthermore influenced by factors such as fuel prices, the hauling distance, the moisture content and the truck capacity (McDonald, 2001). The hauling distance could become a limiting factor of profitability in affecting the transportation and delivery costs (Stokes *et al.,*1993).

Three levels of assessment of harvesting costs are necessary: 1) strategic, 2) tactical and 3) operational planning. At a strategic level a decision regarding the site of a biomass plant and the character of harvesting systems must be undertaken. For example, the system may set limits for the degree of integration of harvesting of industrial round wood and forest residues. On the tactical level, decisions must be made regarding how much wood can be harvested annually from every area and where it can be processed. At the operational level, the stands to be harvested must be identified beforehand, which calls for cost estimates of each system of fuel wood recovery (Richardson *et al.,* 2002).

2.4.2 Cost structure example of typical harvesting woody biomass

Cost components depend on the type of harvesting system involved. A typical Finnish supply chain is shown in Figure 6 for early thinning of small trees.

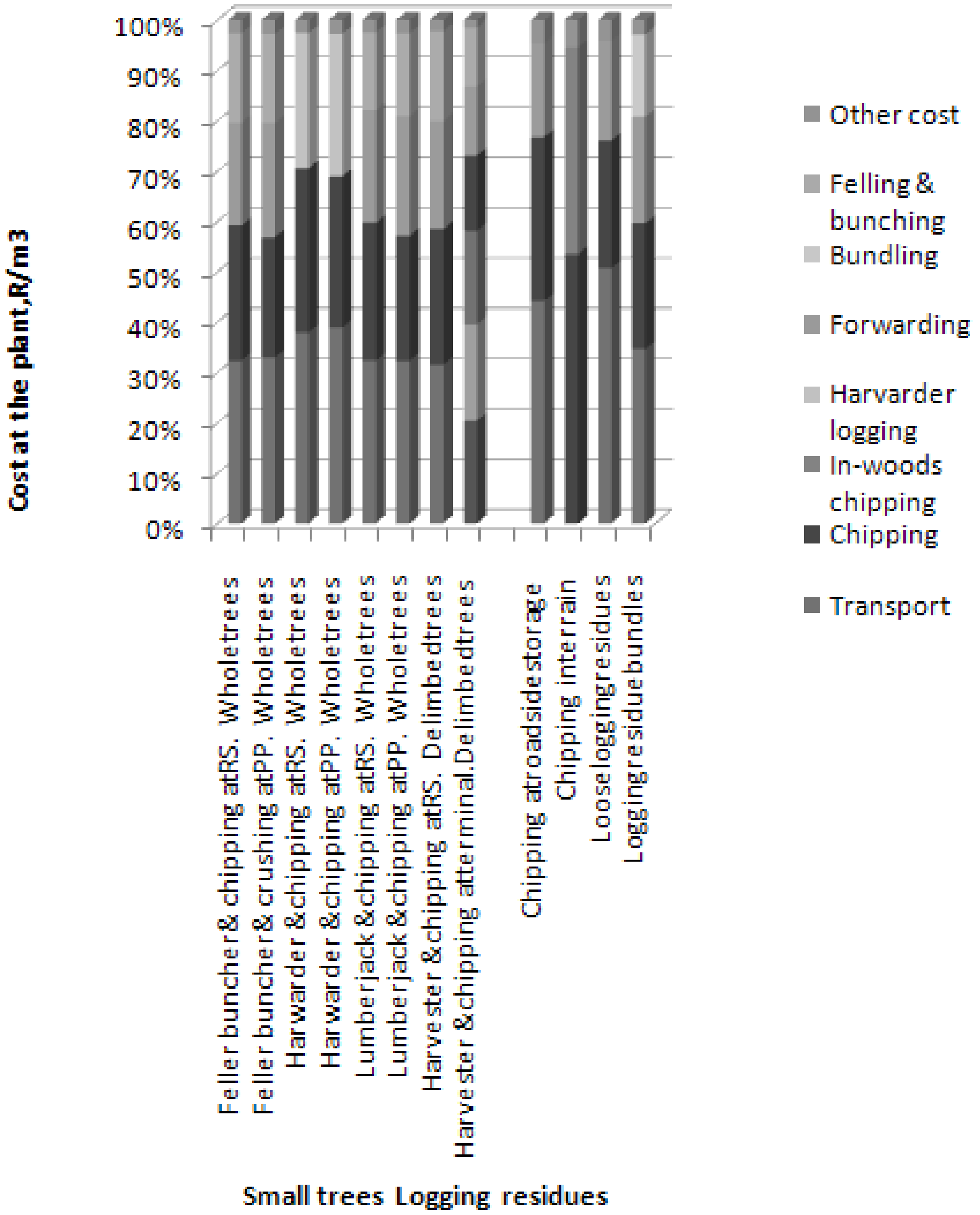

Figure 6: Cost structure of typical harvesting supply chain (adapted from FFRI, Finnish Forest Research Institute, 2005).

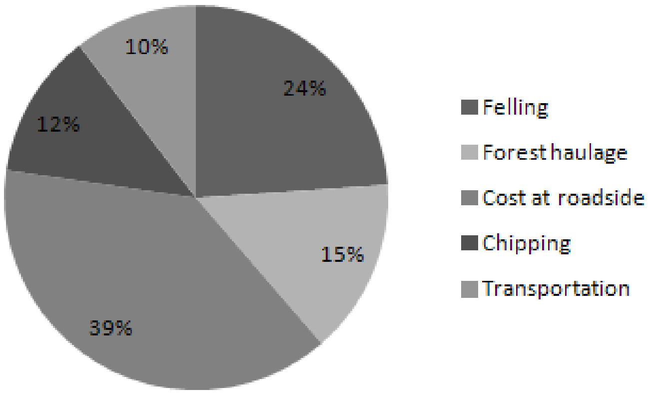

Figure 7: Cost components of typical logging residues chipping (FFRI, 2005).

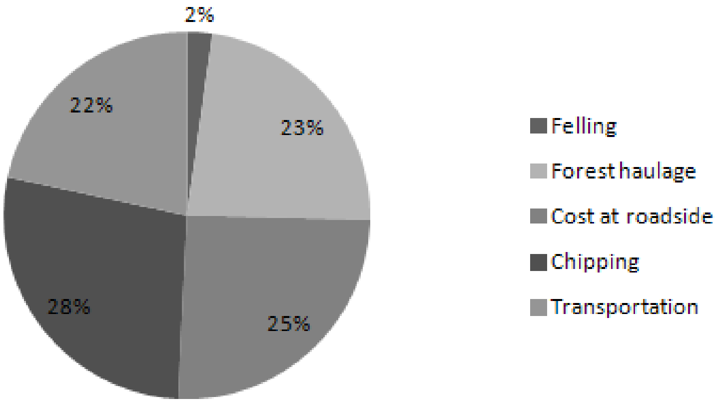

Figure 8: Cost components of typical cut-to-length harvesting system followed by chipping (FFRI, 2005).

2.5 Feedstock properties

2.5.1 Basic chemical characteristics of wood

The chemical composition of wood, including water, organic matter and mineral substances, influences the calorific value of woody biomass in various ways. As illustrated in Table 1, wood is normally constituted of three main chemical component groups: 1) cellulose (which is the principal chemical constituent of cell walls of plants), 2) hemicelluloses and lignin (heat-producing elements) and 3) carbon and hydrogen (Alakangas, 2005; ITEBE, 2006; Jodin, 1994; Huhtinen, 2005). Additionally extractives such as resins, tannins, oils or gums and other volatile substances can be found in wood (Shebani *et al.*, 2008; Tsoumis, 1991).

Some of those affect the heating value positively (Hakkila, 1989). About 99,8% of the dry matter of wood is composed of 49% carbon (C), 45,3% hydrogen (H), 5.5% oxygen (O) and 0,2% nitrogen (N) (Moilanen *et al.,*1996, ITEBE, 2006). The rest is mainly ash, which is a residue in thermal biomass conversion and is rich in macronutrients. Water in wood can be found in capillary systems, e.g. in cell walls and pores of wood and substantially impact on transport weights and heating value.

Table 1: Wood structure distribution (Curkeet, 2011).

Common *Name*	Cellulose	Lignin	Hemicelluloses	Other (organic & mineral substances)
Hardwoods	42.2	15-20	38	0-1
Softwoods	42.2	24-35	28	0-1

2.5.2 Moisture content

Moisture content (MC) refers to how much free water a piece of wood contains relatively to its weight. It is calculated as the difference between fresh and oven-dry mass (ODM), expressed on either a dry or fresh mass basis (Curkeet, 2011). Moisture content (MC) has a significant influence on the net calorific value of the feedstock. If the MC is high, the heating output value will be low. The MC of wood can strongly vary according to the site, season, species, or interval after harvest, therefore oven-dry mass is used for comparison purposes (Curkeet, 2011; FAO, 1990; Huhtinen, 2005; Simpson and TenWolde, 1999). Figure 9 illustrates the effect of the moisture content (MC) on the heating value.

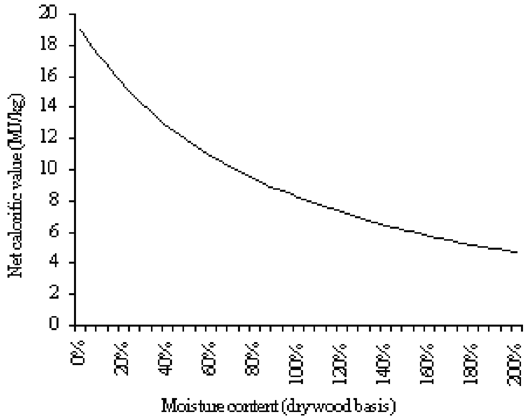

Figure 9: Effect of MC on the heating value of waste wood of *Pinus radiata* (Fordyce and Ensor, 1982).

2.5.3 Heating value

Approximate heating values of various wood components and wood in general (according to Corder 1976) are shown in Table 2.

Table 2: Heating values of wood components and wood (Corder, 1976).

Fuel	Moisture content (%)	Gross calorific values (MJ/kg)
Needles	0	20.4
Branches	0	20.1
Bark	0	19.6
Stemwood	0	19.1
Dry wood (non-resinous)	0	18.0 - 20.0
Dry bark (non-resinous)	0	17.0 – 23.0
Dry wood (resinous)	0	22.0 - 23.0
Dry bark (resinous)	0	20.0 - 25.0
Dry wood (average)	0	19.8
Wood pellets	10	16.75
Dry sawdust	13	16.2
Dry planer shavings	13	16.2
Seasoned wood (air-dried)	20	15.5
Green wood	50	9.5
Green sawdust	50	9.5

The most important characteristic of fuels is the amount of energy gained from burning the substance. This also applies to woody fuels and depends on the chemical properties of the wood in question. Energy content of biomass is expressed in two ways: the higher heating value (HHV), which is the maximum potential energy in dry fuel and the lower heating value (LHV), which includes the water that has to be evaporated (Ciolkosz, 2010). In general, the range of the HHV of wood is 17.7 to 22.3 GJ/t (7,600 to 9,600 Btu/Ib) or 18.5 to 21.9 MJ/kg (Huhtinen, 2005).

2.5.4 Ash content

Ash content is defined as the incombustible minerals in wood fuel, mixed with any unburned carbon. According to Maker (2004), there is about 12 kg of ash in every tonne of fresh biomass burned. The ash content(AC) varies between the whole tree and specific parts of the tree, e.g. stem wood: 0,4 - 0,6%; stem bark: 2 - 5% and 1 - 2% in branches (Askungen, 2011). In the case of wood chips, when the combustion is completed with bark and needles, the ash content percentage might be higher and range from 5 to 10% for wood contaminated with soil and sand (Kofman, 2006).

2.6.5 Energy balance of the biomass system

The energy balance of the biomass system is defined as the relationship of the total energy output to the total energy consumed by the system. Therefore, the net energy can be determined by the ratio of total energy output divided by the total energy input (Westbrook *et al.* 2006). To be recognised as a viable biomass system, the net energy ratio needs to be ≥ 1. The larger this number, the less energy is needed in the energy supply process for a specific fuel (Morice, 2008). This respectively implies that input energy is less than the output energy (Ashton and Cassidy, 2007).

3. Materials and Methods

3.1 Research area description

The study area is located both within the Agulhas National Park and private land surrounding the national park in the vicinity of Bredasdorp and Elim on the Agulhas Plain in the Western Cape Province of South Africa (Figure 10). The region receives about 60 - 70 % of its annual precipitation during winter, between May and October, with an annual average varying between 400 and 600 mm (Agulhas National Park, 2009). The topography of the region is generally a level plain and the climate is Mediterranean, characterized by warm dry summers and cool wet winters. The mean annual temperature is 15 ºC.

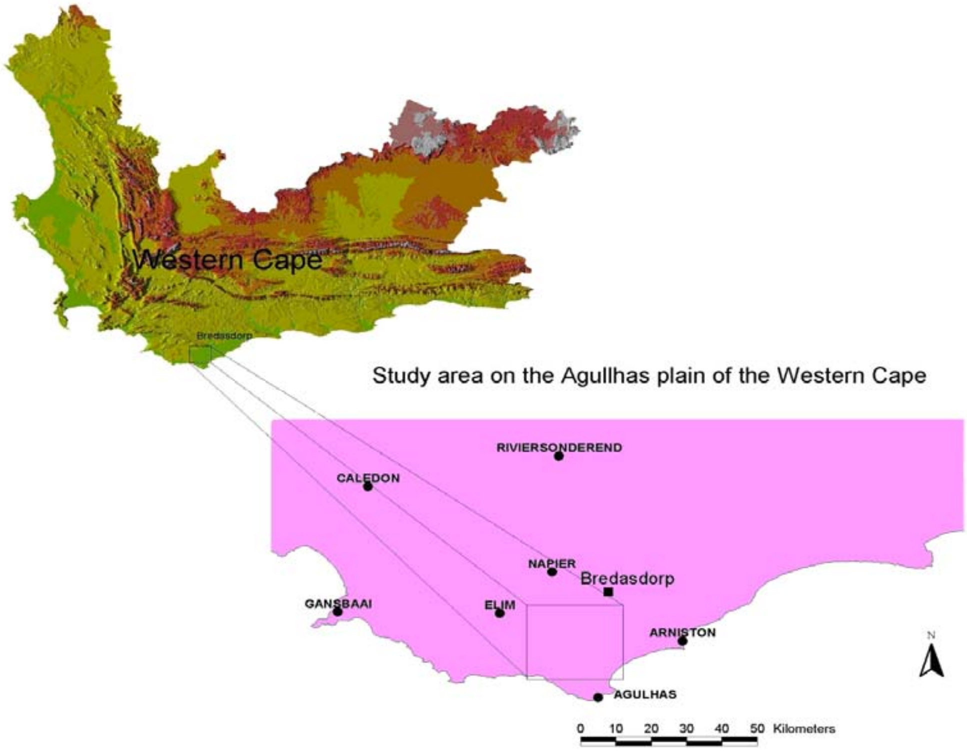

Figure 10: Map of the study area.

3.1.1 Vegetation

The focus of this study is on the invasive woody vegetation which threatens the indigenous biodiversity of the Cape Inland Salt Pans, Central Rûens Shale Renosterveld, Elim Ferricrete Fynbos, and Agulhas Sand Fynbos (Agulhas National Park, 2009). Several potentially invasive species have been identified in the Agulhas area (Table 2) of which three, which form trees and shrubs, were selected for a case study: *Acacia Cyclops* (Rooikrans), *Leptospermum laevigatum* (Myrtle) and *Eucalyptus lehmanii* (Spider Gum) (Fig.11 - 13). The reasons for selecting these species for the case study were: (1) that they were the most common species in the study area and (2) that they have relative uniform density and dimensions. Throughout the thesis, the common names or genus of the three species are used instead of the botanical names (Figures 11 to 13).

Figure 11: *Acacia Cyclops* [Rooikrans]

Figure 12: *Leptospermum laevigatum* [Myrtle]

Figure 13: *Eucalyptus lehmanii* [Spider Gum]

3.1.2 Study area characteristics

Three sites of the selected vegetation types were randomly chosen within the greater study area (Figure 10). In this investigation consideration was given to plant density at each site and proximity to roads to aid transport of the biomass off the site. In order to obtain representative data within the different species, the three sites were divided into two plots each: two in Gum, two in Acacia and two in Myrtle. Plot dimensions were 20m x 20m (400 m^2), laid out with a measuring tape. Each corner was marked with a stake to maintain orientation for both workers and enumerators. All subsequent operations occurred within these boundaries.

Table 3: List of potential exotic plant in Agulhas area (Agulhas National Park, 2009).

No	Scientific name	Common name	No	Scientific name	Common name
1	*Acacia baileyana*	Bailey's	16	*Myoporum tenuifolium*	Manatoka
2	*Acacia dealbata*	Silver	17	*Paraserianthes Lophantha*	Stinkbean
3	*Acacia mearmsii*	Black Wattle	18	*Pinus canariensis*	Canary Pine
4	*Acacia longifolia*	Long-leaf Wattle	19	*Pinus pinaster*	Cluster Pine
5	*Acacia pyncnantha*	Golden Wattle	20	*Pinus pinea*	Stone Pine
6	*Acacia saligna*	Port Jackson	21	*Populus x canescens*	Grey Poplar
7	*Cereus jamacaru*	Queen of the Night	22	*Ricinus communis*	Castor Oil
8	*Cirsium vulgare*	Scotch Thistle	23	*Rubus* spp.	Bramble
9	*Cortaderia selloana*	Pampas Grass	24	*Solanum sisymbriifolium*	Gifappel
10	*Datura stramomium*	Thorn Apple	25	*Spartium junceum*	Spanish broom
11	*Eucalyptus grandis*	Saligna Gum	26	*Opuntia monacantha*	Drooping Prickly Pear
12	*Hakea gibbosa*	Rock Hakea	27	*Agave sisalana*	Sisal
13	*Hakea sericea*	Silky Hakea	28	*Echium plantagineum*	Patterson's Curse
14	*Acacia Cyclops*	Rooikrans	29	*Leptospermum laevigatum*	Myrtle
15	*Lantana camara*	Lantana	30	*Eucalyptus lehmanii*	Spider Gum

To gain work-time and productivity data of manual and motor-manual harvesting methods, two different biomass preparation systems were applied. System 1 included manual felling with bow saws, stacking of all brush by hand, chipping at roadside and road transport of the chips off the site; while System 2 consisted of motor-manual felling, stacking of brush separately from solid wood by hand, chipping and road transport (Table 4). System 1 was only applied in Plot 1, in the Spider Gum site. The remainder of the plots were treated according to System 2 (Table 4). The reason why manual bow saw felling only occurred in one plot was that there was only time to practice this system in one plot due to the non-availability of the manual felling team. In this case the investigator deemed it suitable to extrapolate the results of manual felling of the Spider Gum plot to the other two species, since the other species show a similar growth habitus and, like the Spider Gum, do not have thorns.

Table 4 : Sites, plots, tree species and harvesting method.

Site	Plot	Plot area (m^2)	Species	System
1	1	400	*Eucalyptus lehmanii* (Spider Gum)	Manual felling, stacking of brush only, chipping, road transport
1	2	400	*Eucalyptus lehmanii* (Spider Gum)	Motor-manual felling, stacking of brush and solid wood, chipping, road transport
2	1	400	*Acacia Cyclops* (Rooikrans)	Motor-manual felling , stacking brush and solid wood, chipping, road transport
2	2	400	*Acacia Cyclops* (Rooikrans)	Motor-manual felling, stacking brush and solid wood, chipping, road transport
3	1	400	*Leptospermum laevigatum* (Australian Myrtle)	Motor-manual felling, stacking brush and solid wood, chipping, road transport
3	2	400	*Leptospermum laevigatum* (Australian Myrtle)	Motor-manual felling, stacking brush and solid wood, chipping, road transport

3.3 Harvesting equipment applied to the study

The following harvesting and processing equipment was used in the study: bow saws, chainsaws, disc chipper, three-wheeled loader, chip/solid wood transport truck and a pick-up truck.

3.3.1 Chainsaws and bow saws

A Stihl model MS 380 chainsaw (Table 5) was used for the motor-manual felling operation and a 530 mm Lasher GP bow saw was used for manual felling. Plots with trees of <5 cm DBH were felled manually and those with trees >5 cm motor-manually.

Table 5: Chain saw specifications.

Specifications Stihl model MS 380	
Cylinder displacement (cm^3) or cc	72.2 cc.
Engine power	3.60 kW
Mass (kg)	6.60 kg
Bar Length	50 cm

3.3.2 Chipper

The chipping unit used in the study was a mobile Bandit model 255XP, with a 38.1 x 63.5 cm throat opening and a 38.1 cm diameter capacity disc. The feed system featured two horizontal feed wheels, each 24 1/2" wide, allowing for multiple stem feeding (Table 6 and Figure 14). The machine converted trees into woodchips.

Table 6: Specifications of the chipper.

Model	**255XP**	**Height Adjustable Discharge**	**Hand crank standard**
Capacity	15" (381mm)	Discharge Chute Swivel	Hand crank standard
Engine Brand	CAT	Fuel Tank Capacity	152 litres
Power of the diesel Engine	140 HP (106kw)	Hydraulic Tank Capacity	50 litres
Hydraulic Lift and Crush	Standard	Tyres	215/85R17.5
No. Reversible Blades	4	Chipper Weight	3,400 kg
Feed Roller Description	Two horizontal rollers	Brakes	Electric
Chipper Type	Disc	Chipper Chassis Description	150 x 50 mm RHS steel
Productivity/Feed rate	100 ft/min (31 m/min)	Axle Capacity	3,530 kg
Auto Feed Plus feed control	Standard	Tail Lights	LED standard
Hydraulic Winch	Optional	Chipper Length	4.6 m
Chipper Bearing	2 7/16" (62mm) double row	Available as self-propelled track drive	Yes
Disc / Drum Diameter	45" (115cm)	Chipper Width	2.15 m
In feed Throat Opening Size	15.5" x 25" wide (394 x 635mm)	Suspension Type	Rubber torsion
Tow hitch type	pintle ring		

Figure 14: Bandit model 255XP chipper.

3.3.3 Three-wheeled loader

A three-wheeled loader was used to extract biomass from the brush-lines in which the felled material is located, to the chipper located at a roadside landing. The three-wheeled loader's technical specifications are shown in Table 7.

Table 7: Specifications of the three-wheeled loader.

Model	**Logger 225A**
Engine net power	49kW
Operating mass	5 200 kg
Grapple capacity	0.35 m^2
Hydraulic oil volume	102 l
Fuel tank volume	76 l
Tyres	FRONT Tyre: Size 18.4 x 30 10 Ply Type: Forestry REAR Tyre: Size 4.00 x 15.5 10 Ply Type : High Flotation Forestry
Transmission	Hydrostatic Maximum travel speed:9 km/h

Figure 15: Three-wheeled loader model logger 225A.

3.3.4 Tip Truck

Two material transport modes, a 9.5 m^3 volume tipper truck and a one-tonne pick-up truck, were used to deliver chips and/or solid wood from the various landings to the Bredasdorp weighbridge. The load bodies of the trucks were covered with tarpaulins to prevent the loss of chips while travelling. Loaded and empty travel speeds (time study) of the vehicles were determined over these routes.

Figure 16: Truck with carrier bin without raised load body sides.

3.4 Harvesting team

Working for Water (WfW) clearing teams, experienced in felling and processing of the vegetation in question, were employed to carry out prescribed harvesting operations in each site. WfW felling team comprised of one supervisor, two chainsaw operators and seven workers. In addition, a chipper operator was assisted by two workers who fed material into the chipper chute manually when automatic feeding of material by the three-wheeled loader failed. The tip-truck, pick-up truck and the three-wheeled loader each had a dedicated driver/operator.

3.5 Methods

3.5.1 Production assumptions and field work description

Production assumptions used during the study observations were defined according to the variability found on sites and plots. The production assumptions from the observation period were based on a shift production interval of nine hours. During the shift, one hour was allowed for start-up, shut down, cleaning of both the site and machines at the end of the shift and for travelling to work. In total, the task was determined on a 480 min operational time per shift. The average rest allowance allocated to chainsaw operators was 23% (13.8 min hour^{-1}) and 20% for manual workers (12 min hour^{-1}). These allowances have been included into the standard time of the operation. Therefore, a chainsaw operator was expected to work at standard performance, for a 370 min shift^{-1} and manual operations for a 384 min shift^{-1}. Other details on the production assumptions are provided in Appendix 1. Felling was done either manually or motor-manually with manual stacking of felled material. A three-wheeled loader was used for the extraction of biomass from stump to roadside and the actual feeding of the chipper at the roadside landing, while a tip truck and a pick-up truck travelled from the roadside landing to the weighbridge located some 51 km from the working site. Figure 17 shows a typical work sequence matrix and equipment used in harvesting operations.

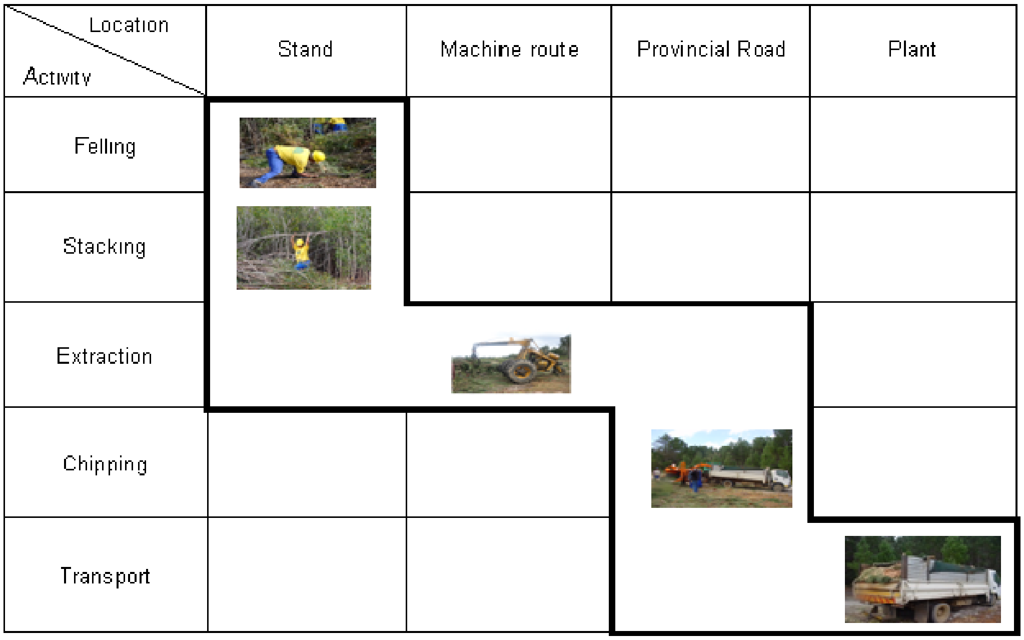

Figure 17: Biomass harvesting systems matrix.

3.5.2. Data collection

Equipment for the time study included pre-compiled time study forms/sheets, a stopwatch, 50 m tape measure, pencil and clipboard. During the layout of plots, the 50 m tape measure was used to fix plot sizes. Activity sampling and time studies techniques were used, proving useful to measure and evaluate the performance accuracy of the specific work carried out under particular conditions (Kanawaty, 1992). With these techniques, time spent on the individual work phases could be determined in order to enhance the accuracy of the productivity rate and cost of the entire biomass production system, while eliminating unnecessary time use (Richards *et al.,* 1995).

3.5.2.1 Activity sampling

Activity sampling is the determination of the percentage occurrence of specific well defined work elements using statistical sampling and random observation (Kanawaty,1992). Each element is instantaneously recorded, and the percentage of time for each particular element is the number of observations for that element divided by the total number of observations, over the entire timing period which could be an entire work shift (Miyata *et al.,* 1981).

Activity sampling was the preferred method of observation for the manual and motor-manual felling operations because of:

1) short element times in the observations which are not accurately measurable with a stop watch;
2) variable working methods and multiple team members involved with the felling and
3) peripheral integrated activities all of which need to be measured and monitored.

Activity sampling in manual and motor-manual tasks was set in such way that at minute intervals a work element was recorded with regard to what each member of the harvesting team or chain saw operator was performing at that specific time and recorded in the prepared sampling data form. Study specific issues under the activity sampling method are described below.

3.5.2.2 Recording the manual harvesting activity

The working elements (Table 8) of manual harvesting tasks were recorded according to the observation done at minute intervals (e.g. at minute interval one: worker 1 - cutting, worker 2 - moving empty, worker 3 - spraying and worker 4 - standing idle, etc).

Table 8: Elemental time functions for manual activity.

Cut	Felling tree by cutting it with hand saw or bow saw
Moving empty	Movement by worker when positioning before cutting
Spraying	Spraying chemicals on the cut stump
Idle time	No value adding activities

After cutting and before chipping of the biomass, trees with DBH between (and including) 3.0 to 10.0 cm was stacked in a single brush line 10 m apart. Then trees with DBH > 10.0 cm were stacked in piles at the roadside as the firewood component of the biomass was harvested. This was done in order to facilitate the collection of the biomass by the three-wheeled loader. The stacking work elements (activity sampling) were recorded (at one minute intervals) in the same manner as described above and shown in Table 8. At the end of the shift, the data from the activity sampling forms was captured in a Microsoft Excel spreadsheet to calculate the percentage of time taken for each single work element of the manual operation.

Table 9: Elemental time functions for stacking activity.

Stack	Place biomass on stack row
Pickup	Worker caching the biomass
Moving load	Worker carrying the biomass to the stacking area
Moving Empty	Worker moving to biomass pick-up point (after stacking the biomass)
Idle	No value adding activity

3.5.2.3 Recording motor-manual harvesting activities

Per definition, felling starts with the felling cut and ends when the biomass (tree) drops/falls on the ground (i.e. the tree is felled). Two chainsaw operators felled all the trees on the plot in varying directions, while a team of workers separated the solid wood (diameter wise) to either the brush line stacking area as described above.

An initial chainsaw cut was made about 1 m above the ground to provide access to the stump, after which the second cut was made at ground level to bring the whole tree down to the ground. Trees larger than 10.0 cm DBH were physically separated for firewood. The activity sampling of motor-manual activities was based on work elements performed by the chainsaw operators (Table 10). At every minute a corresponding work element was recorded for each chainsaw operator. At the end of the shift, the sum of each single work element was calculated and its percentage contribution to the entire work phase determined.

Table 10: Elemental time functions of the chain saw.

Cutting	Felling tree
Cross cutting	Tree splitting
Refuel	Fuelling of chain saw
Filing	Sharpening or replacing a damaged chain
Observation	Planning tree felling operation (felling direction)
Moving	Movement of the operator to the next tree
Broken	Operational delays (broken chain etc)
Debranch	Removal of branches from the main stem
Idle time	No value adding activities

3.5.2.4 Time study

Time study was used to obtain data regarding chipping and truck transport activities and to identify factors affecting the work process, in order to gain accurate productivity and process information.

3.5.2.5 Extraction process

Biomass extraction was executed with the three-wheeled loader. The three-wheeled loader was also responsible for placing the biomass to be chipped into the chipper in-feed chute. Before the extraction, transport distances were measured by pre-marking all the extraction routes within a range of 5 to 45 m and measuring the matching distances with a tape measure. Work elements comprised of collecting the biomass, feeding the chipper and travelling between the collection point and the chipper and back to the collection point in the field (Table 11). Each work element was recorded on a time study form and then entered into a spreadsheet for analysis (Appendix 5).

Table 11: Time elements for extraction process.

Move loaded	Machine starts moving after grabbing the biomass
Move empty	Starts moving after feeding the biomass into the chipper
Feeding	Starts when biomass touches the chipper mouth
Grapple time	Starts when the grapple touches the biomass
Idle time	Starts when the machine stops with no value adding activity

3.5.2.6 Chipping process

The chipping operation consisted of the actual chipping process and the subsequent blowing of the chipped biomass directly into the truck bin which was parked next to the chipper, and waiting time (Table 12). Chipping time ceased when the whole load carried by the three-wheeled loader had been fed into the chipper and been chipped (blown into the receiving bin/s). The times spent waiting for the biomasses from the three-wheeled loader were also recorded. The work elements were captured in the time study form. Variables of the chipper were evaluated by time study in order to examine their effect on the productivity.

Table 12: Elemental time functions of chipper.

Feeding	Starts when the biomass reaches the chipper mouth
Waiting	Starts when the chipper has no more material to chip

3.5.2.7 Road transport

Road transport of the biomass was defined to begin when the tip truck had been loaded and was ready to depart for the weighbridge. The truck was sent to the weighbridge to establish the fresh mass of harvested biomass. The volume of the load was known from the dimensions of the truck. Travel time started from the roadside landing and ended when the tip truck again reached the roadside landing after unloading at the weighbridge site in Bredasdorp. Travel loaded and travel empty times were recorded.

3.5.3 Productivity calculation

All biomass masses were converted to oven-dry tonnes (ODT) and formed the basis of all productivity and cost calculation for the purpose of a standardised measurement. The productivity of different activities was expressed in productive machine hour (PMH), which was determined by the ODT mass of biomass harvested or prepared over a unit period time. According to Grobbelaar (2000), the productivity outcome can be defined as the result of the quotient of the volume or mass of harvested material produced in a defined time period.

Equipment productivity in this study is reported as productive machine hour excluding all delays (PMHo). This is done assuming that the delays which are normally presented as a percentage of scheduled machine hours (SMH) were considered equal to zero (Spinelli *et al.*, 2009). Therefore all delay categories such as hours of mechanical delay, hours of operator delay, and hours of organisational and other delay were not included. The calculations were done for chainsaws, chipper and three-wheeled loader (Equation 3-1). The labour force productivity was also defined as the output per man day (Equation 3-2).

$$P = \frac{ODT}{PMHo} \qquad \text{Equation 3-1}$$

Where:

$P = productivity\,(t/hr)$

$PMHo = productive \ machine \ hour \ without \ delays \ (hr)$

$ODT = Oven - dry \ tonnes \ (t)$

In the case of labour intensive operations, the productivity was calculated as:

$$P = \frac{ODT}{MAN \quad DAY} \qquad \text{Equation 3-2}$$

Where:

$P = productivity \ (Odt/man \ \ days)$

$ODT = Oven - dry \ tonnes \ (t)$

$MAN \ DAY = time \ for \ one - man \ work \ (hr)$

3.5.4 Biomass calculation

The fresh biomass mass of each species was obtained by measuring the mass at the weighbridge in Bredasdorp and then converting this to ODT by a conversion factor determined in laboratory tests, based on samples that were weighed fresh and after oven-drying to constant mass. The calculation of dry mass from fresh mass was then calculated according to Equation 3-3. The biomass constant value of the three species was referred to the ODT of the samples. The average and the standard deviation are shown (Table 13).

$$ODT = FRESH \ BIOMASS \cdot \beta \qquad \text{Equation 3-3}$$

Where:

$ODT = Oven - dry \ tonnes \ (t)$

$FRESH\,BIOMASS = wet\ \ mass\ \ (t)\ \ at\ \ harvesting\,\%$

$\beta = biomass\ \ conversion\ \ factor$

Table 13: Species specific conversion factors from fresh to dry biomass.

Genus	Mean	SD
Gum	0.81	0.1
Acacia	0.82	0.15
Myrtle	0.69	0.12

3.5.5 Harvesting system cost

The harvesting system cost comprised manual and motor-manual harvesting, extraction, chipping and transport costs. Overheads were not included.

3.5.5.1 Basic equipment cost calculations, labour and other assumptions

The South African Harvesting and Transport System Costing Model by Hogg *et al.* (2008) was used to calculate the labour, machine cost and system cost. The following was assumed:

Labour costs: The wages use by the WfW program for a general worker employed was R125 shift^{-1}. This cost was related to determined productivity as per analysis explained in the results section, for the felling and preparation of the three species within the six biomass groups (Gum 1, Gum 2*,* Acacia 1, Acacia 2, Myrtle 1 and Myrtle 2*)*. The outcome was costs in R ODT^{-1} produced. Hours worked per day were assumed at 8 hrs.

Assumptions for machine cost (Appendix 6)**:** The cost of a chainsaw operator is calculated at a WfW program of R 250 shift^{-1} and the three-wheeled loader operator at R 200 shift^{-1}. Costs of the three-wheeled loader were quantified in R ODT^{-1} set at four extraction distances, i.e. 10 m, 20 m, 30 m and 40 m. The chipper operator cost R 200 shift^{-1}. All the costs were expressed in R ODT^{-1}.

Transport of solid wood and chips

Although the time studies for the research were done on the tip truck, this vehicle was not of optimum size (payload) and configuration to support a commercial transport operation of this type. For this reason the following was proposed:

Transport of chips

Since our transport setup did not meet real operational conditions, we used a virtual transport setup for calculations. The data for the transport costs and productivity were calculated according to the RFA (2010). Four distances (radii): 40 km, 30 km, 20km and 10 km around a source were used to cost transport of chipped material. A 20 ft container with an internal volume of 34.5 m^3 was used to carry the chipped material. The motivation here was to match the mass of chips to the legal payload of the envisaged vehicle. The container/body adaptation was mounted to a 6x4 tip truck (or accommodating a tipping mechanism) with an average payload of 15.0 t.

The mass of chips to a full container was 11.5 t (34.5 m^3 * 0.33 SVF ,solid volume factor) – (standard conversion at 30% MC of chips). A standard day of 8 hours and a total of 240 working days/yr, were used for calculation, seeing that night work and hence chip or chunk loading is mostly not possible without adequate lighting and extraordinary safety and security measures (RFA, 2010). Time was allocated for travel both loaded and unloaded, at an average of 25km/h travel speed, i.e. study norm plus loading and unloading time. A time of 2.7 h (chipping study average of 4.28 [~ 4.3 t]) was allocated to the chip loading as the chipper blows the chips directly into the bin. A 0.5 hr delay is built into every load for contingencies. In all cases an unloading time of 0.5 hrs was allowed.

It was assumed that the truck was dedicated to chip transport and, as such, the distances travelled would be both for the loaded and unloaded leg of the cycle. Fixed and variable costs of the 6x4 tip truck were based on the Road Freight Association's (RFA, 2010) vehicle cost schedules. Estimated transport costs were calculated as R ODT^{-1} km^{-1}.

Transport of solid wood for conversion to chunks to processing site

The transport of solid wood, as above, was calculated over four distance radii: 40 km, 30 km, 20 km and 10 km. In order to complete the costing the following assumptions were made:

1) A flatbed 6x4 tip truck with modified body carrying an average payload of 15.0 t was applied with the truck body possibly having to be adapted to accommodate the potential load (height of load, but remaining legal);
2) A standard day of 8 hours and 240 working days/yr were used for calculation costs;
3) Time for travel both loaded and unloaded was allocated at an average of 25km/h travel speed, i.e. study norm plus loading and unloading time;
4) A time of 0.5 hrs was allocated to loading solid wood lengths of 1.2 m, which had been piled in the preparation phase of the operation by means of a three-wheeled loader directly onto the truck;
5) A 0.5 hr delay is built into every load for contingencies. In all cases an unloading time of 0.2 hr was allowed (this could change depending on the efficiencies at the centralised site).

It was assumed that the truck was dedicated to solid wood transport and as such the distances travelled would be both for the loaded and unloaded legs of the cycle. As mentioned above, the fixed and variable costs of the 6x4 tip truck were based on current (2011) Road Freight Association (RFA) vehicle cost schedules. Unloading at the processing site was done manually or by three-wheeled loader (or tipped depending on the configuration). Estimated transport costs were also calculated as R ODT^{-1} km^{-1}.

3.5.6 Energy yield and calculations

Before determining the wood energy content of the different species under investigation, it is important to have prior knowledge of the total mass of produced biomass and the related moisture content. Based on the method suggested by Serup *et al.* (2002), the moisture content of the three species was determined in two weeks interval after felling in the laboratory by taking random samples from each biomass load, and determining the average. In practice, this was done in the following way: 1) the mass of the samples was determined; 2) the samples were dried in the oven set at 103 °C to constant weight for about 24 hours (Walker *et al.,*1993); and 3) moisture content calculated using Equation 3-4:

$$MC\,\% = \frac{FSM - ODM}{FSM} \cdot 100\,\% \quad \text{and} \quad MC\,\% = \frac{FSM - ODM}{ODM} \cdot 100\,\%$$

Equation 3-4

Where:

$MC\ \% = Moisture\ content\ expressed\ in\ percentage$

$FSM = wet\ mass\ of\ the\ wood\ sample\ (g)$

$ODM = Oven - dry\ mass\ of\ the\ wood\ sample\ (g)$

The TAPPI standard T 211 om-85 method was used to measure the ash content of samples according to Munalula and Meincken (2008). Before placing in the furnace at 575˚C for three hours, the oven-dried pieces of the woodchips were weighed. After combustion the samples were placed in desiccators to prevent moisture absorption while cooling. The ash content was determined according to Equation 3-5:

$$AC\% = \frac{MA \cdot 100}{ODM}$$

Equation 3-5

Where:

$AC\% = Ash\ content$

$MA = Ash\ mass\ (g)$

$ODM = oven - dry\ mass\ (g)$

The dry matter calorific value, also called net calorific value of dry wood (H_n), of each species was expressed in GJ/t. The procedure required complete combustion of about 0.5 g oven-dried wood under a pressurized atmosphere of 3000 kPa oxygen. This resulted in a specific rise of the temperature of the cylinder which allows for calculating the net calorific value when the exact weight of the sample is known (Munalula and Meincken, 2008). The net calorific value of fresh biomass was determined by using the following Equations 3-6 and 3-7 proposed by Serup *et al.* (2002):

$$H_{n,v} = H_n - (0.2144 \cdot MC\%) \qquad \text{Equation 3-6}$$

Where:

$H_{n,v}$ = is the net calorific value of fresh wood (GJ/tonne total weight)
H_n = is the net calorific value of dry wood (GJ/tonne)
MC% = moisture content of the biomass in percentage (in a whole number)
0.2144 = is the correction factor of the enthalpy of vaporization

The net calorific value of fresh wood ($H_{n,v}$) was used to achieve the exact net calorific value as received for each wood species in this investigation. Then the output energy was considered as the net energy content of the total mass of produced biomass. The output energy was obtained by using a simple calculation as following:

$$E_o = F_b \cdot H_{n,v} \qquad \text{Equation 3-7}$$

Where:

E_o = Wood energy content (energy output) (GJ)
F_b = Fresh biomass tonnes (t)
$H_{n,v}$ = is the net calorific value of fresh wood (GJ/tonne total weight)

The energy input of harvesting (felling, extraction, chipping and transport) of biomass was defined as the direct energy consumed (Grobbelaar, 2000; Fei Pan *et al.,* 2008). In the present investigation, this refers to the energy density of the amount of lubricant and fuel used by different machines. This was calculated for each single machine based on the following assumptions: the lubricant and fuel consumption in litres of each machine are multiplied by the determined productive machine hours done (Table 14).

Table 14: Direct fuel consumption for machines.

Machines	**Fuel**	**Lubricant use (% of fuel consumption) (l/PMH)**	**Actual PMH & Km travelled**	**Direct Lubricant use[l]**	**Direct fuel used[l]**	**Total fuel and lubricant use**
Chain saw	1.5 l/hr	0.3 (20%)	30	9.0	45.3	54.3
Three-wheeled loader	6.0 l/hr	1.2 (20%)	7.96	9.55	48	57.55
Chipper	7.8 l/hr	1.17 (15%)	8	9.36	72	81.36
Truck	4.5 km/l	0.09 (2%)	102	0.92	22.8	22.92
Pick-up truck	8.0 km/l	0.16 (2%)	102	0.16	12.8	12.96
						229.09

Hence, the sum of fuel used by the chain saw, chipper, three-wheeled loader and the truck plus pick-up truck was calculated. The resulting volumes are then converted into MJ and KWh. Calculations were based on Equation 3-8.

$$E_i = \sum Fc + Fch + Ftwl + Ftp \qquad \text{Equation 3-8}$$

Where:

$E_i = \text{Input energy of the system (GJ)}$

$Fc = \text{direct fuel consumption of chain saw}$

$Fch = \text{direct fuel consumption of chipper}$

$Ftwl = \text{dicrect fuel consumption of the three-wheeled loader}$

$Ftp = \text{direct fuel consumption of truck and pick} - \text{up truck}$

The energy output and the input were used to determine the energy balance of the system which was based on Equations 3-10 given by Fei Pan *et al.,* (2008) and Westbrook *et al.* (2006).

$$E_b = E_o - E_i \qquad \text{Equation 3-10}$$

Where:

$E_b = \text{energy balance}$

$E_o = \text{Output energy (GJ)}$

$E_i = \text{Input energy (GJ)}$

3.5.7 Statistical data analysis

The statistical packages, R, Statistica, Origin, and Microsoft Excel were used in data analysis. The procedure of data analysis entailed scatter plots, correlation, regression analysis, and the test for significant differences. The input variables are the activity sampling of manual and motor-manual harvesting and the time study elements of the three-wheeled loader and the chipper.

The first step in the analysis consisted of measuring whether the underlying assumptions for the analysis of variance (ANOVA) test were met in the raw data. For that, the Shapiro-Wilk normality test was used in order to test the normality distribution of the data. ANOVA is also based on an assumption of equal variances to produce credible results. This was tested by using Bartlett and Levene’s test in order to establish if variables have the same variance in all groups that should be tested (Dalgaard, 2008). When the original data violated those assumptions, the natural logarithm In(x) transformation option was used. When the data still did not fulfil the assumptions, the Kruskal-Wallis test, which is the nonparametric counterpart of a one-way ANOVA, was applied as an option (Siegel and Castellan, 1988). This allowed progressing to the second step of the data analysis. The statistical output for the Kruskal-Wallis test was then presented into Kruskal-Wallis by ranks table, graphical representation and categorized histogram variable for each evaluated variable. The Kruskal-

Wallis by ranks table included: variables (independent and dependent), codes (i.e. helping to identify the group membership of each case), and sum of ranks (allows for the characterization of the dependent variable between samples, without paying attention to which group each value belongs).

The regression analysis and correlation were used to determine the regression model that characterized the relationship between independent(explanatory) and dependent(response) variables of the extraction operation for the machinery. In the case of the simple linear regression, four principal assumptions should be fulfilled before deciding to use the linear regression. This includes linearity, independence of errors, homoscadasticity of the error and the normality of the error distribution (Clewer and Scarisbrick, 2001). The linear regression was fitted into the data when the scatter plots were presenting a linear pattern.

$$y = a_1 + a_2(x)$$ Equations 3-11

Where:

y = *dependent variable*

x = *independent variable*

a_1, a_2 = *regression parameters*

When the scatter plots were indicated as a curve, a nonlinear power regression was more appropriate. This was based on the power function (Equations 3-12):

$$y = a x^b$$ Equations 3-12

Where:

y = *dependent variable*

x = *independent variable*

a, b = *regression parameters*

Before being analysed by linear regression, variables had to be logarithmically transformed (Payandeh, 1981). As the logarithmic transformations were used for fitting allometric equations to data, the logarithmic correction factor (CF) suggested by Sprugel (1983) was applied in order to remove a systematic bias as per Equation 3-13

$$CF = e^{(\frac{SSE^2}{2})}$$ Equation 3-13

Where:

$CF = correction\ factor$

$SSE = standard\ error\ of\,estimate\ of\,the\ regression$

$e = euler's\,number$

The output analysis of the regression model is summarized in Table 15.

Table 15: Output model of the regression.

Parameter statistics			**Lower 95%**		**Upper 95%**
A			Confidence limits		Confidence limits
B					
R^2	Degree of determination	SD	standard deviation	N	sample number
R	Correlation parameter	CF	logarithmic correction factor	P	P-value

Before accepting the outcome of a linear regression, the predictive ability and the goodness of fit of the regression models were examined by residual diagnostic analysis. This was done visually by examining the residual errors which were supposed to be random and normally distributed. Two residual plots type were used: the residual errors over their fitted values and then the Q-Q plot (Dalgaard, 2008).

4. Results

4.1 Recoverable biomass per hectare under prevailing conditions

The average mass of fresh recoverable biomass was 150.04 t ha^{-1} (i.e. 115.5 ODT ha^{-1}) (Table 16).

Table 16: Harvested biomass per plot and per hectare, given in fresh and oven dry biomass.

Species	**Fresh Solid Wood t plot^{-1}**	**ODT Solid Wood plot^{-1}**	**Fresh Wood chips t plot^{-1}**	**ODT Wood chips plot^{-1}**	**Total fresh biomass t plot^{-1}**	**Total ODT biomass plot^{-1}**	**Total fresh biomass t ha^{-1}**	**Total ODT biomass ha^{-1}**
Gum 1	0.00	0.00	4.53	3.67	4.53	3.67	113.25	91
Gum 2	1.38	1.12	3.96	3.21	5.34	4.33	133.5	108
Acacia1	1.00	0.82	5.79	4.75	6.79	5.57	169.75	138.86
Acacia2	1.00	0.82	5.59	4.58	6.59	5.40	164.75	134.77
Myrtle 1	0.64	0.45	5.79	4.00	6.43	4.44	160.75	111.24
Myrtle 2	0.64	0.45	5.69	3.93	6.33	4.37	158.25	109.51
Mean	0.77	0.61	5.22	4.02	6.00	4.63	150.04	115.5

Figure 18: Average biomass yield grouped by species with 95%-confidence intervals.

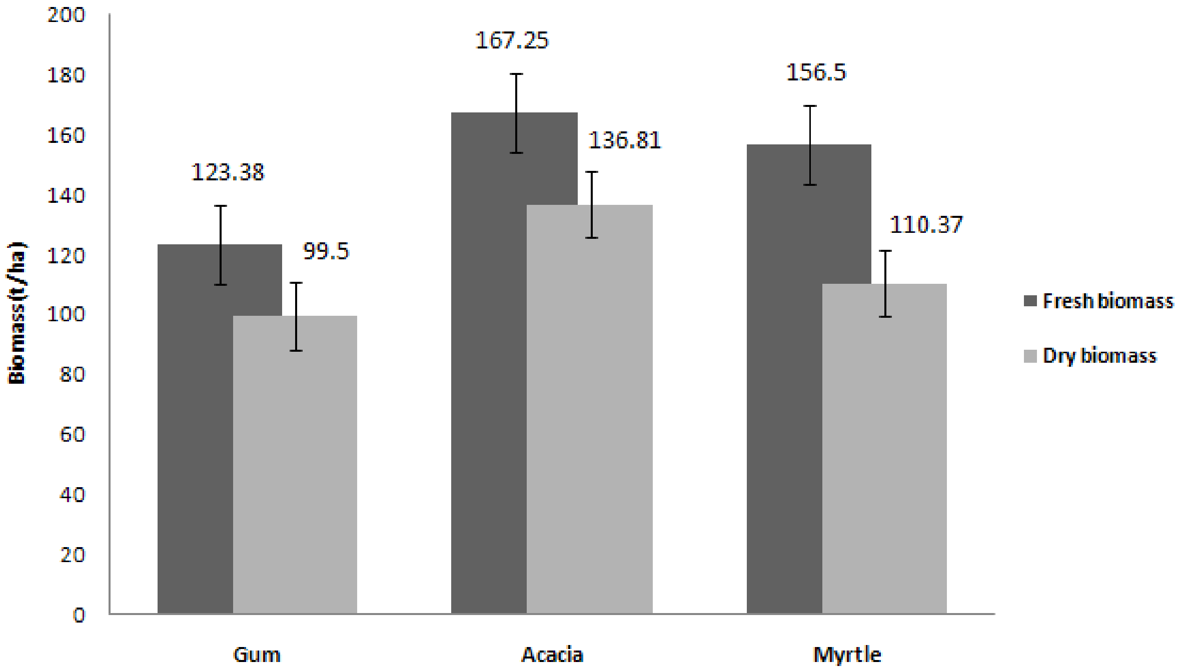

Figure 19: Average biomass yield grouped by species with 95%-confidence intervals.

4.2 Activity sampling results

4.2.1 Proportion of effective time of manual harvesting tasks and productivity between species

Figure 19 and Table 17 show the difference between manual activities of the different species plots and harvesting methods. The results indicated that clearing time of manual activities (Pickup, Moving empty, Idle, Spraying, Move loaded, Cutting, Stacking) on the Spider Gum site consumed 47% of the total working time. This was followed by Myrtle at 38% and Acacia at 15%.

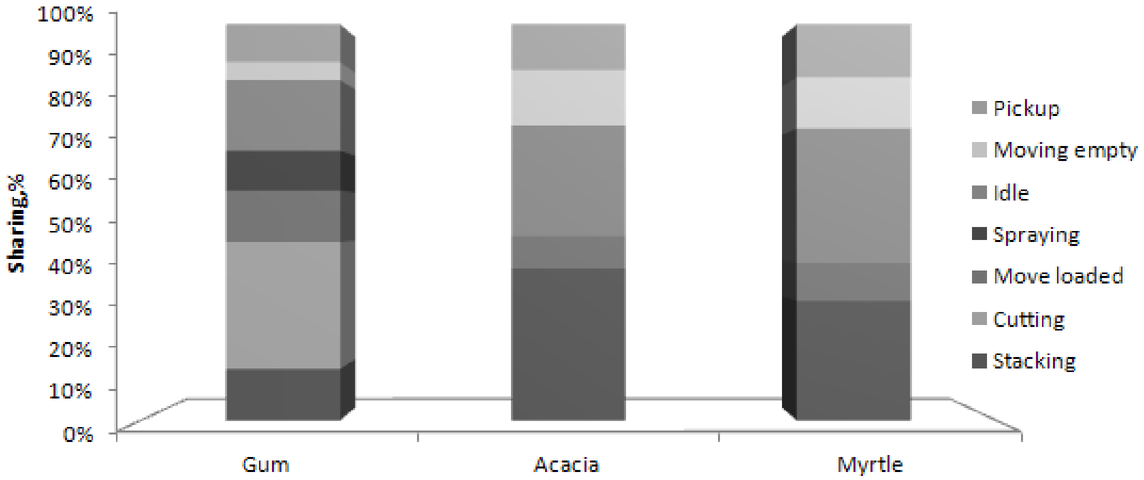

Figure 20: Species comparison of the proportion of total time used by the different harvesting activities.

As indicated in Fig.19, the cutting element appeared only in the Spider Gum species because in the two others species (Acacia and Myrtle), cutting was done motor-manually. The spraying element was absent in Acacia and Myrtle due to the difficulty of spraying each single stump after cutting.

Table 16: Share of elemental times of the working cycle of manual harvesting.

Work element	Percentage (%)
Idle time	26
Stacking	23
Cutting	15
Move load	11
Pickup	11
Move empty	9
Spraying	5

The manual productivity results expressed in terms of ODT per man day revealed that the productivity ranged from 0.5 to 1.8 ODT man day^{-1} (Table 18).

Table 17: Manual harvesting yields (ODT).

Species	Number of workers	Labour clearing time(min)	Total biomass (ODT plot^{-1})	Productivity (ODT man day^{-1})
Gum 1	6	248	3.66	0.61
Gum 2	8	415	4.32	0.54
Acacia 1	3	461	5.56	1.85
Acacia 2	8	470	5.39	0.67
Myrtle 1	3	433	4.45	1.48
Myrtle 2	4	446	4.38	1.10
Average	**5**	**412**	**5**	**1.04**

4.2.2 Proportion of effective time of motor-manual harvesting tasks and productivity in a comparison of species

Figure 20 shows the breakdown of the various elements recorded, and the proportional percentage of time used for the chainsaw operator to fell and prepare the biomass before the extraction phase. In Myrtle for example, the actual cutting time was calculated at 47% of the total work time, which was greater than that of Spider gum (39%) and Acacia (14%).

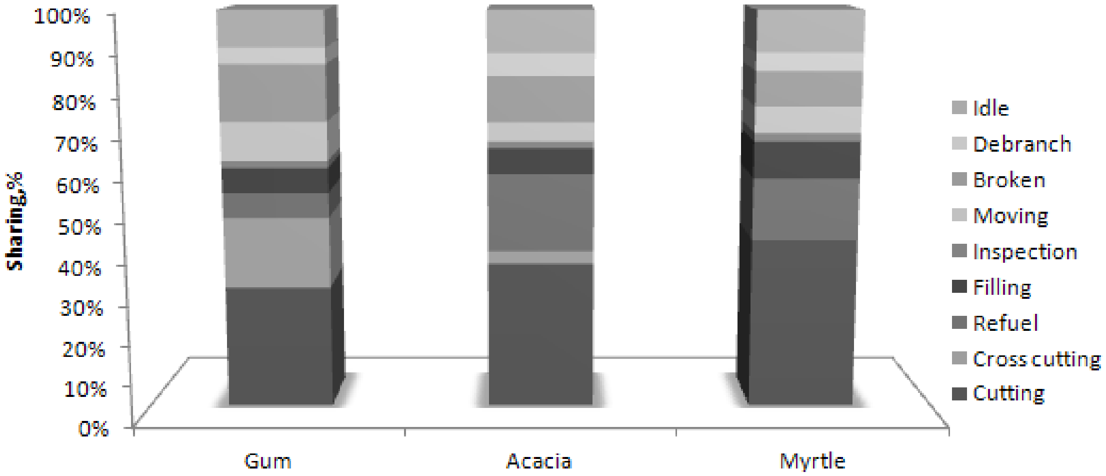

Figure 21: Proportion of time used by the different motor-manual activities.

The cutting consumed the greatest amount of time during the chain-saw operation cycle (37%), while the inspection amounted to the smallest part of cycle time (2%) (Table19).

Table 18: Share of elemental times of working cycle of motor-manual harvesting.

Work element	Percentage (%)
Cutting	37
Refuel	13
Broken	11
Idle time	10
Filling	8
Moving	8
Cross cutting	7
Debranching	4
Inspection	2

An investigation of the motor-manual production rates reveals a range from 0.7 to 1.7 ODT PMHo^{-1} (Table 20).

Table 19: Productivity of motor-manual activity harvesting (ODT).

Species	Chain saw operators	Chain saw clearing time (min)	Total biomass (ODT plot^{-1})	Productivity (ODT PMH^{-1})	Potential productivity (ODT PMH^{-1})
Gum 1	-	-	-	-	-
Gum 2	2	291	4.32	1.78	3.56
Acacia 1	1	328	5.56	1.02	2.03
Acacia 2	2	456	5.39	1.42	2.84
Myrtle 1	1	374	4.45	0.71	1.43
Myrtle 2	1	365	4.38	0.72	1.44
Average	**1**	**302**	**4**	**1**	**2.26**

4.3 Time study results

4.3.1 Testing Alternative Hypothesis 1: It is possible to identify variables that significantly affect the productivity of biomass extraction for the three prevailing tree species

4.3.1.1 Relationship between distance and productivity of the three wheeled loader

A regression analysis between distance and productivity of the original data was conducted in order to test Alternative Hypothesis 1. The cloud shape of data points in the scatter plot of this relationship shows a typical nonlinear correlation (Figure 22). A curved line was judged more suitable to fit the data than a straight line, thus the power regression (Equation 4-1) was applied to the data.

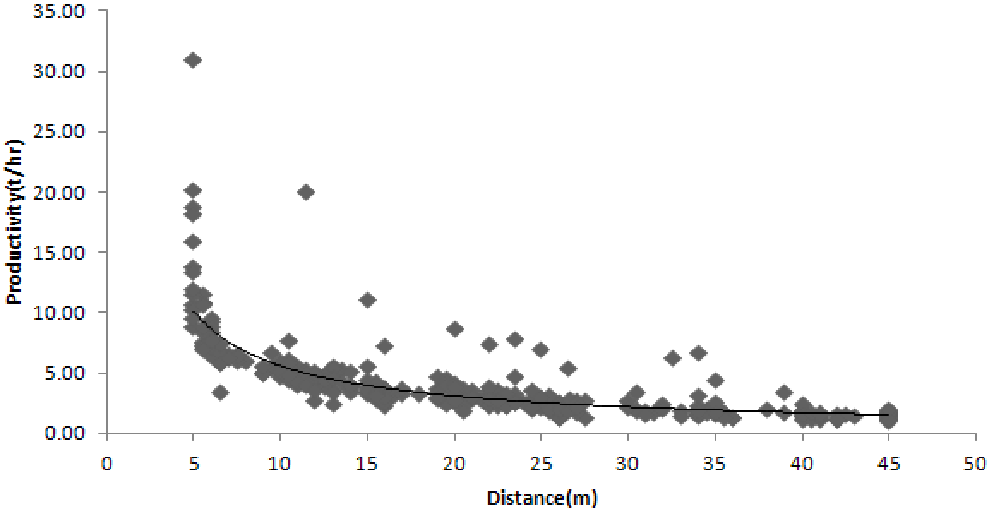

Figure 22: Power regression model of Distance and Productivity for the three-wheeled loader extraction.

The function used for the power regression analysis can be written as followed:

$$y = a \quad x^{b}$$ Equation 4-1

Where:

$y = productivity\ of\ dry\ mass\ [t/hr]\ as\ the\ dependent\ variable$

$x = extraction\ \ distance\ \ [m]\ \ as\ the\ \ independent\ variable$

$a, b = regression\ \ variable\ \ parameters$

Parameter statistics and degree of determination, standard deviation, sample number and p-value of the regression of the power regression model (Equation 4-1) for distance and productivity of the three-wheeled loader extraction are shown in Table 21.

Table 20: Parameter statistics for distance and productivity of the three-wheeled loader extraction.

<table>
<tr><th colspan="2">Parameter</th><th colspan="2">Value</th><th colspan="2">Lower 95%</th><th colspan="2">Upper 95%</th></tr>
<tr><td colspan="2">a</td><td colspan="2">78.6</td><td colspan="2">62.08</td><td colspan="2">95.22</td></tr>
<tr><td colspan="2">b</td><td colspan="2">-0.97</td><td colspan="2">-1.07</td><td colspan="2">-0.88</td></tr>
<tr><td>R^2</td><td>0.41</td><td>SD</td><td>2.48</td><td>N</td><td>352</td></tr>
<tr><td>R</td><td>-0.64</td><td></td><td></td><td>p-value</td><td><0.0001</td></tr>
</table>

It can be seen from the plot illustrating residuals over the fitted values (Figure 23), that the residuals vary around the curved line in a non- constant way. This suggests that the assumption of equal variances is violated.

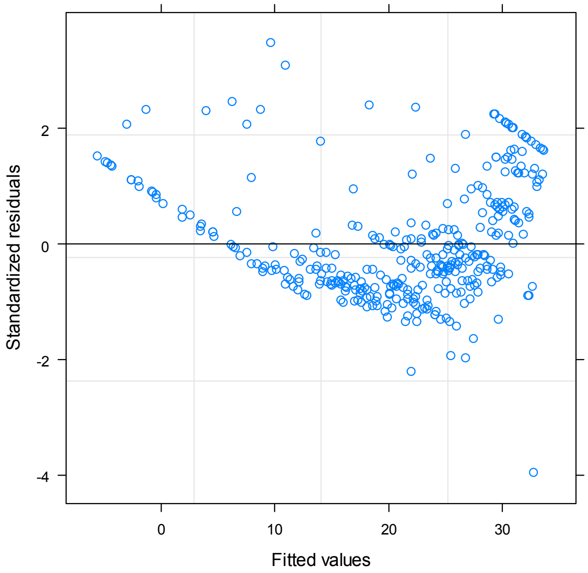

Figure 23: Residual plot of Productivity vs. Distance for the three-wheeled loader extraction.

The model shows outliers and the inequality of the error variances. In order to improve the current model, the regression analysis was carried out, based on transformed data of the two variables (Figure 23).

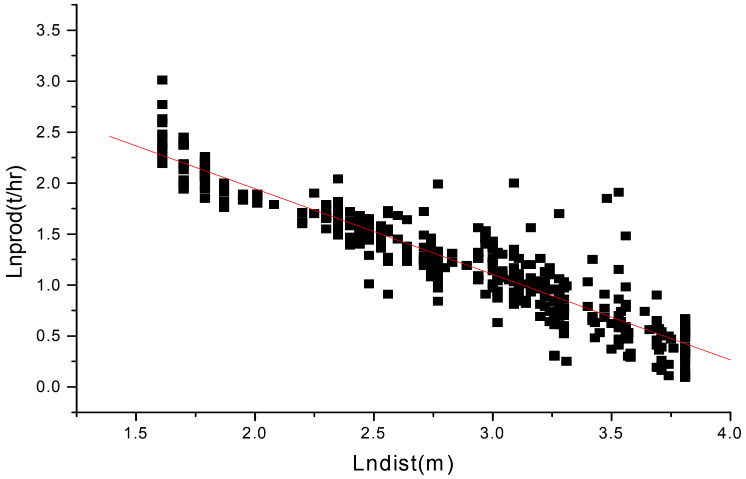

Figure 23: Linear regression model of natural logarithmic transformed Distance and Productivity for the three-wheeled loader extraction.

The corresponding function for the linear regression analysis is seen in Equation 4-2.

$$\ln(y) = a_1 + a_2 \ln(x)$$ Equation 4-2

Where:

$y =$ *Ln(prod) natural logarithmic transfomation of the productivity of dry mass [t/hr] as the dependent variable*

$x =$ *Ln(dist) natural logarithmic transfomation of extraction distance[m] as the independent variable*

$a_1, a_2 =$ *regression parameters*

Parameter statistics and degree of determination, standard deviation, sample number and p-value of the regression of the linear regression model (Equation 4-2) for distance [Ln (dist)] and productivity transformed data of the three-wheeled loader extraction are shown in Table 22.

Table 21: Parameter statistics for natural logarithmic transformation of extraction distance and natural logarithmic transformation of productivity of the three-wheeled loader extraction.

<table>
<tr><th colspan="2">Parameter</th><th colspan="2">Value</th><th colspan="2">Lower 95%</th><th colspan="2">Upper 95%</th></tr>
<tr><td colspan="2">*a1*</td><td colspan="2">3.62</td><td colspan="2">3.54</td><td colspan="2">3.83</td></tr>
<tr><td colspan="2">*a2*</td><td colspan="2">-0.83</td><td colspan="2">-0.90</td><td colspan="2">-0.80</td></tr>
<tr><td>R^2</td><td colspan="2">0.77</td><td>SD</td><td>0.23</td><td colspan="2">N</td><td>342</td></tr>
<tr><td>R</td><td colspan="2">-0.87</td><td>CF</td><td>1.04</td><td colspan="2">p-value</td><td><0.0001</td></tr>
</table>

The regression diagnostics for the model are presented through the residual errors plotted vs. the corresponded fitted values (Figure 25).

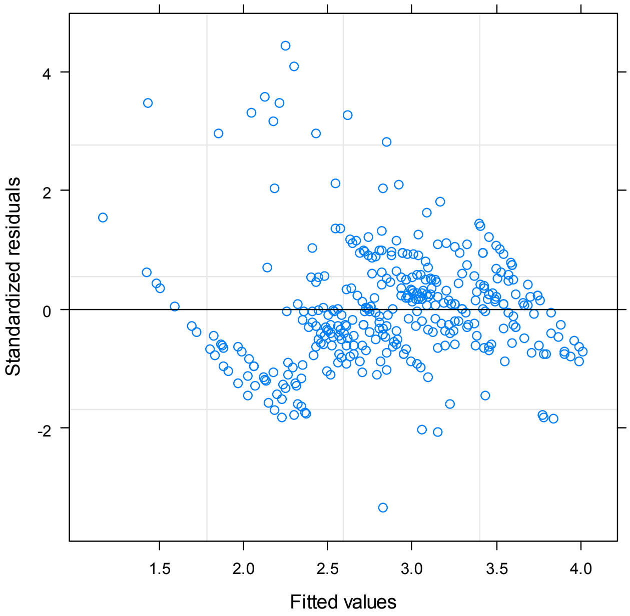

Figure 24: Residual plot of natural logarithmic transformed Production vs. Distance of the three-wheeled loader extraction.

The distribution of residuals around the fitted line was definitely improved, compared to Function 4-1, as well as the R^2. Figure 26 shows the standard Q-Q plot.

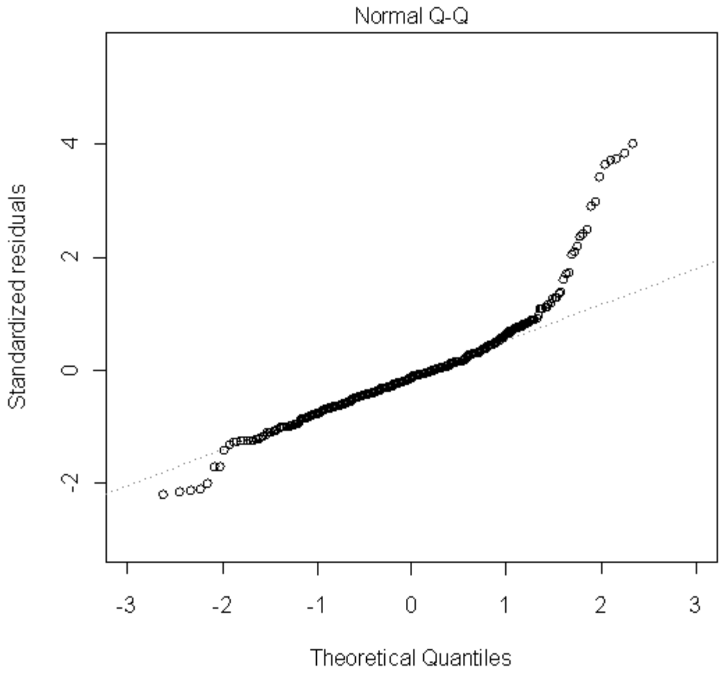

Figure 25: Standard residual Q-Q plot of Lnprod. vs. Lndist. of the three-wheeled loader extraction.

In both original and transformed data, the regression was highly significant (p-value< 0.0001) between distance and productivity during extraction by the three-wheeled loader. This indicated a noteworthy influence of distance on the productivity during extraction by the three-wheeled loader. Additionally, all parameters were also considerable (indicated by their 95% confidence limits that did not encompass zero). This provided the necessary evidence to accept the Alternative Hypothesis ($H_A 1$). According to the results, short distance corresponded to higher productivity (t PMH^{-1}). The regression functions (Equations 4-1 and 4-2) implied that an increase in extraction distance was negatively affecting the productivity of the three-wheeled loader. The relationship between distance and productivity yielded a tight negative correlation (R=-0.87) for the linear model. The corresponding coefficient of determination (R^2=0.41 and R^2=0.77) in the two regression models is indicative of two things: that 41% and 77% of differences in productivity could be explained by the variations in the distances and that the fitting of the point to the regression line was sufficient, particularly for transformed data as opposed to the untransformed data.

In Table 23 the three-wheeled loader productivity, based on four extraction distances (10m, 20m, 30m and 40m), is presented and compared with the potential productivity rate, implying 100% machine utilisation.

Table 22: Three-wheeled loader production rate set at 10m, 20m, 30m and 40m extraction distances.

Extraction distances	**Current productivity rate(ODT PMH^{-1}) at 50 % machine utilisation**	**Potential productivity rate(ODT PMH^{-1}) at 100 % machine utilization**
10m	5.34	10.68
20m	2.25	4.5
30m	1.99	3.98
40m	1.53	3.06
Average	3	6

4.3.1.2 Relationship between other variables of the three-wheeled loader extraction

In Figures 26, 30 and 33 below, the simple linear regression model of variables (cycle time vs. distance, travel loaded vs. distance and travel empty vs. distance) is illustrated.

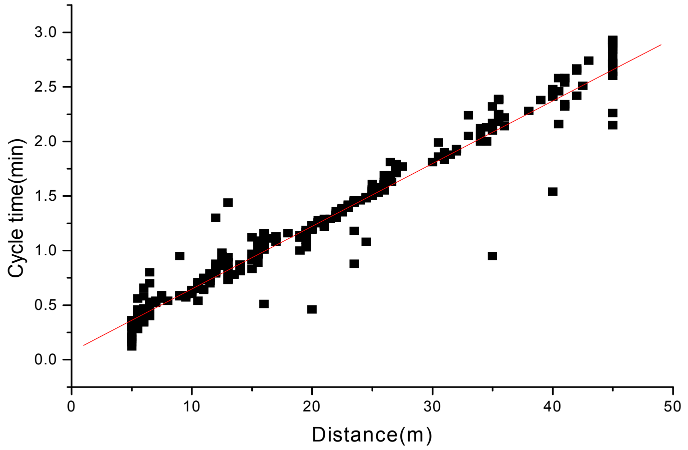

Figure 26: Simple linear regression between Distance time and Cycle time for the three-wheeled loader extraction.

The regression diagnostics for the model are presented through the analysis of residuals (Figures 28 & 29).

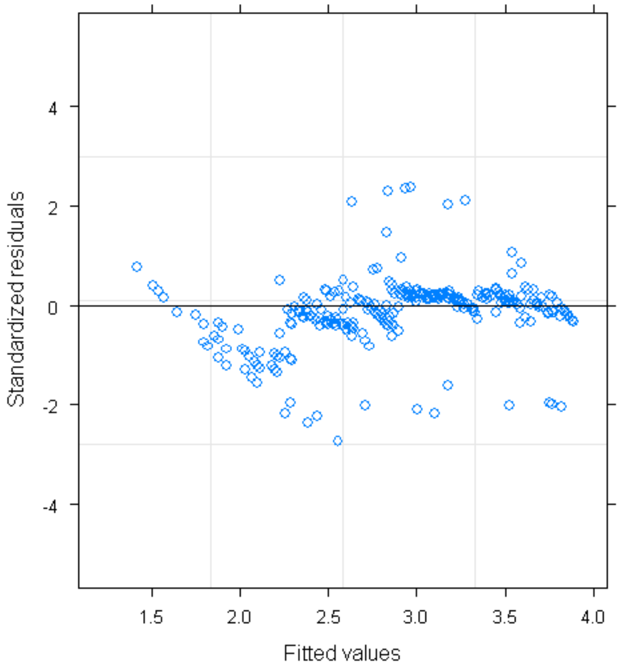

Figure 27: Residual plot of Cycle time vs. Distance of simple linear regression.

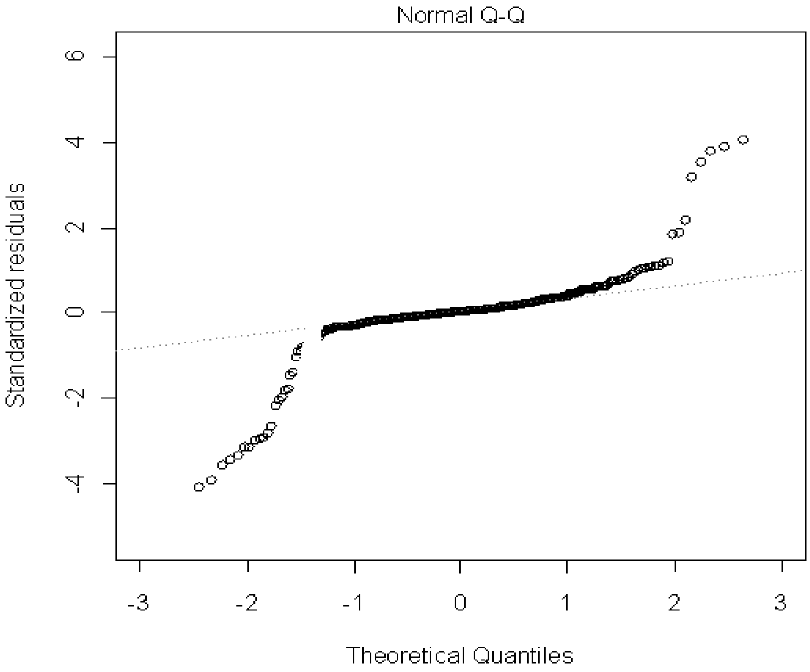

Figure 28: Standard residual Q-Q plot of cycle time vs. Distance

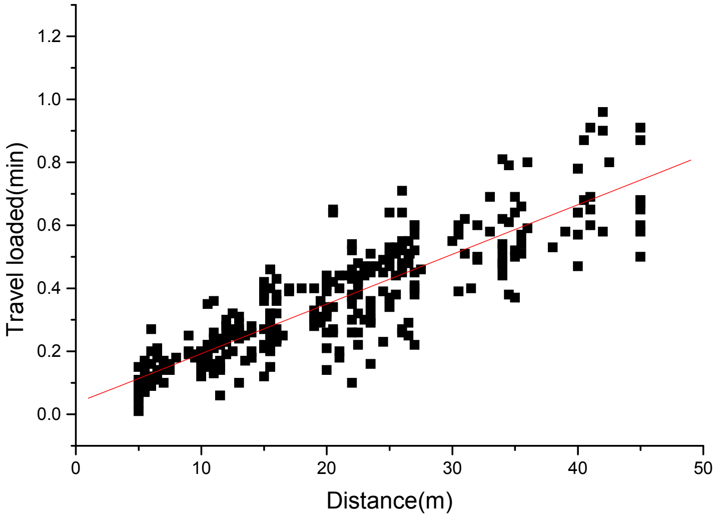

Figure 29: Simple linear regression between distance time and travel loaded.

The regression diagnostics for the model are presented in the analysis of residuals where a typical heteroscedastic fanning is visible with increasing fitted values (Figure 31).

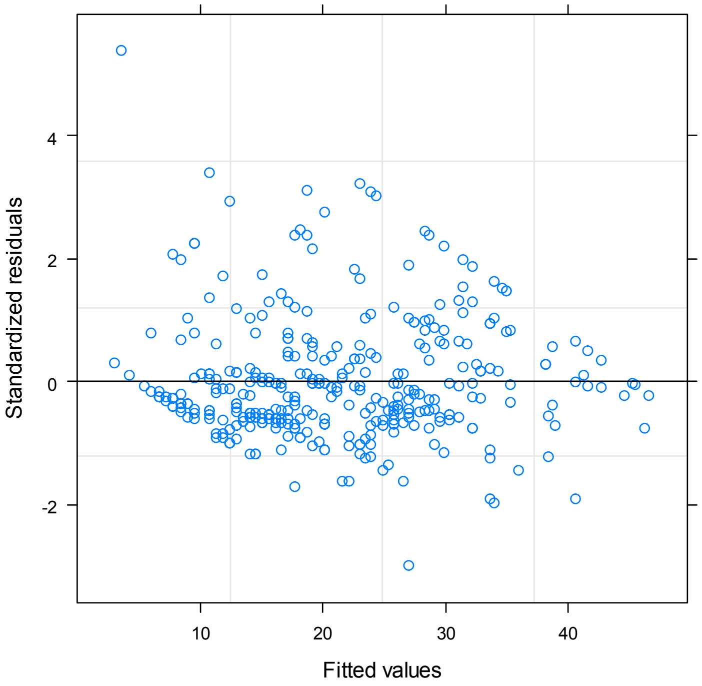

Figure 30: Residual plot of Travel loaded vs. Distance of simple linear regression.

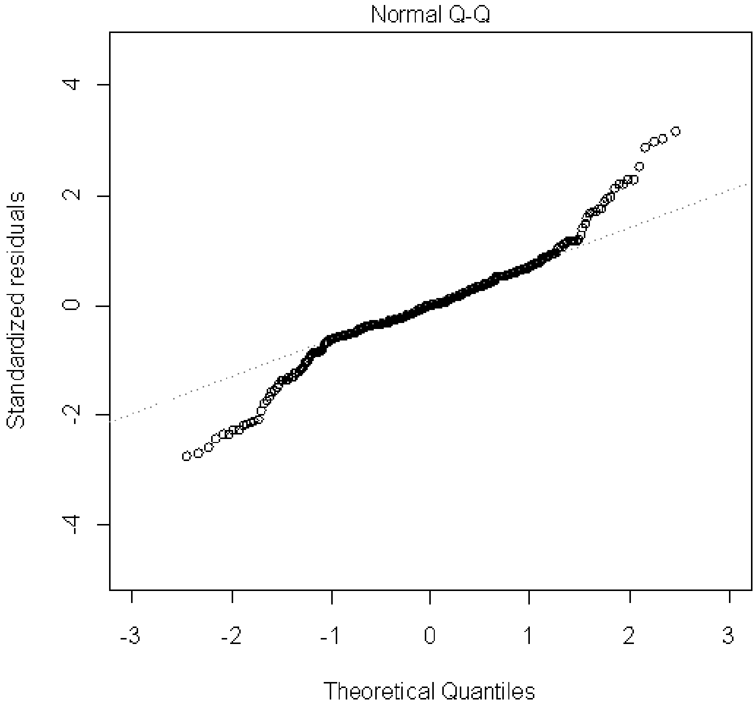

Figure 31: Standard residual Q-Q plot of Travel loaded vs. Distance.

In order to improve the situation, the transformed linear regression with an ln transformation was applied (Figure 33).

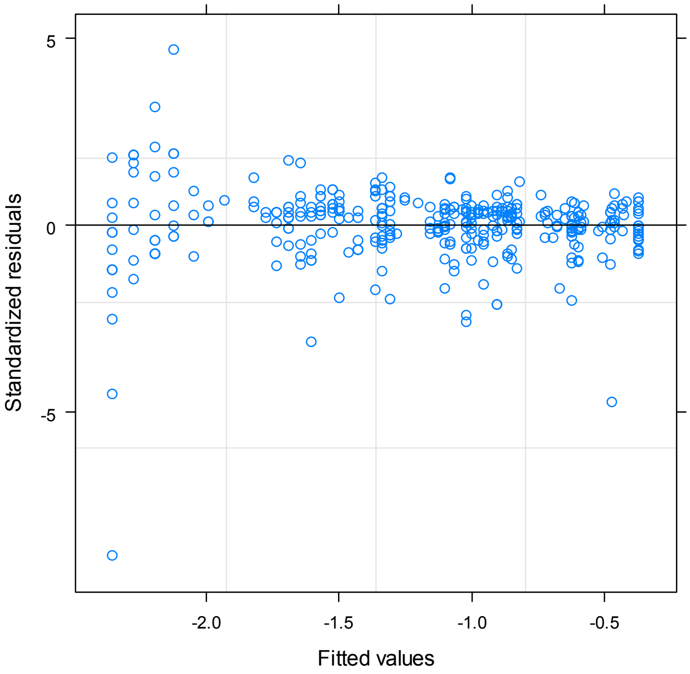

Figure 32: Residual plot of LnTravel load vs. Lndist of simple linear regression.

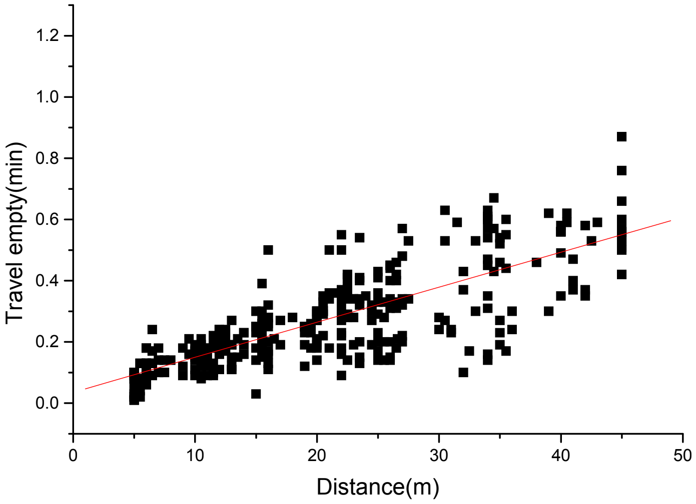

Figure 33: Simple linear regression between Distance time and Travel empty.

The regression diagnostics for the model are presented through the analysis of residuals (Figure 35). A heteroscedastic fanning of the residuals with higher prediction values is also apparent here. This means the In transformation was needed (Figure 36).

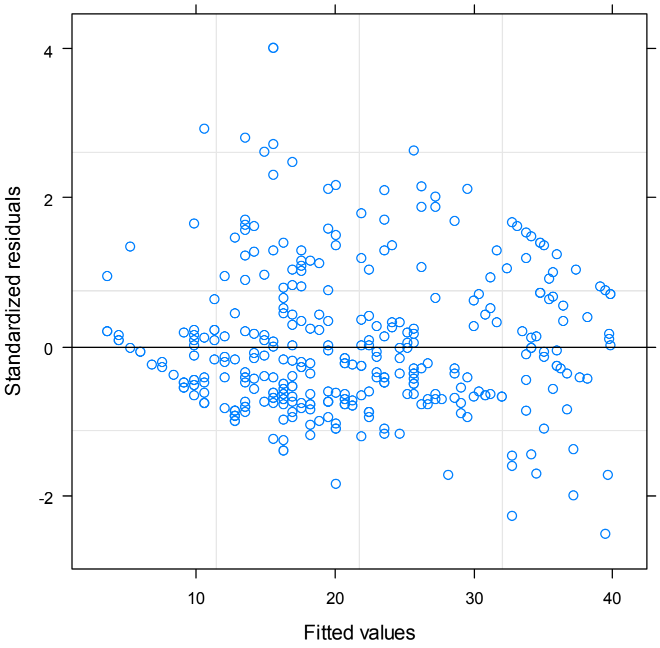

Figure 34: Residual plot of Travel empty vs. Distance of simple linear regression.

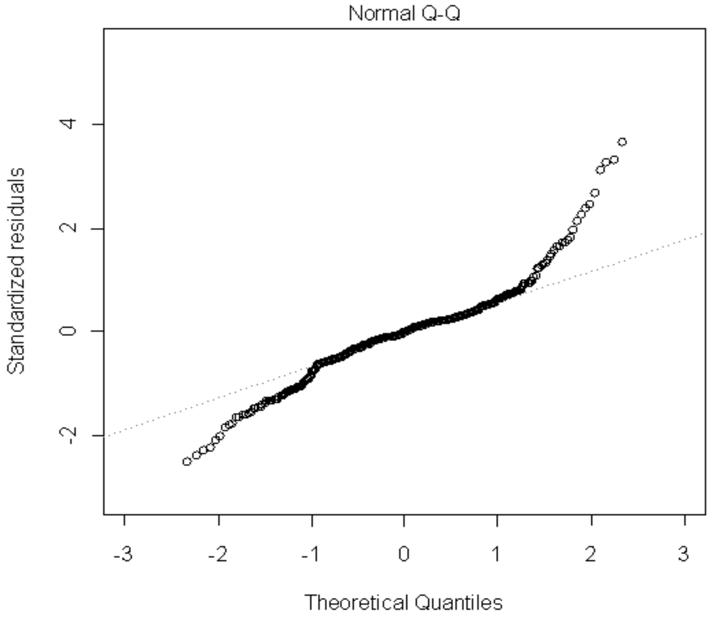

Figure 35: Standard residual Q-Q plot of Travel empty vs. Distance.

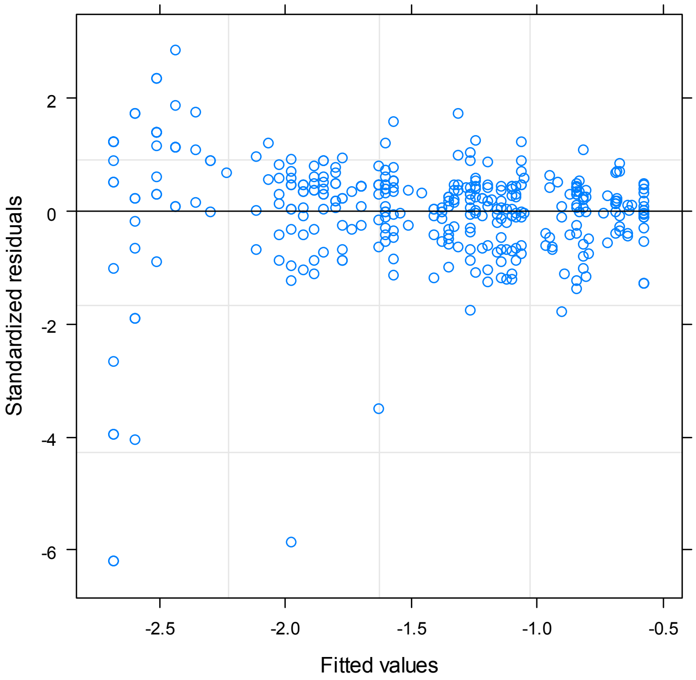

Figure 36: Residual plot of Lntravel empty vs. Lndist of simple linear regression.

Table 23: Simple linear regressions of variables.

Variables	**Linear regression model**	**N**	**R^2**	**p-value**
Cycle time vs. Distance	Y(Cycle time) = 0.074 + 0.057 ·X(Distance)	340	0.91	<0.0001
Travel loaded vs. Distance	Y(Trav.loaded) = 0.034+0.015 · X(Distance)	334	0.72	<0.0001
Travel empty vs. Distance	Y(Cycle time)= 0.022+ 0.012 ·X(Distance)	343	0.62	<0.0001

All three independent variables showed a significant relationship with the distance ($p<0.001$), the dependant variable. Once again, the alternative hypothesis (H_A1) was accepted for these three relationships, whereas the coefficient of determination (R^2) for the regression model indicated a good to sufficient fit. The variation in the independent variables was thus explained by the distance.

4.3.2 Testing Alternative Hypothesis 2: Productivity of biomass extraction with the three-wheeled loader differs between the three prevailing tree species

As the productivity data does not satisfy the underlying assumption of normal distribution and equal variance for the one-way analysis of variance (ANOVA) (Appendix 6), a Kruskal–Wallis test was conducted to determine the effect of the six species group. The statistical output for the Kruskal–Wallis test is illustrated in an error bar plot (Figure 38).

The Alternative Hypothesis (H_A2) of difference on machine productivity in ODT PMH^{-1} was accepted at a significance level of 0.05, indicating that the Kruskal-Wallis test was highly significant ($p< 0.001$). The same observation was confirmed with the Kruskal-Wallis median test ($p<0.001$) (Appendix 6).

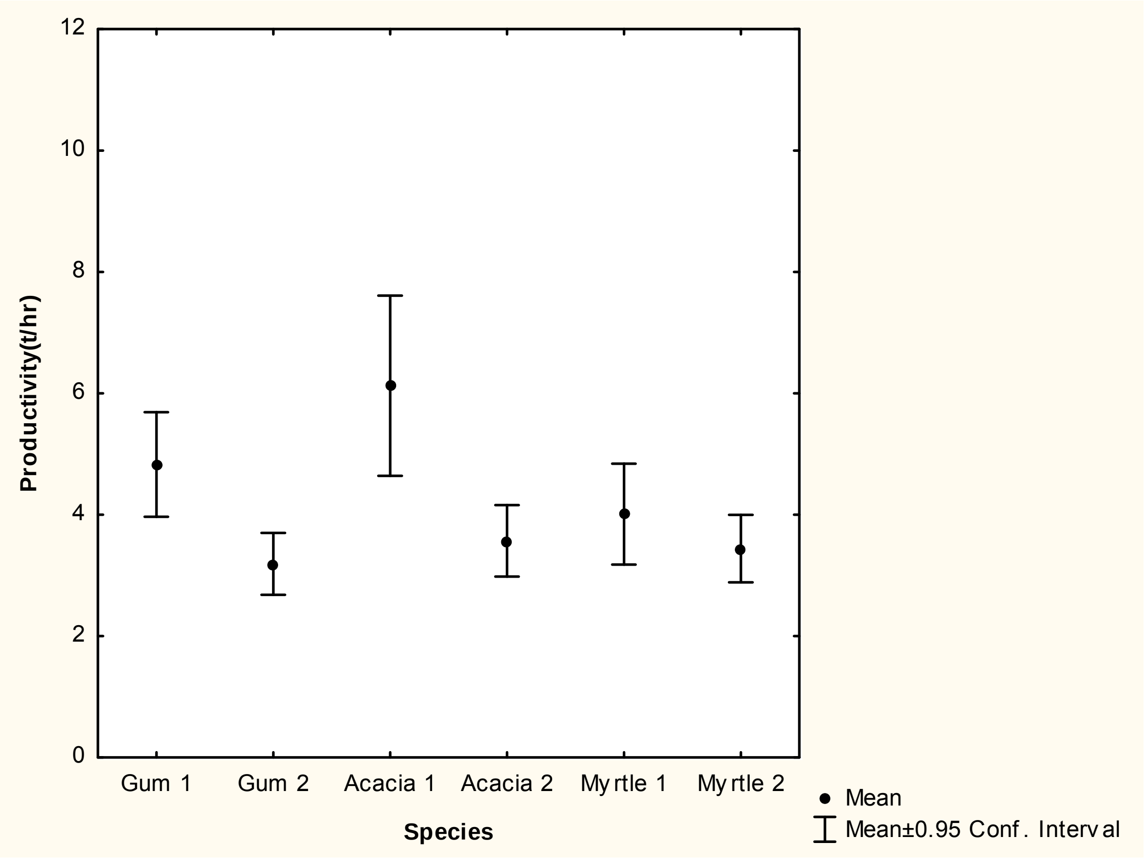

Figure 37: Mean productivity and 95% confidence interval grouped by species.

The Kruskal-Wallis test rank table clarified in detail the difference between species (Table 25): the highest rank sum was achieved by Gum 1 and the lowest rank sum by Gum 2.

Table 24: Kruskal-Wallis ANOVA by rank.

Independent variables: species	Kruskal-Wallis test: H(5, N= 352)= 34.72083 p= 0.001		
	Code	**Valid N**	**Sum of Ranks**
Gum 1	101	61	12801.5
Gum 2	102	49	7159.5
Acacia 1	103	46	10972
Acacia 2	104	63	10501
Myrtle 1	105	64	10375
Myrtle 2	106	69	10319

4.3.3 Testing Alternative Hypothesis 3: The total cycle time of biomass extraction with the three-wheeled loader differs between the three prevailing tree species

Data of total cycle time was analysed using the Kruskal–Wallis test because the data did not satisfy the assumption for normality ($p<0.001$) that validates the use of the one-way ANOVA test. The results of the Kruskal–Wallis test are reported according to each species (Figure 39). There were significant differences between species ($p<0.001$), indicating that the alternative hypothesis (H_A3) is to be accepted. The same results were confirmed by the Kruskal-Wallis median test (Appendix 6).

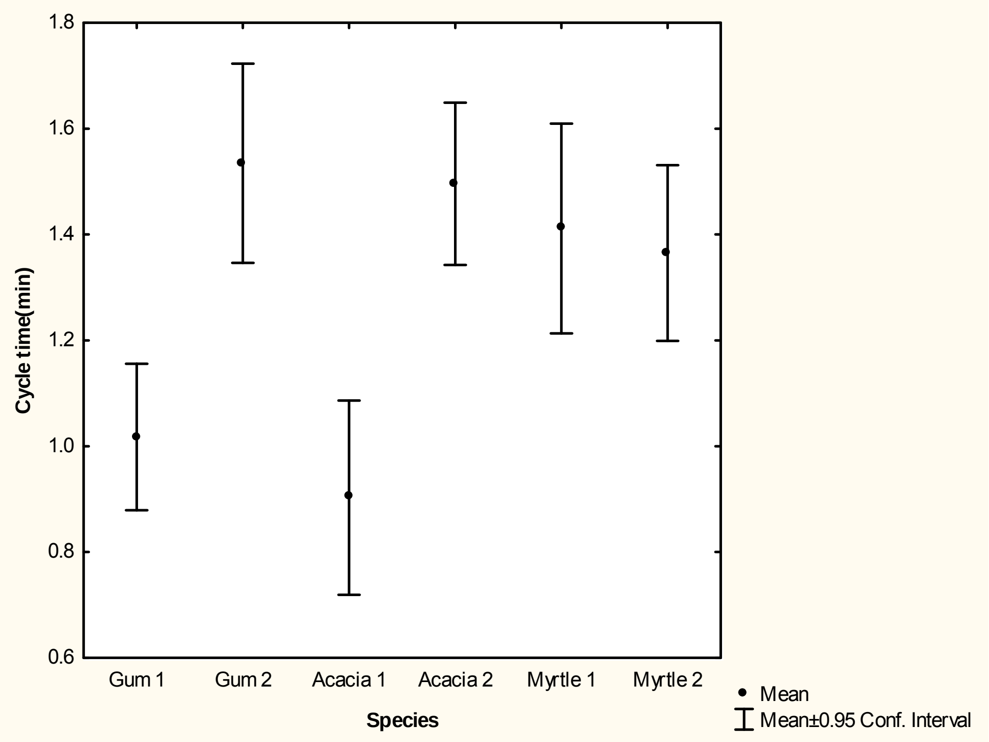

Figure 38: Mean plot of total cycle time grouped by species.

The difference in cycle time of the three-wheeled loader between species is provided in the Kruskal-Wallis Test rank table (Table 26), clearly showing which species was consuming more extraction time than others.

Table 25: Kruskal-Wallis ANOVA by rank.

Independent variables: species	Kruskal-Wallis test: H(5, N= 352)= 43.99169 p= 0.001		
	Code	**Valid N**	**Sum of Ranks**
Gum 1	101	61	8328.50
Gum 2	102	49	10465.50
Acacia 1	103	46	5101.00
Acacia 2	104	63	13325.00
Myrtle 1	105	64	12013.00
Myrtle 2	106	69	12895.00

4.3.4 Testing Alternative Hypothesis 4: The chipper productivity differs between the three prevailing tree species

An analysis of variance (one-way ANOVA) was conducted for comparing the productivity between species. The chipping productivity data was transformed to satisfy the ANOVA assumptions (i.e. Shapiro-Wilk normality test [p= 0.73] and Levene's test for equal variance [p= 0.05], Appendix 6). The results show that species do differ significantly ($p < 0.001$) with respect to productivity in ODT hour^{-1} at $\alpha = 0.05$. A graphical illustration of the chipper productivity results are shown in Figure 40.

Current productivity rates were compared to the potential productivity rate, which refers to 100% machine utilisation (Table 27).

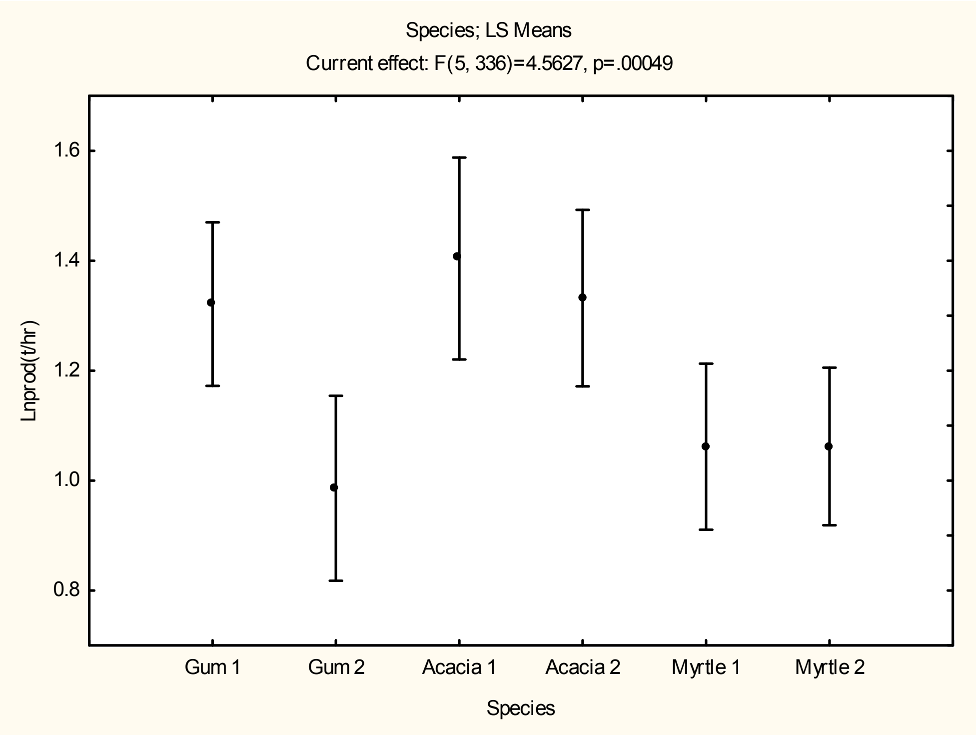

Figure 39: Error bar plot of productivity with mean value and 95% confidence intervals, grouped by species for chipping productivity.

Table 26: Chipping productivity rate between plots.

Species	**Current productivity Rate (ODT PMH^{-1}) at 50 % machine utilisation**	**Potential productivity rate (ODT PMH^{-1}) at 100 % machine utilization**
Gum1	3.13	6.27
Gum2	1.96	3.93
Gum ave.	**2.5**	**5.1**
Acacia1	4.72	9.44
Acacia2	3.79	7.59
Acacia ave.	**4.20**	**8.5**
Myrtle 1	2.49	4.98
Myrtle2	2.48	4.97
Myrtle ave.	**2.4**	**4.9**
Average	**3**	**6.1**

4.3.5 Testing Alternative Hypothesis 5: The total cycle time for chipping differs between the three prevailing tree species

As the ANOVA assumptions were not met by the data (Appendix 6), the Kruskal-Wallis test was used for the analysis. Remarkable differences at a significance level of 0.05 in terms of cycle time between species were observed. There were noteworthy differences ($p< 0.001$), indicating that chipping time was not the same. Results of the chipping cycle time comparison are illustrated in Figure 41.

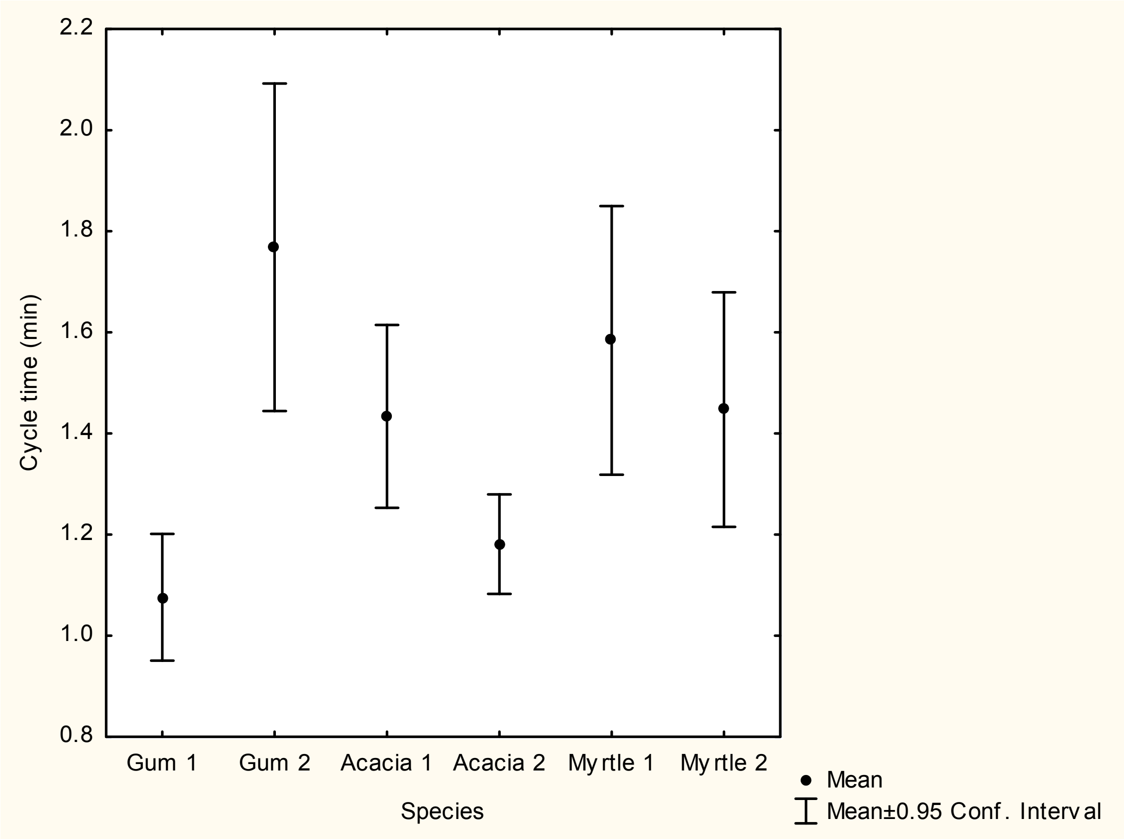

Figure 40: Results for the chipping cycle time between species.

The above results were confirmed in the Kruskal-Wallis ANOVA by rank (Table 28) and in the Kruskal-Wallis median test (Appendix 6).

Table 27: Kruskal-Wallis ANOVA by rank.

Independent variables: species	Kruskal-Wallis test: H (5, N= 342)= 18.629212 p< 0.001		
	Code	**Valid N**	**Sum of Ranks**
Gum 1	102	64	8509.50
Gum 2	103	50	10070.00
Acacia 1	104	42	8213.50
Acacia 2	105	55	8665.50
Myrtle 1	106	62	11304.00
Myrtle 2	107	69	11890.50

4.3.6 Testing Alternative Hypothesis 6: The waiting time of the chipper differs between the three prevailing tree species

The difference between species in waiting time of the chipper for the biomass was examined using the Kruskal-Wallis test because the data did not meet the required assumption of ANOVA test (Appendix 6). There were significant differences between species (p< 0.001). The results of the waiting time are presented graphically in Figure 42.

Table 28: Kruskal-Wallis ANOVA by rank.

Independent variables: species	Kruskal-Wallis test: H(5, N= 342)= 25.65087 p< 0.001		
	Code	**Valid N**	**Sum of Ranks**
Gum 1	102	64	10444.00
Gum 2	103	50	9585.00
Acacia 1	104	42	8777.50
Acacia 2	105	55	10463.00
Myrtle 1	106	62	7609.00
Myrtle 2	107	69	11774.50

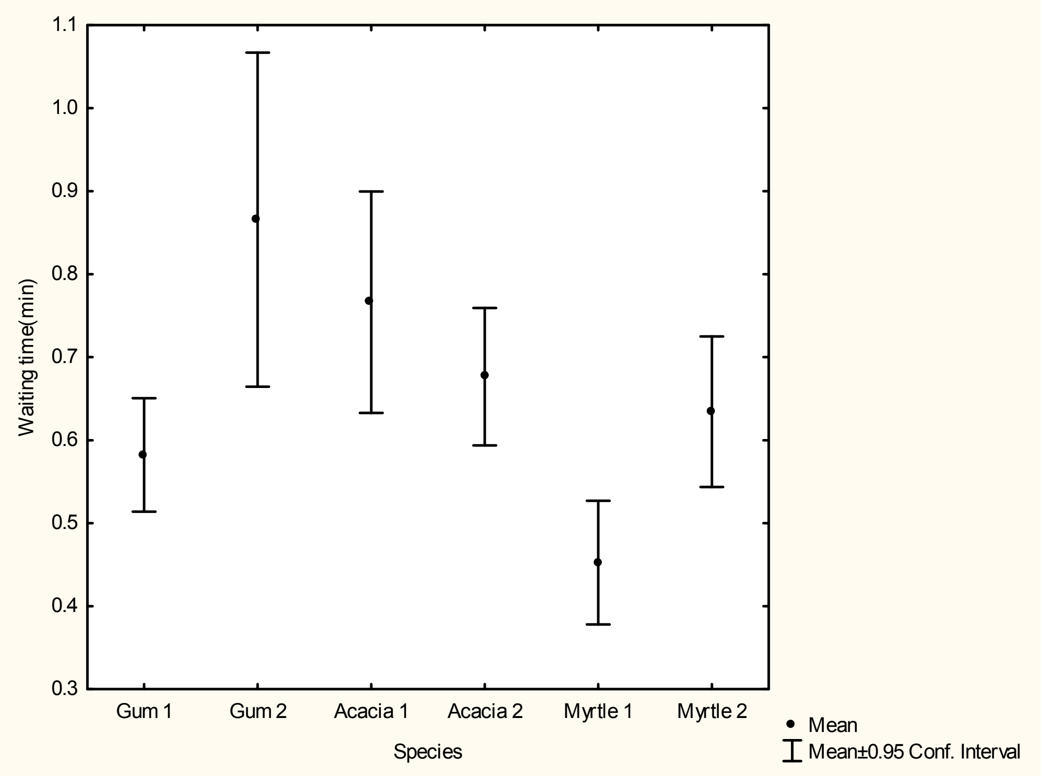

Figure 41: Results for the chipping waiting time between species.

More details are given in the Kruskal-Wallis ANOVA by Rank (Table 29) and in the Kruskal-Wallis median test (Appendix 6) which confirmed the results, so the Alternative Hypothesis could be accepted.

4.3.7 Testing Alternative Hypothesis 7: The chipper feeding time differs between the three prevailing tree species

Here again, the data did not satisfy the underlying assumption of ANOVA (Appendix 6; Shapiro-Wilks test for normality and Bartlett test for homogeneity of variances of feeding time). The analysis to determine the differences between the feeding times of biomass into the chipper between species was done using the Kruskal-Wallis test. The results show that the times were significantly different ($p<0.001$) between feeding times of species. In conclusion, the null hypothesis (H_o) was rejected and the alternative hypothesis accepted. Figure 43 below presents the Kruskal-Wallis test of feeding times.

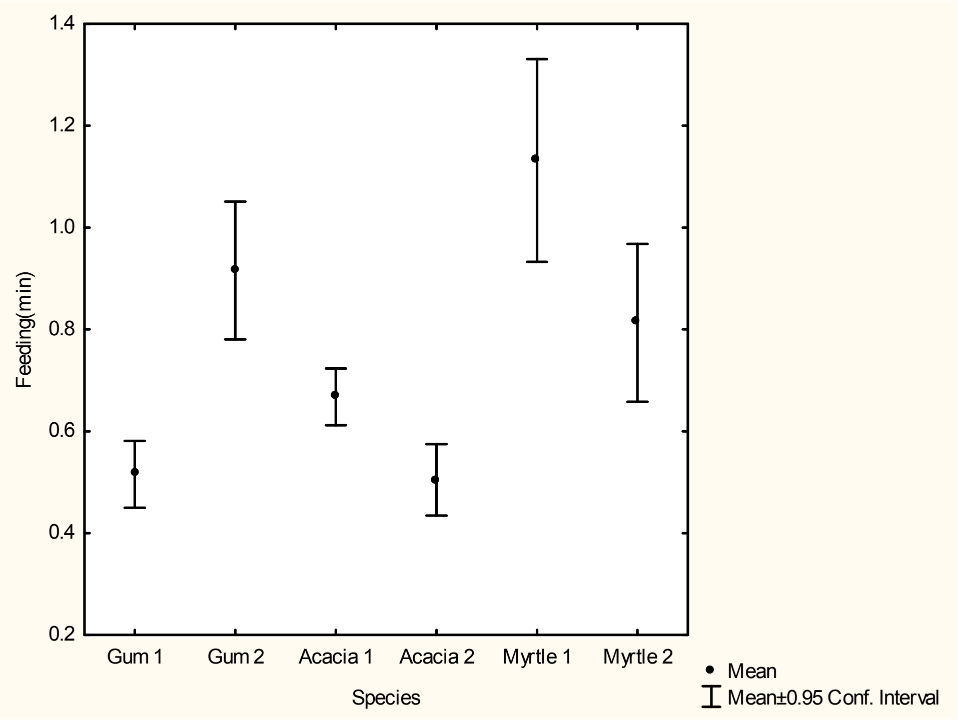

Figure 42: Results for the chipping feeding time between species.

Table 29: Kruskal-Wallis ANOVA by rank.

Independent variables: species	Kruskal-Wallis test: H(5, N= 342)= 65.04607 p< 0.0001		
	Code	**Valid N**	**Sum of Ranks**
Gum 1	102	64	7526.00
Gum 2	103	50	10746.00
Acacia 1	104	42	7468.50
Acacia 2	105	55	6601.50
Myrtle 1	106	62	14216.50
Myrtle 2	107	69	12094.50

4.4 Energy yield of harvested biomass

4.4.1 Fuel characteristics

Results showed that the *Acacia* species contained more water than the other species. In terms of energy content, the three species were similar, while minimal variance was detected in the ash content of the three species. The results on moisture content, energy content and ash content of biomass species used in the study are illustrated in Table 31. Based on Equation 3-6, the net calorific value of every species was estimated after subtraction of the energy content necessary to evaporate the water.

Table 30: Moisture content, energy content, ash content of species.

Species	Moisture content (%)	Net calorific value of dry biomass(GJ/t)	Net calorific value of fresh biomass(GJ/t)	Ash content (%)
Gum	25	19.36	14	1.38
Acacia	34	19.18	11.9	1.77
Myrtle	30	19.93	13.5	1.37

4.4.2 Gross energy output

Table 32 below shows the results of the calculated estimated energy derived from each plot and the extrapolation to a hectare level. An average energy of 76 GJ was calculated based on the fresh mass multiplied by the energy content per plot. When expressed in hectares, this represents about 3 364 GJ ha^{-1}. Conversion calculations indicated that the total equivalent energy from the six plots (i.e. Gum 1, Gum 2, Acacia1, Acacia 2, Myrtle 1 and Myrtle *2*) amounted to 13 0938 KWh, while the corresponding energy per hectare was 3 273 450 kWh. It is clear from the results that the output energy was higher on Acacia 1 and lower for Gum 1.

Table 31: Estimated woody biomass energy content.

Species	Energy plot^{-1} (GJ)	Energy plot^{-1} (kWh)	Energy ha^{-1} (GJ)	Energy ha^{-1} (kWh)
Gum 1	63.42	17 630.76	1 585.50	440 769.00
Gum 2	74.76	20 783.28	1 869.00	519 582.00
Acacia 1	81.48	22 651.44	2 037.00	566 286.00
Acacia 2	79.08	21 984.24	1 977.00	549 606.00
Myrtle 1	86.81	24 131.79	2 170.13	603 294.75
Myrtle 2	85.46	23 756.49	2 136.38	59 3912.25
Total	471.00	13 0938	11 775.00	3 273 450.00
Average	76.00	21 823	3 364.00	54 557.00

4.4.3 Energy input and energy balance

The results of the energy input indicated that the total direct lubricant and fuel consumption was about 229.09 litres for all systems, which corresponds to 8 338.87 MJ (8.33 GJ) of heating value, equivalent to 2 318.20 KWh. The chipper used the largest proportion (35.5%) of the total direct energy input of the system studied. The fuel used by the three-wheeled loader represented 25.12% of the total direct energy input, while the chain saw and the transport operation of both the truck and the pickup truck were responsible for 23.7% and 16% respectively. The direct energy input for the five machines is presented in Figure 44.

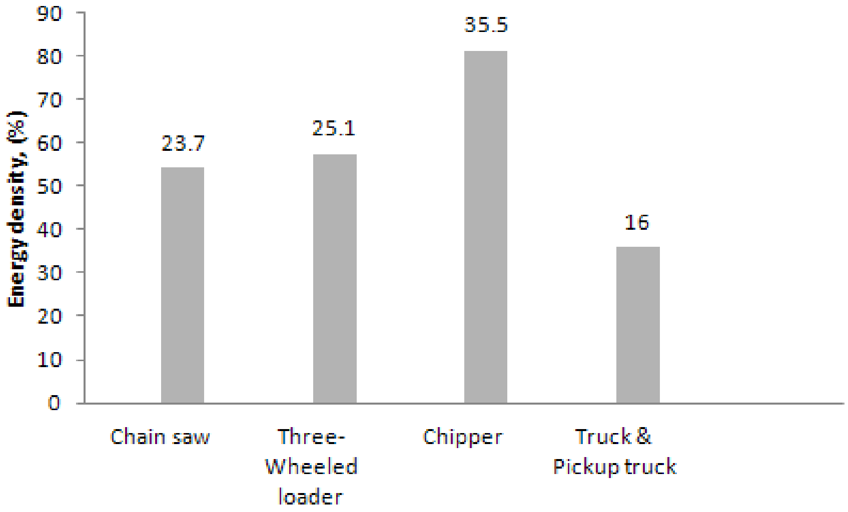

Figure 43: Direct energy input of the system.

Energy balance

Based on formula 3-10, the net energy balance of the harvesting system was determined by:

$$E_b = \quad 471 - 8.33 = 463$$

4.5 Operation costing

4.5.1 Labour costing

The labour cost results per ODT are presented in Table 33, and were calculated based on the number of workers/shift and the estimated productivity (i.e. ODT man day^{-1}, ODT hr^{-1}).

Table 32: Labour cost between species.

Cost components	Species					
	Gum1	Gum2	Acacia1	Acacia2	Myrtle1	Myrtle2
# of worker/ Shift	6	8	3	8	3	4
Estimated productivity ODT/man-day	0.61	0.54	1.85	0.67	1.48	1.10
Estimated productivity ODT/hr	0.08	0.07	0.23	0.08	0.18	0.13
Total cost R ODT^{-1}	195.31	223.21	67.93	195.31	86.81	120.19

According to the results in Table 33, Gum 2 had higher labour costs than Acacia 2, Gum 1, Myrtle 2, Myrtle 1, and Acacia 1. The average labour cost in general was R 148.12 ODT^{-1}. The Acacia plots differed strongly, with large variance between plots (i.e. 67.93 to R1 95.31 ODT^{-1}), while the labour costs on the Myrtle stand were similar at R 86.81 and 120.19 ODT^{-1}.

4.5.2 Machines costing

Based on the assumptions around the equipment used in this investigation (Appendix 7), the individual output calculations of the chainsaw, chipper and the three-wheeled loader are presented in Tables 34 to 36. The harvesting chain saw costs done on each plot were compared within species (Table 34).

Table 33: Cost breakdown of the chain saw between species per ODT.

Output calculations	**Gum 1**	**Gum 2**	**Acacia 1**	**Acacia 2**	**Myrtle 1**	**Myrtle 2**
Depreciation	0	3.03	5.29	3.8	7.61	7.5
Cost of Capital	0	0.34	0.6	0.45	0.86	0.89
Insurance	0	0	0	0	0	0
Total Fixed Costs	**0**	3.38	5.9	4.25	8.47	8.39
Fuel	0	7.38	12.88	9.25	18.51	18.25
Oil and Lubricants	0	1.48	2.58	1.85	3.7	3.65
Maintenance and repairs	0	3.37	5.88	4.23	8.45	8.33
Cutting bar	0	1.12	1.96	1.41	2.82	2.78
Cutting chain	0	1.07	1.87	1.34	2.68	2.65
Sprocket	0	0.18	0.31	0.23	0.45	0.44
Flat File	0	0.09	0.16	0.11	0.23	0.22
Round File	0	0.09	0.16	0.11	0.23	0.22
Total Variable Costs	**0**	14.78	25.8	18.53	37.06	36.55
TOTAL COSTS R ODT^{-1}	**0**	18.16	31.69	22.78	45.53	44.94

Chain saw cost per ODT between species ranged from R 18.16 /ODT to R 45.53 /ODT with an average cost of R 27.1 /ODT. On plot Gum 1, the chain saw costs were zero because felling had been done manually (Table 34).

The cost of the chipping activity was broken down in order to show the variation which could be observed between plots (Table 35).

Table 34: Cost breakdown of the Bandit model 255XP chipper.

Output calculations	**Gum1**	**Gum2**	**Acacia1**	**Acacia2**	**Myrtle1**	**Myrtle2**
Depreciation	12.04	19.23	7.99	0.97	15.14	15.2
Cost of Capital	8.29	13.24	5.5	0.68	10.42	14.28
Insurance	0	0	0	0	0	0
Relocation costs	0	0	0	0	0	0
Total Fixed Costs	20.33	32.47	13.48	1.65	25.56	29.48
Fuel	19.94	31.84	13.22	16.46	25.06	25.16
Oil and Lubricants	3.99	6.37	2.64	3.29	5.01	5.03
Maintenance and repairs	13.42	21.43	8.9	1.11	16.87	16.94
Tyres	0.04	0.06	0.03	0.03	0.05	0.05
Consumable/s	0	0	0	0	0	0
Total Variable Costs	37.38	59.69	24.79	20.9	46.99	47.18
TOTAL COSTS R ODT^{-1}	57.71	92.16	38.27	22.55	72.55	76.65

Chipping production costs are calculated at an utilisation rate of 50%. Gum 2 cost more at R92.16 ODT^{-1}, followed by Myrtle 2 at R76.65 ODT^{-1}, Myrtle 1 at R76.55 ODT^{-1}, Gum 1 at R57.71/ODT, Acacia 1 at R38.27 ODT^{-1} and Acacia 2 at R 22.55 ODT^{-1}.

Extraction costs based on four different travelled distances in meters were important because this indicated how the distance parameter can influence the extracting cost (Table 36).

Table 35: Cost breakdown of the three wheeled loaded at different extraction distances (10m, 20m, 30m and 40m).

Output calculations	**Travelled distance**			
	At 10m	**At 20m**	**At 30m**	**At 40m**
Depreciation	4.79	11.37	12.86	16.73
Cost of Capital	5.06	12.01	13.58	17.66
Insurance	0	0	0	0
Relocation costs	0	0	0	0
Total Fixed Costs	9.85	23.38	26.44	34.38
Fuel	8.99	21.33	24.12	31.37
Oil and Lubricants	1.8	4.27	4.82	6.27
Maintenance and repairs	5.62	13.33	15.08	19.61
Tyres	1.28	3.04	3.44	4.48
Total Variable Costs	17.69	41.98	47.46	61.73
TOTAL COSTS R ODT^{-1}	27.54	65.36	71.22	96.12

4.5.3 Secondary transport cost

The impact of the travelling distance of the truck from the harvesting site to the biomass plant was calculated at four road transports of 10km to 40km in order to provide a possible range of transport costs (Table 37).

Table 36: Woodchips and solid wood transport cost at different road transport distances.

	Species											
Cost components	**Gum**				**Acacia**				**Myrtle**			
Road transport distances	10km	20km	30km	40km	10km	20km	30km	40km	10km	20km	30km	40km
Woodchip transport cost R ODT^{-1} km^{-1}	26.9	30	114	120.4	26.6	29.8	112.8	119.2	31.5	35.2	134.4	142
Solid wood transport cost R ODT^{-1} km^{-1}	5.7	11.2	25.2	27.6	5.6	11	24.9	27.2	6.6	13	29.4	32.4
Total road transport cost R ODT^{-1} km^{-1}	32.6	41.2	139.2	148	32.2	40.8	137.7	146.4	38.1	48.2	163.8	174.4

4.5.4 Estimated total supply cost of both wood chips and solid wood

Wood chip and solid wood production costs (R ODT^{-1}), including manual harvesting, motor-manual harvesting, extraction, chipping and road transport within the current harvesting system for each biomass species ranged from R 322.77 ODT^{-1} to R 689.76 ODT^{-1} over road transport distances of 10 to 40 km (Table 38,39 and 40). This estimated cost is based on the energy contained in the biomass feedstock.

Table 37: Detailed cost analysis of the supply chain system based on different extraction and road transport distances.

Species	**Gum1**				**Gum2**			
Extraction distances	**10m**	**20m**	**30m**	**40m**	**10m**	**20m**	**30m**	**40m**
Cost components								
All fixed costs								
Chain saw	0	0	0	0	3.38	3.38	3.38	3.38
Three-wheeled loader	9.85	23.38	26.44	34.38	9.85	23.38	26.44	34.38
Chipper	20.33	20.33	20.33	20.33	32.47	32.47	32.47	32.47
Total	30.18	43.71	46.77	54.72	45.7	59.23	62.28	70.23
All variable costs								
Chain saw	0	0	0	0	14.78	14.78	14.78	14.78
Three-wheeled loader	17.69	41.98	47.46	61.73	17.69	41.98	47.46	61.73
Chipper	37.38	37.38	37.38	37.38	59.69	59.69	59.69	59.69
Total	55.07	79.36	84.84	99.11	92.16	116.45	121.94	136.21
All operators								
Chain saw	0	0	0	0	51.57	51.57	51.57	51.57
Three-wheeled loader	8.03	8.03	8.03	8.03	5.16	5.16	5.16	5.16
Chipper	13.69	13.69	13.69	13.69	18.22	18.22	18.22	18.22
Total	21.72	21.72	21.72	21.72	74.95	74.95	74.95	74.95
All worker								
Stack	195.31	195.31	195.31	195.31	223.21	223.21	223.21	223.21
Total	195.31	195.31	195.31	195.31	223.21	223.21	223.21	223.21
All additional personnel								
Other	7.02	16.67	18.84	24.51	7.02	16.67	18.84	24.51
Total	7.02	16.67	18.84	24.51	7.02	16.67	18.84	24.51
All overheads								
Total overhead cost	0	0	0	0	0	0	0	0
Total R ODT^{-1}	309.3	356.77	367.48	395.37	443.04	490.51	501.22	529.11
All together at different road transport distances R ODT^{-1}								
10 km	341.9	389.37	400.08	427.97	475.64	523.11	533.82	561.71
20km	350.5	397.97	408.68	436.57	484.24	531.71	542.42	570.31
30km	448.5	495.97	506.68	534.57	582.24	629.71	640.42	668.31
40km	457.3	504.77	515.48	543.37	591.04	638.51	649.22	677.11

Table 38: Detailed cost analysis of the supply chain system based on different extraction and road transport distances (continued).

Species	**Acacia1**				**Acacia2**			
Extraction distances	**10m**	**20m**	**30m**	**40m**	**10m**	**20m**	**30m**	**40m**
Cost components								
All fixed costs								
Chain saw	5.9	5.9	5.9	5.9	4.24	4.24	4.24	4.24
Three-wheeled loader	9.85	23.38	26.44	34.38	10.14	24.06	45.49	27.2
Chipper	13.48	13.48	13.48	13.48	1.65	1.65	1.65	1.65
Total	29.23	42.76	45.81	53.76	16.02	29.95	51.38	33.09
All variable costs								
Chain saw	25.8	25.8	25.8	25.8	18.53	18.53	18.53	18.53
Three-wheeled loader	17.69	41.98	47.46	61.73	16.4	38.93	73.61	44.02
Chipper	24.79	24.79	24.79	24.79	20.9	20.9	20.9	20.9
Total	68.28	92.57	98.05	112.32	55.83	78.36	113.04	83.45
All operators								
Chain saw	105.04	105.04	105.04	105.04	62.88	62.88	62.88	62.88
Three-wheeled loader	8.03	8.03	8.03	8.03	12.44	12.44	12.44	12.44
Chipper	5.04	5.04	5.04	5.04	8.08	8.08	8.08	8.08
Total	118.11	118.11	118.11	118.11	83.4	83.4	83.4	83.4
All worker								
Stack	67.93	67.93	67.93	67.93	195.31	195.31	195.31	195.31
Total	67.93	67.93	67.93	67.93	195.31	195.31	195.31	195.31
All additional personnel								
Other	7.02	16.67	18.84	24.51	11.7	27.78	52.52	31.41
Total	7.02	16.67	18.84	24.51	11.7	27.78	52.52	31.41
All overheads								
Total overhead cost	0	0	0	0	0	0	0	0
Total R ODT^{-1}	290.57	338.04	348.74	376.63	362.55	414.8	495.65	426.66
All together at different road transport distances R ODT^{-1}								
10 km	322.77	370.24	380.94	408.83	394.75	447	527.85	458.86
20km	331.37	378.84	389.54	417.43	403.35	455.6	536.45	467.46
30km	428.27	475.74	486.44	514.33	500.25	552.5	633.35	564.36
40km	436.97	484.44	495.14	523.03	508.95	561.2	642.05	573.06

Table 39: Detailed cost analysis of the supply chain system based on different extraction and road transport distances (continued).

Species	**Myrtle1**				**Myrtle 2**			
Extraction distances	**10m**	**20m**	**30m**	**40m**	**10m**	**20m**	**30m**	**40m**
Cost components								
All fixed costs								
Chainsaw	8.47	8.47	8.47	8.47	8.39	8.35	8.35	8.35
Three-wheeled loader	9.85	23.38	26.44	34.38	9.85	23.38	26.44	34.16
Chipper	25.56	25.56	25.56	25.56	29.48	25.66	25.66	25.66
Total	43.88	57.41	60.46	68.41	47.72	57.39	60.45	68.17
All variable costs								
Chainsaw	37.06	37.06	37.06	37.06	36.55	36.55	36.55	36.55
Three-wheeled loader	17.69	41.98	47.46	61.73	17.69	41.98	47.46	61.33
Chipper	46.99	46.99	46.99	46.99	47.18	47.18	47.18	47.18
Total	101.74	126.03	131.51	145.78	101.41	125.7	131.19	145.05
All operators								
Chainsaw	144.59	144.59	144.59	144.59	62	62	62	62
Three-wheeled loader	14.46	14.46	14.46	14.46	14.88	14.88	14.88	14.88
Chipper	14.46	14.46	14.46	14.46	5.16	5.16	5.16	5.16
Total	173.51	173.51	173.51	173.51	82.04	82.04	82.04	82.04
All worker								
Stack	86.81	86.81	86.81	86.81	120.19	120.19	120.19	120.19
Total	86.81	86.81	86.81	86.81	120.19	120.19	120.19	120.19
All additional personnel								
Other	11.7	27.78	31.41	40.85	7.02	16.67	18.84	24.35
Total	11.7	27.78	31.41	40.85	7.02	16.67	18.84	24.35
All overheads								
Total overhead cost	0	0	0	0	0	0	0	0
Total	417.64	471.54	483.7	515.36	358.38	401.99	412.71	439.8
All together at different road transport distances R ODT^{-1}								
10km	455.74	509.64	521.8	553.46	396.48	440.09	450.81	477.9
20km	465.84	519.74	531.9	601.66	406.58	450.19	460.91	488
30km	581.44	635.34	647.5	679.16	522.18	565.79	576.51	603.6
40km	592.04	645.94	658.1	689.76	532.78	576.39	587.11	614.2

4.6 Energy cost

The energy cost results expressed in R GJ^{-1} for each plot are shown in Table 41.

Table 40: Estimated energy cost.

Species	Average Cost Extraction (distance -25m) & Road transport (distance - 25km) R ODT^{-1}	Energy density GJ ODT^{-1}	Cost R GJ^{-1}	Energy density GJ $Fresh^{-1}$	Average Cost Extraction (distance -25m) & Road transport (distance - 25km) R fresh t^{-1}
	OD biomass			Fresh biomass	
Gum 1	447	19.36	23	14	323
Gum 2	581	19.36	30	14	420
Acacia 1	427	19.18	22	12	267
Acacia 2	514	19.18	27	12	322
Myrtle 1	578	19.93	29	14	406
Myrtle 2	509	19.93	26	14	358

Table 41 indicates that the Gum 2 site had the highest energy cost and the lowest was found on the Acacia 1 site, while the average energy cost across species was 26 R GJ^{-1}.

5. Discussion

This chapter investigates the biomass potential of the Agulhas region, followed by an outline of variables affecting cost and productivity of the harvesting system and the identification of feedstock characteristics. Hereafter, a cost sensitivity analysis to predict project performance is discussed. The chapter concludes with an examination of future research needs and potential limits in the use of biomass of invasive woody vegetation for energy generation.

5.1 Biomass potential of invasive tree vegetation in the Agulhas plain

The findings suggest that the physical recovery of invasive woody biomass has potential as bioenergy feedstock in South Africa. The biomass showed similar fuel characteristics as those of other forest biomass resources such as harvesting residues or short rotation tree crops, as reported by Röser *et al*. (2008). During this study, an average of 150 fresh biomass tonnes (115.6 ODT ha^{-1}) (in the form of solid stems and woodchips) were harvested per hectare from the six different study sites (Figure 45).

Figure 44: Harvested biomass (solid and woodchips) on the Acacia site on the Agulhas plain.

5.2 Evaluation of productivity of individual harvesting processes in the entire harvesting system

5.2.1 Manual harvesting

A comparison of the manual harvesting of different species (Figure 19) revealed that the Acacia harvesting was more economical than the other species due to wider spacing between larger trees (DBH 8.0 to 9.0 cm). Access to Spider Gum sites was limited by a higher density of small diameter stems per unit area (65 stem m^{-2}) of DBH's ranging from 1.0 to 7.0 cm, with almost 100% tree coverage and a dominant tree height estimated at 4 m (Figure 46). The highest productivity rate was achieved in the Acacia 1 and Myrtle 1 plots (Table 18), which can be attributed to the high vegetation density on these plots.

Figure 45: Dense biomass stand at the Spider Gum site on the Agulhas plain.

The results of activity sampling showed that worker productivity was however non-optimal during the study because of inordinately high portions of idle time (26%). This idle time could be attributed to the use of bow-saws and the associated fatigue element (bent posture and cutting action). With the introduction of ergonomically designed machines such as brush-cutters to allow a more upright posture and mechanically assisted cutting, it can be expected that productivity rates will be raised substantially. The introduction of brush-cutters could, for example, improve average productivity by 0.05 wet tonnes man day^{-1} (1.3 to 1.7 wet tonnes man day^{-1}), as found by Leinonen (2007).

The fact that the gender of the workers was predominantly female could furthermore have decreased the productivity rate, as females usually have a weaker physique than males. This can be demonstrated by the dominance of male workers in several physically demanding job sectors, such as mining, forestry and construction. A study by Barbini *et al.*

(2005) revealed that men were more tolerant of adverse conditions, as indicated by the following tolerance rates: noise (54% for men vs. 34% for women), vibration (25% for men vs. 6% for women), extreme temperatures (41% for men vs. 12% for women), holding an uncomfortable posture (20% for men vs. 7% for women), and overtime (60% for men vs. 50% for women). In order to improve productivity both in practice and in this case study, team composition could be revised by using more males than females, as pointed out by Heidi (2007).

5.2.2 Motor-manual process

Activity sampling of motor-manual harvesting operations revealed that chain saw activities across all sites were more efficient when compared to manual cutting with bow-saws. However, the high percentage of clearing time observed on the Myrtle site (i.e. 47% of the total time), can once again be attributed to site vegetation density, complicating chain saw operators' movements on the stand. With regards to the working elements on the three sites, idle time once again seemed to be a problem (i.e.10% of the total time). If the idle time could be reduced, this will positively impact on productivity of motor-manual operations. The observed productivity of the chain saw varied between 0.71 and 1.78 ODT PMH^{-1} across all plots. These variations can be attributed to operational factors such as the distance between stems and the large stem size variations. Studies by Behjou *et al*. (2009) on the influence of DBH and distances between trees support this finding.

5.2.3 Comparison between manual and motor-manual harvesting productivity

Iindications of higher motor-manual productivity when compared to manual harvesting are reflected in Table 42.

Table 41: Motor-manual and manual harvesting yields (ODT).

Species	**Motor-manual Productivity (ODT pmh$^{-1)}$)**	**Manual harvesting Productivity (ODT man day^{-1})**
Gum 1	-	0.61
Gum 2	1.78	0.54
Acacia 1	1.02	1.85
Acacia 2	1.42	0.67
Myrtle 1	0.71	1.48
Myrtle 2	0.72	1.10
Average	**1**	**1.04**

5.2.4 Evaluation of extraction and chipping operations

Productivity results of the three-wheeled loader suggest that the extraction operation significantly differs between species ($p>0.05$). As such, the null hypothesis of equal productivity of biomass extraction with the three-wheeled loader with respect to the three prevailing tree species was not supported for this part of the study. The reason for the different results can be attributed to the work conditions for Spider Gum, Acacia and Myrtle. These conditions were based on the available amount of biomass, stem density and extraction distance. Cycle time of the three-wheeled loader was found to be significantly different for Spider Gum, Acacia and Myrtle ($p<0.05$). Once again, the difference in cycle time was attributed to work conditions of the three sites.

The relationship between distance and productivity was found to be noteworthy in both the non-linear and the In-transformed linear regression model fitted to the data. Distance was found to be inversely proportional to the production rate of the three-wheeled loader. The average production rate of the machine over the various sites under study was 5.3 fresh t PMH^{-1} (3.1 ODT PMH^{-1}). Material collection (small piece sizes and a large number of stems) and average extraction distance had an impact on the machine productivity. To match the potentially sustained productivity of the chipper (4.0 – to 9.4 ODT PMH^{-1}), extraction distances should be reduced. Alternatively, additional three-wheeled loaders or alternative extraction and feeding systems could be used, and alternative chipper feeding methods employed in order to maintain chipper productivity. Spinelli *et al.* (2004) suggested the

employment of either a tractor-trailer system or a purpose-built forwarder to improve the utilisation of the chipper.
Results obtained from chipper studies suggest that productivity significantly differs between group species ($p<0.05$). This is attributed to the difference in biomass volume fed into the chipper by the three-wheeled loader. Volume availability for Gum, Acacia and Myrtle sites contributed to this difference. A closer examination of chipping cycle times revealed that chipping time was highly variable between the Spider Gum, Acacia and Myrtle species (Figure 38). This difference was caused by the waiting and feeding time of biomass by the three-wheeled loader.

It was concluded that a buffer in front of the chipper and/or the employment of additional extraction equipment are a necessity. A chipper equipped with a knuckle boom loader could be a solution in dealing with the self-loading of a buffer in front of the machine. This, however, would increase the cost of the chipping operation because a more expensive machine is used. The other problem observed during the chipping operation was related to the dependency of the chipper on the road transport as biomass had to be blown directly into the truck container. This caused an operational delay as it was time consuming for the truck to be emptied. It furthermore contributed to low machine utilisation rates and increased chipping costs. Similar problems were noted in studies conducted by FFRI (2005). The implementation of a hot harvesting system (i.e. machines are dependent on each other) would improve the conditions. Another possible solution would be to add an additional long distance truck trailer (Leinonen, 2004) of large capacity and also to utilise a chipper with self feeding to reduce the delay by increased machine utilisation rates. The other option would be to use two exchangeable containers: while the truck takes the full container to the biomass plant, the chipper can continue working by blowing the biomass into the second exchangeable container (Figure 47).

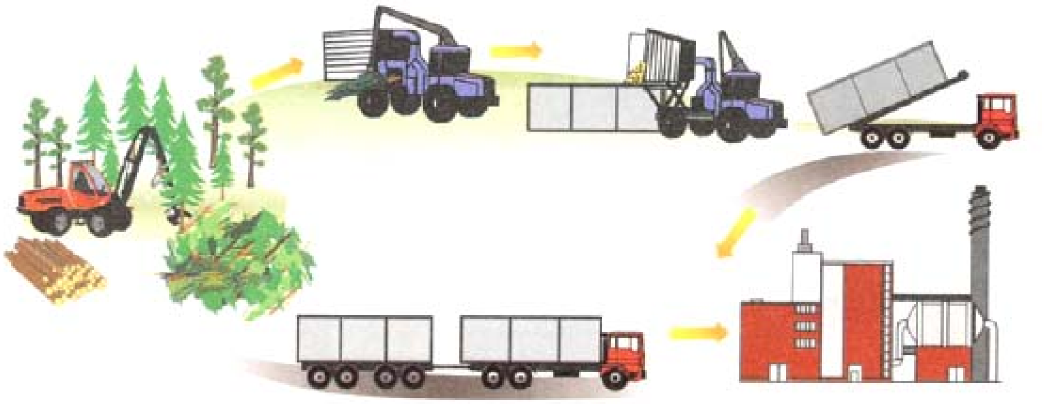

Figure 46: Exchangeable containers in terrain chipping (Leinonen, 2004).

5.3 Energy of the feedstock

From the results in this study it is clear that, despite variation in moisture content, the calorific value of the three species is similar. Compared to the average calorific value established in the literature (i.e. 17 and 20 MJ kg^{-1} for oven-dried wood) (Fengel and Wegener, 1983), the calorific values of the three species (19.18,19,36 and 19.93 MJ kg^{-1}) are in the range recognized to any wood fuel.

The ash content of the three species did not differ significantly. In all three species it was above 1%, which, according to the literature (Abbot *et al.* 1996, Fuwape and Akindele, 1997), is the required content for energy production for most species. The high ash content of the three species can be attributed to the fact that the whole tree was analysed. This is supported by Kofman (2007), who reported ash contents in the range of 1 - 2% on dry mass basis, which can be increased to 1.5 to 2.5% when the needles are included in the combustion across different wood species. The impact of impurities such as soil and sand should also be taken in account. The higher levels of ash will in all likelihood negatively impact on the energy conversion process of the three species under consideration. In order to avoid this, it would be advantageous to separate bark from the other tree components, i.e. foliage, wood and seeds. This is however not feasible as it is costly to debark the biomass and may affect the eventual product.

The net calorific value of fresh biomass found in the study varied from 11 to 14 GJ tonne^{-1}, which was less than the range proposed by other authors. It is clear that the higher ash content of the three species had strongly influenced the net calorific value of fresh biomass.

The Acacia species had higher energy values compared to the other two species due to the higher oven-dry biomass recoverable on the given site (Figure 18). The energy balance, the difference between energy output and energy input, was found to be sufficient (463) for qualifying the current biomass system to be viable. This is because the difference was above 1 (Morice 2008 and Westbrook, 2006).

5.4 Sensitivity analysis on harvesting production system and cost

From the results of the study it was clear that manual labour operation costs are higher than motor-manual operation costs. This is due to the higher number of workers employed and the significantly lower productivity rate of manual harvesting (Figure 48). In order to optimize the harvesting work, it would be advisable to use the motor-manual method instead of full manual harvesting.

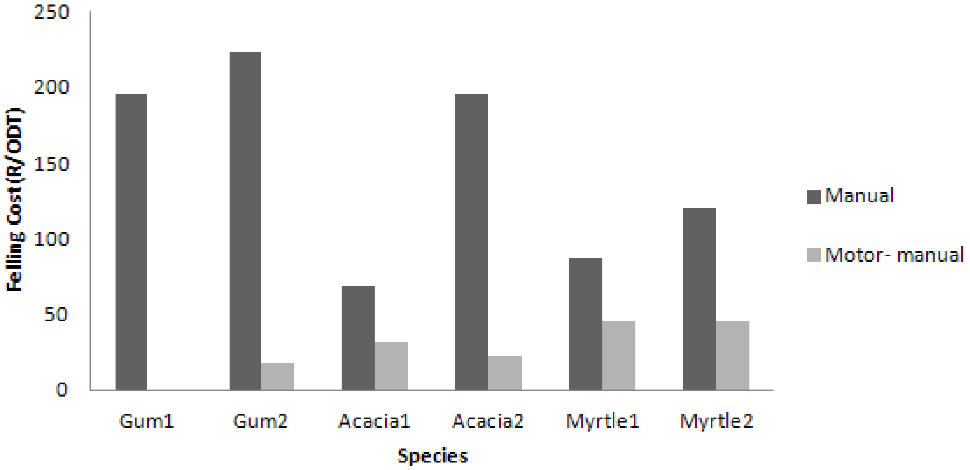

Figure 47: Harvesting cost comparison between manual and motor-manual methods on different plots [Gum 1, Gum 2, Acacia 1, Acacia 2, Myrtle 1 and Myrtle 2].

A sensitivity analysis of the data in this case study showed that for the three-wheeled loader extraction, an increase of 133% in extraction costs will occur with a 10 m increase in the extraction distance from 10 m to 20 m. Similar increases in extraction costs were notable in an increase from 20 m to 30 m (13% increase) while an increase from 30 m to 40 m resulted in a 29% increase (Figure 49). By considering the optimal productivity of the three-wheeled loader, extraction costs can be decreased from an average of R 65.05 ODT^{-1} to R 30.31 ODT^{-1}.

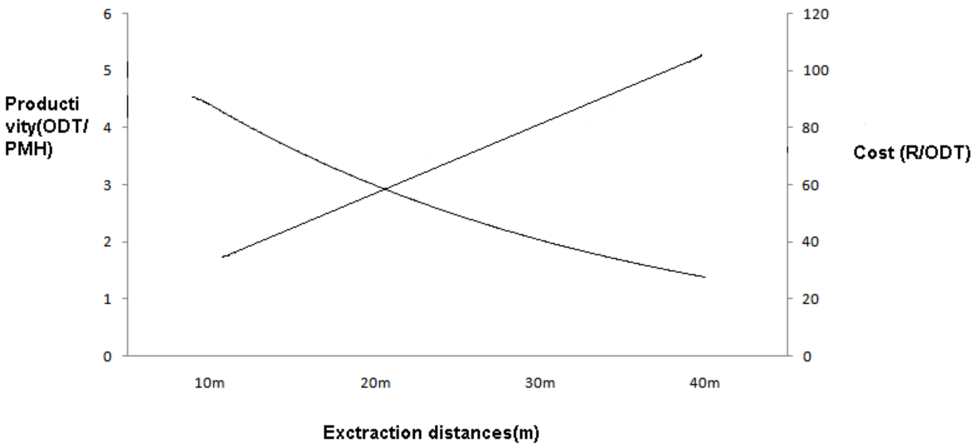

Figure 48: Interaction between cost and productivity based on various extraction distances of the three-wheeled loader (falling curve represents productivity, and rising curve the costs involved).

A sensitivity analysis of the chipping operation shows that the chipping costs are very sensitive to the machine utilisation rate. The higher the machine utilisation rate, the lower the chipping costs. In the current study, an assumed machine utilisation rate of 50% resulted in over-proportionally higher chipping costs than for example an utilisation rate of 100% (Figure 50 and 51). It is clear that chipper utilisation should be as high as possible to maintain costs within acceptable limits. However, direct feeding and truck transport rotation will impact on utilisation. With no truck available to load the chipper, high levels of utilisation will be improbable, unless the chips are stored on the ground. This once again poses a problem in chip recovery, causes contamination of the chips and reduces the energy quantity of the biomass.

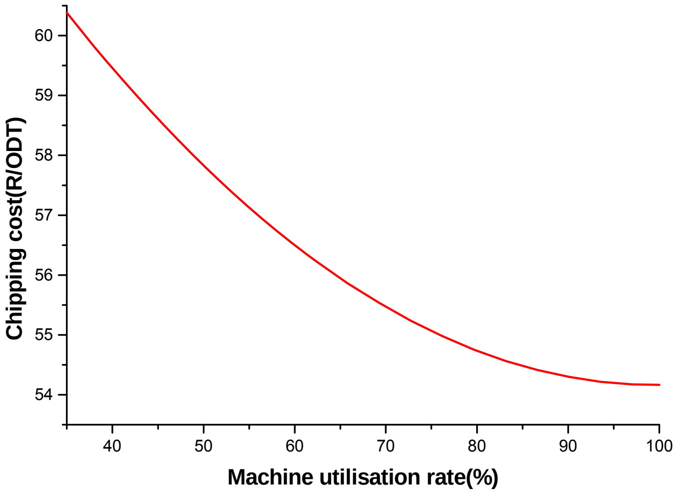

Figure 49: Chipping cost vs. chipper machine utilisation rates.

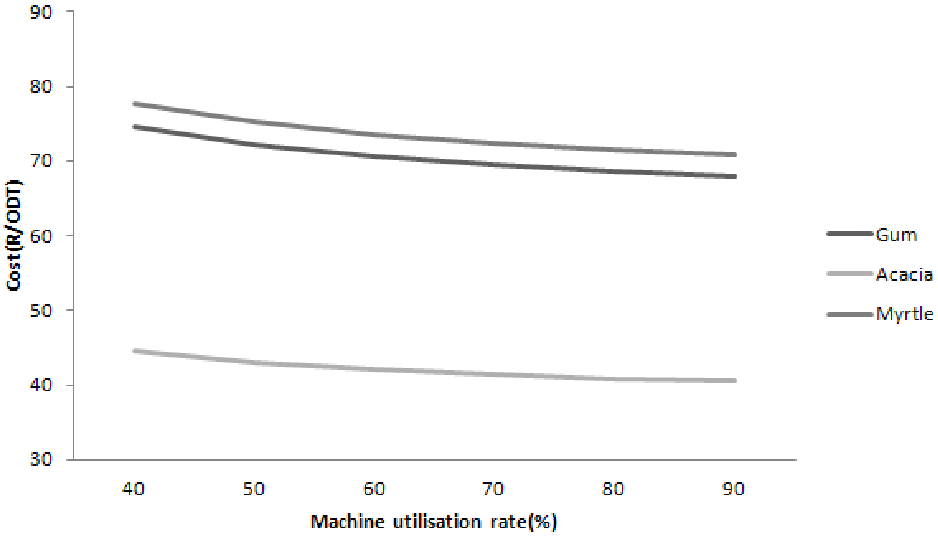

Figure 50: Chipper production cost vs. chipper machine utilisation rates at actual productivity of different species.

If productivity and machine utilisation rates are high, costs could normally be maintained at lower levels (Figure 52). But in order to use the chipper at high machine utilisation levels, the option of accumulating a large quantity of biomass material in front of the chipper could be considered, as advocated by FFRI (2005). The alternative of moving the chipper from site to site further impacts on the utilisation of the machine (lower utilisation and additional movement costs). In order to maximise productivity, it may be profitable to adopt chipping at the plant, characterised by a higher degree of machine utilisation and low chipping costs. The self-feeding of the chipper would increase chipping rates and reduce costs.

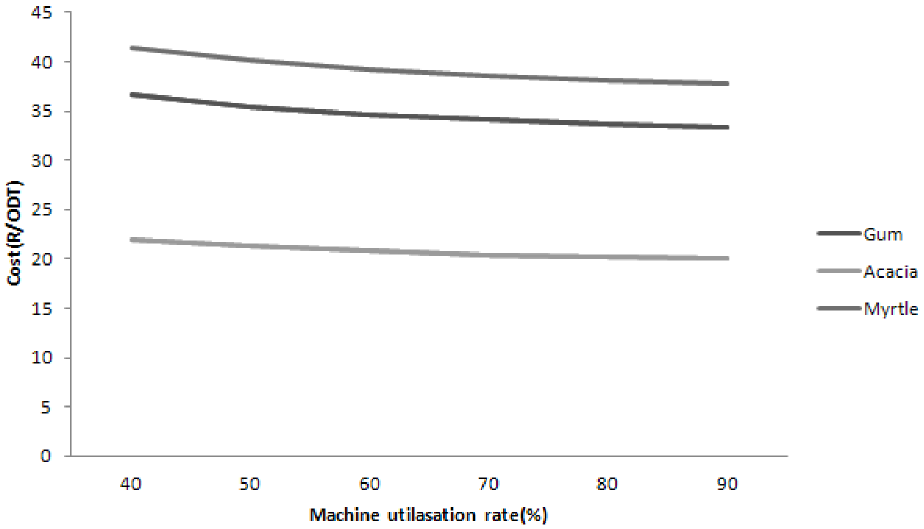

Figure 51: Chipper production cost vs. chipper machine utilisation rates at optimal productivity.

Results indicate that an increase in transport distances produced an increase in costs. Costs for 10 km, 20 km, 30 km and 40 km distances increased by 16%, 17%, 18% and 19% respectively across all species. This provided an understanding of how distance affected transport costs of either chips or solid material. Richardson *et al.* (2002) found that as long as the road transport could be contained to economically acceptable distances of less than 100 km, it could be profitable for biomass harvesting. The harvesting site should thus be close to the biomass plant in order to avoid higher road transport costs (Figure 53). This clearly favours decentralised plant locations, which also contribute positively to the development of rural areas.

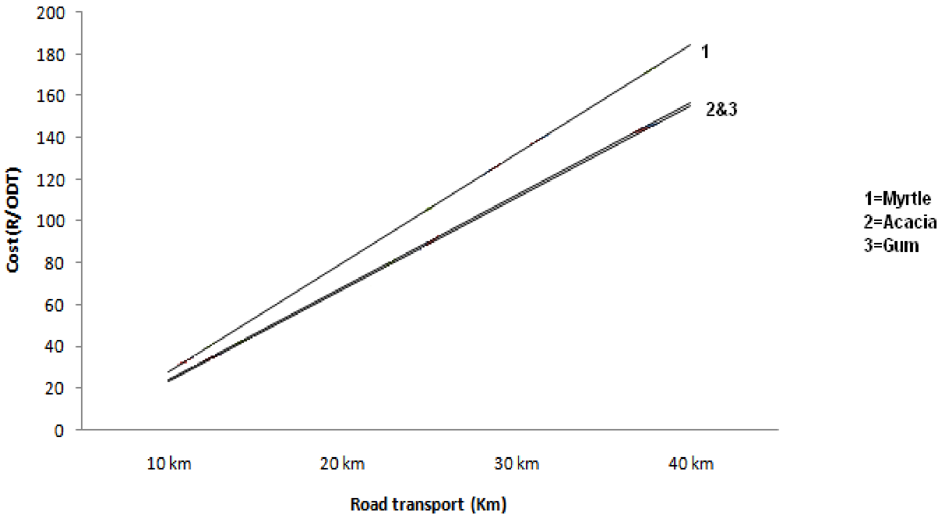

Figure 52: Road transport cost vs. distances for each biomass species.

The effect of various road transport distances (10, 20, 30 and 40 km) on total production cost is illustrated in Figures 54, 55 and 56 below.

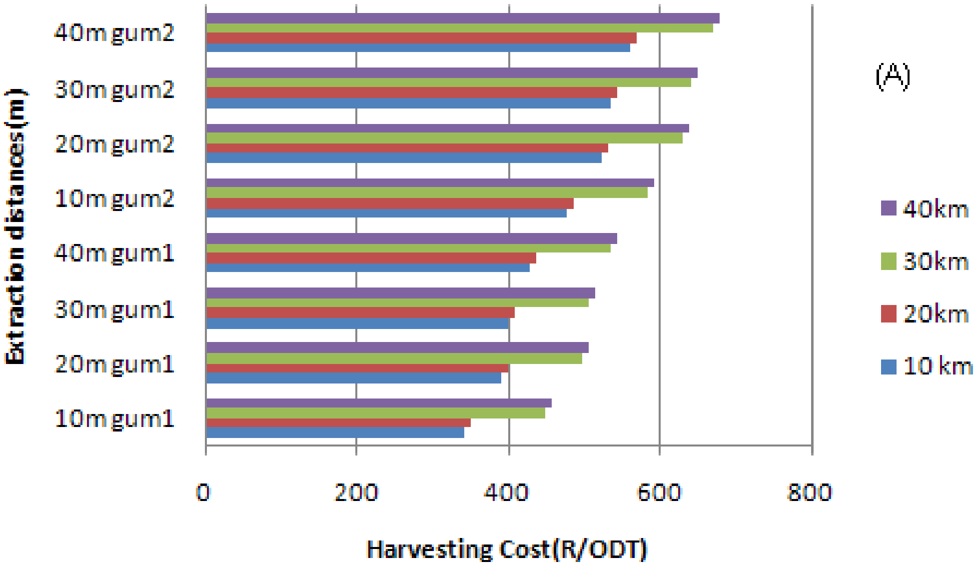

Figure 53: Harvesting system cost comparisons as a function of road transport distances based on extraction distances of the three biomass species: (A).

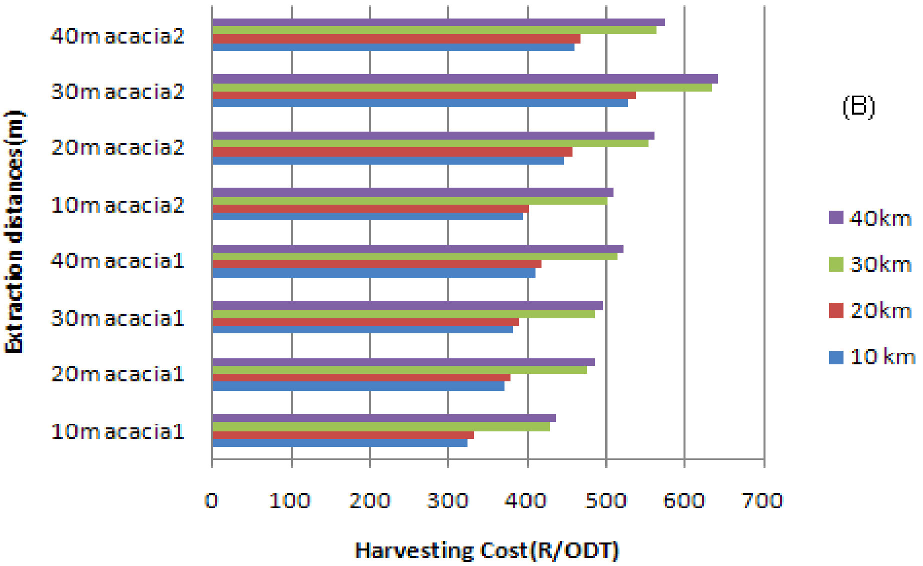

Figure 54 Harvesting system cost comparisons as a function of road transport distances based on extraction distances of the three biomass species: (B).

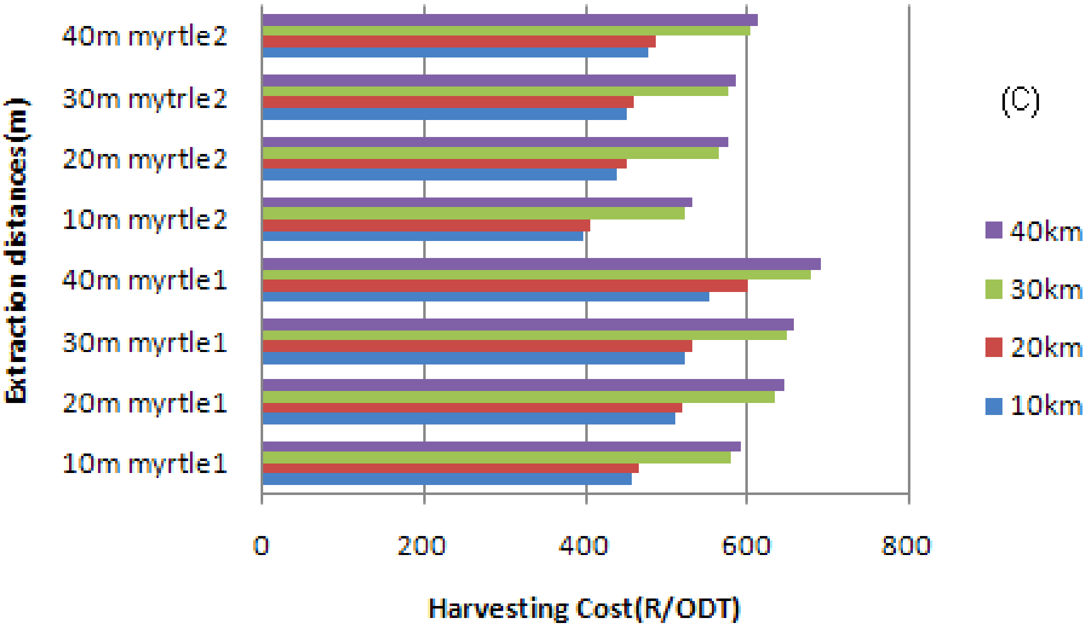

Figure 55: Harvesting system cost comparisons as a function of road transport distances based on extraction distances of the three biomass species: (C).

When combining the optimal production rates (i.e. 60% for the chain saw, 70% for the three-wheeled loader and 85% for the chipper) with the higher level machine utilisation, the average harvesting system costs decreased sensibly from R 506.26 ODT^{-1} to R 376.44

ODT^{-1}. This leads to a cost decrease and the availability of useful information for dealing with the three invasive vegetation species relevant to this study.

5.5 The importance of future research on the use of woody biomass of invasive vegetation as bioenergy feedstock

This study, which focuses on the evaluation of biomass recoverability from invasive vegetations, revealed important information. However, further investigation is necessary into the available biomass quantity, specifically on capturing a range of tree sizes, stem / ha counts, canopy densities and species mixes in alternative sites. Based on the results, it can be concluded that it may be possible to improve mechanical felling methods with multi-stem handling and other small wood fuel harvesting machines. Other possible areas of investigation include the compression, binding and bundling of the biomass and optimal chipping locations both in forests (terrain chipping) and at biomass plants.

6. Conclusion and recommendations

6.1. Conclusion

This study focused on the feasibility of using *Acacia Cyclops* [Rooikrans], *Leptospermum laevigatum* [Myrtle] *and Eucalyptus lehmanii* [Spider Gum] as energy feedstock. The potential availability of 693.38 oven-dry tonnes (ODT) of biomass can be harvested from six hectares of invasive stands. This proves that biomass from invasive vegetation could be considered as a viable energy feedstock of substantial quantity. It is therefore clear that the recovery of woody biomass of these three invasive species has significant potential in sustaining a bioenergy project in the Agulhas area. These findings can aid decision-making in other areas in the country where similar conditions occur.

When comparing manual and motor-manual felling in the harvesting system, the study revealed that the two methods did not reach the expected output for an effective harvesting system. This was due to a low productivity rate which increased the harvesting costs. Manual felling costs were R 148.12 ODT^{-1}, as compared to motor-manual felling costs of R 27.1 ODT^{-1}. Motor-manual felling should thus be given preference over full manual tree felling.

The extraction operation by the three-wheeled loader was found to be ineffective because inappropriate equipment was used due to limited logistical resources. The relationships between independent and dependent variables of the three-wheeled loader did not provide a good and predictable model, which could possibly indicate the need for machine performance evaluation in the extraction work. The sensitivity analysis showed that the extraction distance was a crucial factor affecting yield productivity and resulting in higher extraction costs, ranging from R 27.54 to R 96.12 ODT^{-1}. This placed a limitation on the chipping operation. Therefore, the three-wheeled loader should be replaced by more suitable extraction machines in order to ensure higher productivity rates.

Chipping appears to be suitable for small biomass volumes located at one site, but not suited for dispersed sites because this adds additional costs of relocation. The sensitivity analysis indicated that an increase in the chipper utilisation is advisable, resulting in a decrease of 104% of chipping costs in all species.

The sensitivity analysis showed that an increase in road transport distance results in increased transport costs of the woody biomass in all species. This emphasised the fact that harvesting operations should be done close to the biomass plant in order to minimise road transport costs. An estimation of secondary transport costs across species, based on various transport distances, was as follows: 7% at 10 km, 9% at 20 km, 26% at 30 km and 27% at 40 km.

Finally, the results from this study clearly indicated that woody biomass from invasive trees have reasonably suitable fuel characteristics as far as net calorific value, moisture content and ash content are concerned. The difference between energy input and output (463 GJ) was a good indicator for a feasable bioenegy system based on invasive vegetation. This leads to the conclusion that a harvesting biomass system like the one tested can be viable because substantially more energy than emissions is produced. The average estimated energy cost across the species was R 26 $G^{-1}J$.

6.2. Recommendations

Results obtained from this study significantly contributed to the body of knowledge regarding the harvesting of woody biomass from invasive tree vegetation in South Africa, particularly in the Western Cape. The presented results may provide more information to forest harvesting and transportation contractors on how to efficiently manage wood fuel from invasive woody vegetation. It may also assist forest contractors and bio-energy companies in their decision-making on different aspects of machine combinations and costs to assist in sound business and resource management decisions.

Despite the strong argument for the useful exploitation of invasive vegetation for the production of energy, this sector particularly can only be developed with firm political will and consistency. Research is necessary on resource use and the implementation of an information campaign in order to promote the benefits of wood energy extracted from invasive vegetation. This requires the establishment of financial incentives to contractors, ensuring the purchase of suitable tools and equipment for harvesting this biomass resource. Only in this manner would woody biomass from invasive vegetation species be an economic solution, similar to other biomass energy commonly produced today.

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8. Appendices

Appendix 1: Production assumptions.

Harvesting condition	**Gum1** High density young small trees (10 – 65stem/m^2, aver: 20stem/m^2; tree diameter 1 – 7cm, aver: 2.5cm) and dominant tree height 4 metres; 100% tree coverage on site.	**Gum2** Dense larger trees (5 – 20 stem/m^2, aver: 8 stem/m^2; tree diameter 2 – 15cm, aver: 7.5cm) and dominant tree height 12 metres; 100% tree coverage on site
Operational method	The workers using loppers and bowsaws fell and stack trees to a single brushline formed every 10 m in the area. Maximum carry distance for stacking 5 m.	The two chainsaw operators felled all trees on the site and crosscut out all utilisable solid wood timber. There was no directional control on the felling of trees. A team of six workers separated and stacked brush in a second operation for the chipping operation in a single brushline formed on the 10m spacing.
Team structure & size	The team consisted of six workers; two workers predominately cut trees with the remaining four stacking and preparing brushlines.	The team consisted of two chainsaw operators and six brush stackers. The two chainsaw operators felled and crosscut out solid wood sections. The brush stackers sorted brush and solid wood sections ready for extraction or chipping.
Harvesting condition	**Acacia1** Larger mature dense acacia site on level terrain	**Acacia2** Dense acacia site, 2 – 5cm stems, 4 m height, 100% coverage
Operational method	The single chainsaw operators felled all trees on the site and crosscut out all utilisable solid wood timber. A team of three workers separated solid wood and stacked brush on a single brushline formed on the 10m spacing.	The single chainsaw operators felled all trees on the site and crosscut out all utilisable solid wood timber. A team of four workers separated solid wood and stacked brush on a single brushline formed on the 10m spacing.
Team structure & size	The team consisted of one chainsaw operators and three brush stackers.	The team consisted of one chainsaw operators and three brush stackers.
Harvesting condition	**Myrtle1** Dense myrtle site	**Myrtle2** Dense myrtle site
Operational method	The single chainsaw operators felled all trees on the site and crosscut out all utilisable solid wood timber. A team of three workers separated solid wood and stacked brush on a single brushline formed on the 10m spacing.	The single chainsaw operators felled all trees on the site and crosscut out all utilisable solid wood timber. A team of four workers separated solid wood and stacked brush on a single brushline formed on the 10m spacing.
Team structure & size	The team consisted of one chainsaw operators and three brush stackers.	The team consisted of one chainsaw operators and three brush stackers.

Appendix 2: Method sampling: Observed work elements during manual data collection.

Spp	Element	w1	w2	w3	w4	w5	w6	w7	w8
gum	stack	34	29	25	39	26	66	22	35
gum	cut	111	95	84	80	145	2		0
gum	moveload	45	47	39	36	31	48	15	22
gum	spray	0	0	0	0	0	27	0	0
gum	idle	50	67	80	55	19	44	32	37
gum	Moving Empty	15	18	19	8	12	7	8	9
gum	Inspecting	0	0	0	0	0	0	0	0
gum	Pickup	22	17	39	35	24	11	36	
	Average	46	45	48	42	43	29	23	26
	total	277	273	286	253	257	205	113	103
Spp	Element	w1	w2	w3	w4	w5	w6	w7	w8
jackson	stack	3	4	4	1	5	7	1	2
jackson	cut	23	16	16	23	25	17	22	
jackson	moveload	1	2	3	1	2	9	5	1
jackson	spray	0	0	0	0	0	0	0	0
jackson	idle	6	6	8	3	8	16	22	17
jackson	Moving Empty	1	12	10	11	6	1	4	30
jackson	Inspecting	7	7	3	8	7	7	5	2
jackson	Pickup	0	0	0	0	0	0	0	0
	Average	8	8	7	8	9	10	10	10
	total	41	47	44	47	53	57	59	52
Spp	Element	w1	w2	w3	w4	w5	w6	w7	w8
acacia	stack	56	2	38	18	15	30	34	34
acacia	cut	0	0	0	0	0	0	0	0
acacia	move load	6	7	8	18	0	3	7	
acacia	spray		0	0	0	0	0	0	0
acacia	idle	24	29	24	40	20	21	11	0
acacia	Moving Empty	9	12	18	18	12	7	11	0
acacia	Inspecting	0	0	0	0	0	0	0	0
acacia	Pickup	10	19	14	15	2	0	2	
	Average	21	14	20	22	10	12	13	34
	total	105	69	102	109	49	61	65	34
Spp	Element	w1	w2	w3	w4	w5	w6	w7	w8
myrtle	stack	52	80	100	29	0	0	0	0
myrtle	cut	0	0	0	0	0		0	0
myrtle	move load	23	20	20	22	0	0	0	0
myrtle	spray	0	0	0	0	0	0	0	0
myrtle	idle	110	83	32	66	0	0	0	0
myrtle	Moving Empty	37	29	30	15	0	0	0	0
myrtle	Inspecting	0	0	0	0	0	0	0	0
myrtle	Pickup	13	24	27	51	0	0	0	0
	Average	47	47	41	37	0	0	0	0
	total	235	236	209	183	0	0	0	0

W= worker

Appendix 3: Method sampling: Observed work element in motor-manual harvesting.

Spp	Element	C-saw1	C-saw2	**Avarage**
gum	Cut	59	47	53
gum	Cross cutting	25	37	31
gum	Refuel	15	7	11
gum	Filling	8	14	11
gum	Inspection	2	3	3
gum	Moving	21	12	17
gum	Broken	23	26	25
gum	Debranch	7	7	7
gum	Idle	17	14	16
	Avarage	20	19	
	Sum	177	167	

Spp	Element	C-saw1	C-saw2	**Avarage**
jackson	Cut	26	0	13
jackson	Cross cutting	9	0	4.5
jackson	Refuel	4	0	2
jackson	Filling	2	0	1
jackson	Inspection	0	0	0
jackson	Moving	7	0	3.5
jackson	Broken	14	0	7
jackson	Debranch	2	0	1
jackson	Idle	10	0	5
	Avarage	8.2		
	Sum	74	0	

Spp	Element	C-saw1	C-saw2	**Avarage**
acacia	Cut	45	0	22.5
acacia	Cross cutting	0	4	2
acacia	Refuel	22	2	12
acacia	Filling	8	0	4
acacia	Inspection	2	0	1
acacia	Moving	3	3	3
acacia	Broken	14	0	7
acacia	Debranch	7	0	3.5
acacia	Idle	11	2	6.5
	Avarage	12	1	
	Sum	112	11	

Appendix 3: Method sampling: Observed work element in motor-manual harvesting. (continued)

Spp	Element	C-saw1	C-saw2	**Avarage**
myrtle	Cut	91	89	**90**
myrtle	Cross cutting	0	0	0
myrtle	Refuel	28	38	33
myrtle	Filling	19	20	19.5
myrtle	Inspection	9	0	4.5
myrtle	Moving	12	16	14
myrtle	Broken	19	18	18.5
myrtle	Debranch	18	1	9.5
myrtle	Idle	41	3	22
	Avarage	26	20.5	
	Sum	237	185	

Appendix 4: Three-wheeled loader data summary:

Shown are minimum, 1st quantile, median, arithmetic mean, 3rd quantile and maximum values

```
Belldata<-read.table("clipboard",header=T,na.strings=".",sep="\t")
> summary(Belldata)
     Species     Grapple.min.     Move.loaded.min.  Move.empty.min.
 Acacia 1:46   Min.   :0.0100   Min.   :0.0100    Min.   :0.0100
 Acacia 2:63   1st Qu.:0.1800   1st Qu.:0.2000    1st Qu.:0.1600
 Gum 1   :61   Median :0.3000   Median :0.3200    Median :0.2300
 Gum 2   :49   Mean   :0.3608   Mean   :0.3618    Mean   :0.2880
 Myrtle 1:64   3rd Qu.:0.5000   3rd Qu.:0.4800    3rd Qu.:0.3700
 Myrtle 2:69   Max.   :1.2400   Max.   :1.2000    Max.   :1.0800

  Feeding.min.    Idle.time.min.     Cycle.time.min.  Cycle.time.hour
 Min.   :0.0200   Min.   :  0.0000   Min.   :0.1200   Min.   :0.00200
 1st Qu.:0.1200   1st Qu.:  0.4000   1st Qu.:0.7475   1st Qu.:0.01275
 Median :0.2250   Median :  0.7800   Median :1.2000   Median :0.02000
 Mean   :0.2891   Mean   :  0.7148   Mean   :1.2998   Mean   :0.02174
 3rd Qu.:0.4100   3rd Qu.:  0.9500   3rd Qu.:1.7525   3rd Qu.:0.02900
 Max.   :1.3000   Max.   :  1.9100   Max.   :2.9300   Max.   :0.04900

  Distance.m.     Dry..biomass.kg. Dry.biomass.t.      Volume.m3.
 Min.   : 5.00   Min.   :49.46    Min.   :0.05000   Min.   :0.05000
 1st Qu.:12.00   1st Qu.:54.06    1st Qu.:0.05000   1st Qu.:0.06000
 Median :20.00   Median :61.98    Median :0.06000   Median :0.09000
 Mean   :21.25   Mean   :62.91    Mean   :0.06216   Mean   :0.08747
 3rd Qu.:27.00   3rd Qu.:69.64    3rd Qu.:0.07000   3rd Qu.:0.10000
 Max.   :45.00   Max.   :84.77    Max.   :0.08000   Max.   :0.15000

 Wood.density.at.12.MC Productivity.m3.hr. Productivity.t.hr.     Lnprod
 Min.   :690.0         Min.   : 1.100      Min.   : 1.090     Min.   :0.0900
 1st Qu.:690.0         1st Qu.: 2.820      1st Qu.: 2.200     1st Qu.:0.7875
 Median :800.7         Median : 4.510      Median : 3.230     Median :1.1750
 Mean   :839.5         Mean   : 5.747      Mean   : 4.123     Mean   :1.2199
 3rd Qu.:995.0         3rd Qu.: 7.150      3rd Qu.: 4.915     3rd Qu.:1.5925
 Max.   :995.0         Max.   :53.430      Max.   :30.990     Max.   :3.4300

     Lndist       Lncycletime.min.   Lncycletime.hr.   Lntravel.loaded
 Min.   :1.610   Min.   :-2.12000   Min.   :-6.215   Min.   :-4.6052
 1st Qu.:2.480   1st Qu.:-0.29250   1st Qu.:-4.385   1st Qu.:-1.6094
 Median :3.000   Median : 0.18000   Median :-3.912   Median :-1.1394
 Mean   :2.889   Mean   : 0.09824   Mean   :-3.996   Mean   :-1.2097
 3rd Qu.:3.300   3rd Qu.: 0.56250   3rd Qu.:-3.533   3rd Qu.:-0.7340
 Max.   :3.810   Max.   : 1.08000   Max.   :-3.019   Max.   : 0.1823

 Lntravel.empty
 Min.   :-4.60517
 1st Qu.:-1.83258
 Median :-1.46968
 Mean   :-1.46703
 3rd Qu.:-0.99425
 Max.   : 0.07696
```

Appendix 4 (continued): Chipper data summary

Shown are minimum, 1st quantile, median, arithmetic mean, 3rd quantile and maximum values

```
Chipperdata<-read.table("clipboard",header=T,na.strings=".",sep="\t")
> summary(Chipperdata)
     Species     Loadcycle          Grab       Waiting.time..min.
 Acacia 1:42   Min.   :1.000   Min.   : 1.00   Min.   :0.0000
 Acacia 2:55   1st Qu.:1.000   1st Qu.: 6.00   1st Qu.:0.3600
 Gum 1   :64   Median :2.000   Median :12.00   Median :0.5900
 Gum 2   :50   Mean   :1.757   Mean   :12.58   Mean   :0.6484
 Myrtle 1:62   3rd Qu.:2.000   3rd Qu.:18.00   3rd Qu.:0.8200
 Myrtle 2:69   Max.   :3.000   Max.   :35.00   Max.   :3.5800
 Cycle.time.min. Cycle.time.hr.    Fresh.biomass.kg..species Dry.Biomass..kg.
 Min.   :0.180   Min.   :0.00000   Min.   : 66.00            Min.   : 49.46
 1st Qu.:0.840   1st Qu.:0.01000   1st Qu.: 71.48            1st Qu.: 54.35
 Median :1.240   Median :0.02000   Median : 80.41            Median : 62.67
 Mean   :1.405   Mean   :0.02368   Mean   : 88.68            Mean   : 68.13
 3rd Qu.:1.657   3rd Qu.:0.03000   3rd Qu.: 91.67            3rd Qu.: 69.64
 Max.   :5.730   Max.   :0.10000   Max.   :173.00            Max.   :141.51
 Dry.Biomass..t.   Productivity.t.hr.     Lnprod        Lncycle.time
 Min.   :0.05000   Min.   : 0.609     Min.   :-0.500   Min.   :-5.809
 1st Qu.:0.05000   1st Qu.: 2.262     1st Qu.: 0.810   1st Qu.:-4.269
 Median :0.06000   Median : 3.345     Median : 1.205   Median :-3.879
 Mean   :0.06675   Mean   : 3.972     Mean   : 1.185   Mean   :-3.914
 3rd Qu.:0.07000   3rd Qu.: 4.910     3rd Qu.: 1.590   3rd Qu.:-3.589
 Max.   :0.14000   Max.   :22.259     Max.   : 3.100   Max.   :-2.349
  Feeding.min.       Lnfeeding
 Min.   :0.1000   Min.   :-2.3026
 1st Qu.:0.4250   1st Qu.:-0.8559
 Median :0.6400   Median :-0.4463
 Mean   :0.7626   Mean   :-0.4695
 3rd Qu.:0.8875   3rd Qu.:-0.1194
 Max.   :3.9200   Max.   : 1.3661
```

Appendix 5: Test of distributional assumptions of ANOVA of variables of the three-wheeled loader and chipper.

In this appendix the necessary tests of the assumptions for conduction an ANOVA are presented, together with the code for the statistical package R (Dalgaard, 2008).

The test was performed in order to determine if the productivity data was comply with the three distributional assumptions of ANOVA (Independence, normality and equality of variances).For the independence assumption, three points were taken in count; the experimental design, the correct identification of the experimental unit and the appropriate randomisation. The normality and equality of variances assumptions were tested by using the Shapiro-Wilk normality test and the Bartlett test of homogeneity of variances. This was also done by using the residual plots in order to study the deviation from group means.

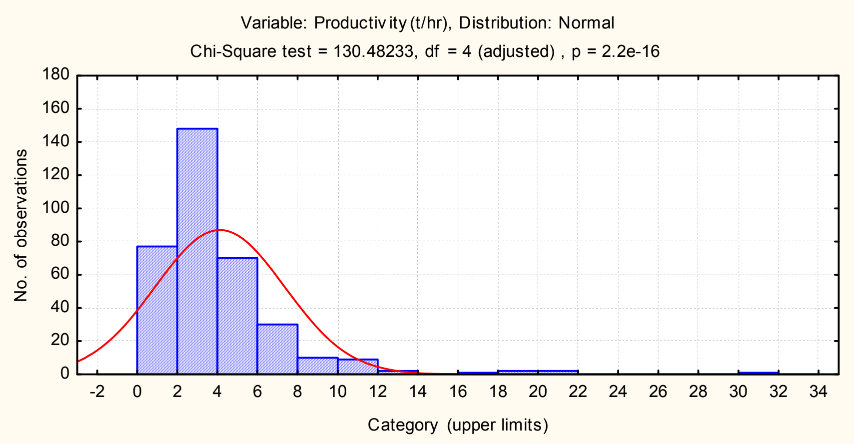
```
> shapiro.test(mistakes)
        Shapiro-Wilk normality test
data:  mistakes
W = 0.9682, p-value = 7.298e-10
```

The raw data was not normal distributed

```
> bartlett.test(resid(Model1), g = Belldatadata$Species)
Error in bartlett.test.default(resid(Model1), g = Belldatadata$Species) : object
'Belldatadata' not found
> bartlett.test(resid(Model1), g = Belldata$Species)
 Bartlett test of homogeneity of variances
data:  resid(Model1) and Belldata$Species
Bartlett's K-squared = 69.248, df = 5, p-value = 1.469e-13
```

The raw data contradicts the assumption of equal variances in the six groups

Histogram of the residual plot of productivity raw data



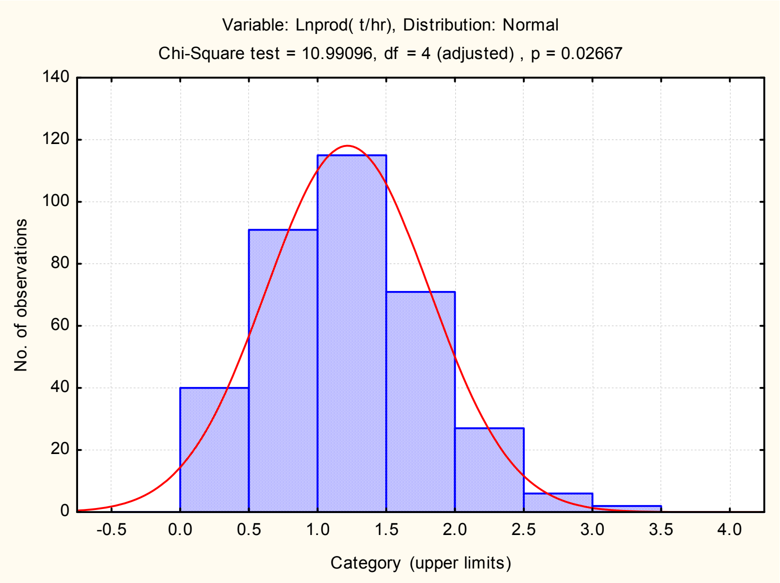
```
> shapiro.test(mistakes)
Shapiro-Wilk normality test
data:  mistakes
W = 0.9682, p-value = 7.298e-10
```

Transformed data of productivity was also not normal distributed

```
> bartlett.test(resid(Model1), g = Belldata$Species )
 Bartlett test of homogeneity of variances
data:  resid(Model1) and Belldata$Species
Bartlett's K-squared = 14.1408, df = 5, p-value = 0.01474
```

P-value < 0.05, Ho is rejected; therefore transformed data contradicts the assumption of equal variances in the six groups. This lead to say that there is no homoscedasticity

Histogram of the residual plot of productivity transformed data (Lnprod)



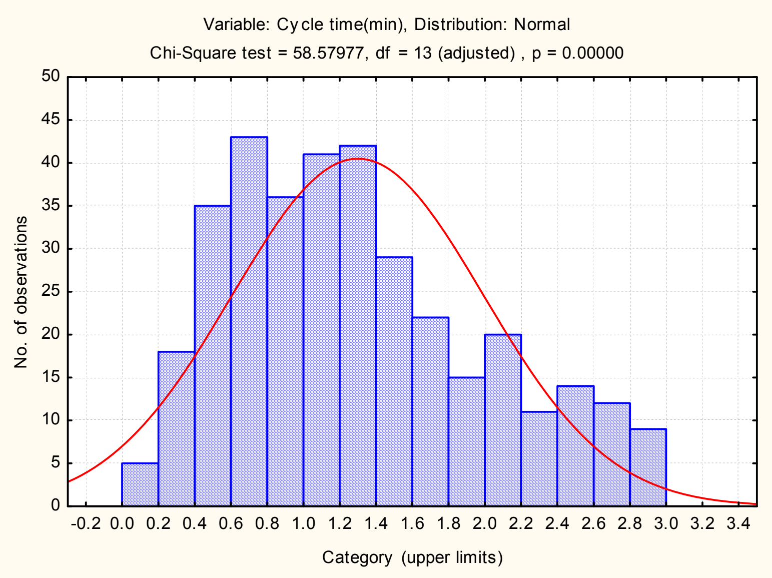
Kruskal-Wallis median test for differences between the median productivity of different species

```
> kruskal.test( Productivity.t.hr. ~Species,data=Belldata)
Kruskal-Wallis rank sum test
data:  Productivity.t.hr. by Species
Kruskal-Wallis chi-squared = 34.7063, df = 5, p-value = 1.722e-06 (0.000001722)
```

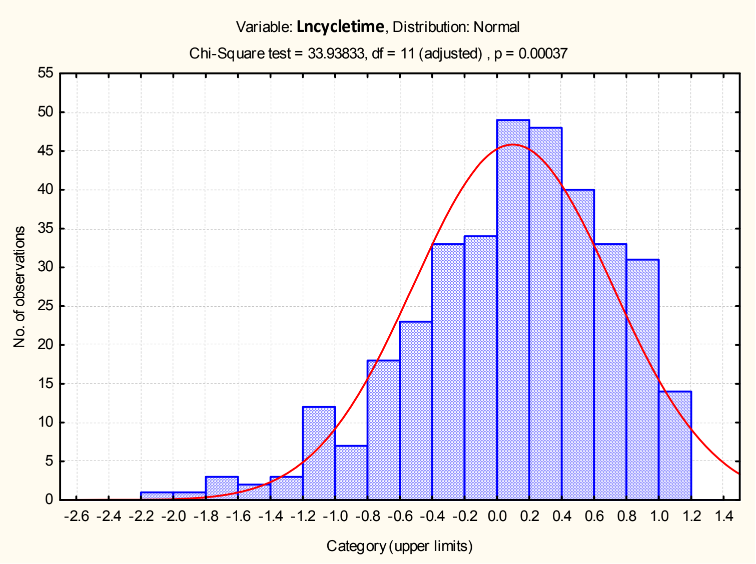
Dependent: Productivity(t/hr)	Median Test, Overall Median = 3.23017; Productivity(t/hr) (Spreadsheet Independent (grouping) variable: Species Chi-Square = 27.49259 df = 5 p = .0000						
	Gum 1	Gum 2	Acacia 1	Acacia 2	Myrtle 1	Myrtle 2	Total
<= Median: observed	22.00000	31.00000	11.0000	33.00000	34.00000	45.0000	176.0000
expected	30.50000	24.50000	23.0000	31.50000	32.00000	34.5000	
obs.-exp.	-8.50000	6.50000	-12.0000	1.50000	2.00000	10.5000	
> Median: observed	39.00000	18.00000	35.0000	30.00000	30.00000	24.0000	176.0000
expected	30.50000	24.50000	23.0000	31.50000	32.00000	34.5000	
obs.-exp.	8.50000	-6.50000	12.0000	-1.50000	-2.00000	-10.5000	
Total: observed	61.00000	49.00000	46.0000	63.00000	64.00000	352.0000	352.0000

Test of normal distribution of Cycle time raw data and Lncycletime

```
> shapiro.test(Belldata$Cycle.time.min. )
Shapiro-Wilk normality test
data:  Belldata$Cycle.time.min.
W = 0.9537, p-value < 0.001
```



```
> shapiro.test(Belldata$ Lncycletime  )
Shapiro-Wilk normality test
data:  Belldata$Lncycletime
W = 0.9666, p-value < 0.001
```

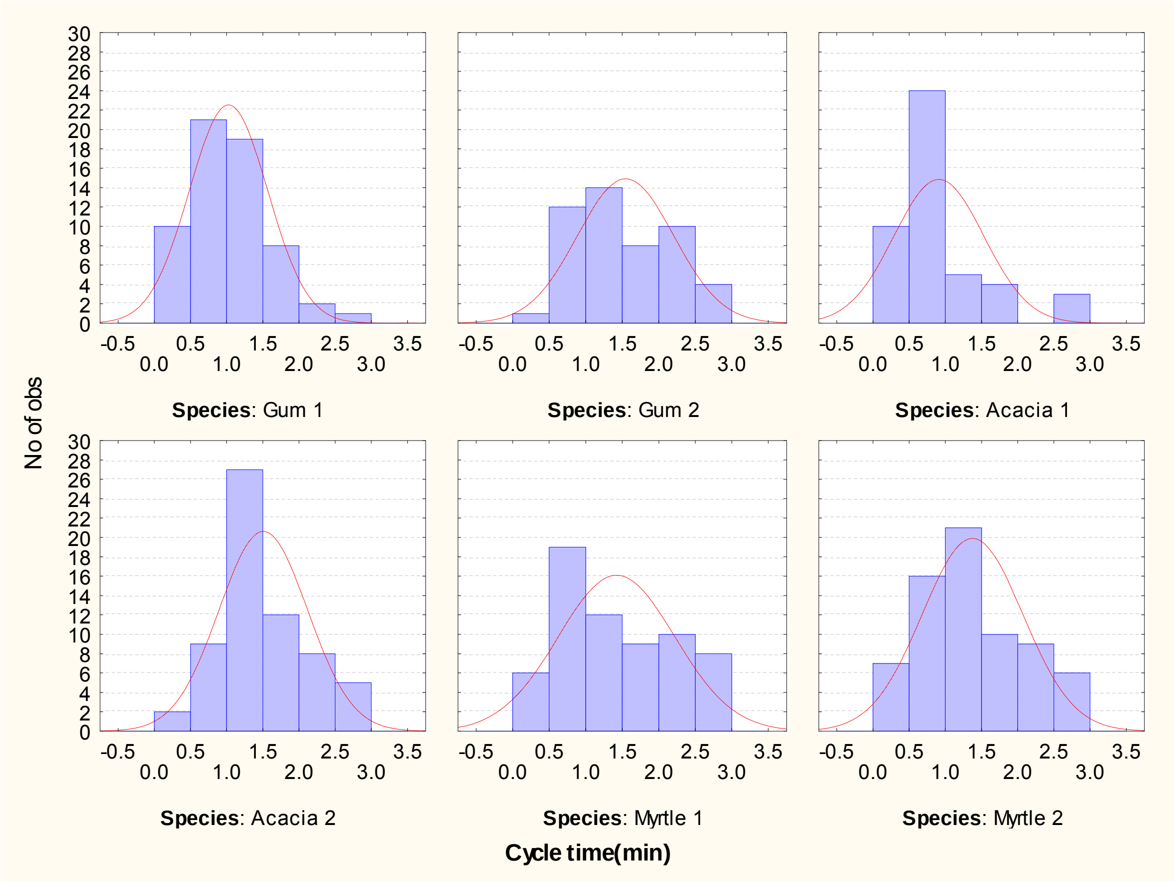


```
> kruskal.test( Cycle.time.min. ~Species,data=Belldata)
 Kruskal-Wallis rank sum test
data:  Cycle.time.min. by Species
Kruskal-Wallis chi-squared = 44.046, df = 5, p-value <0.001
```

Kruskal-Wallis median test

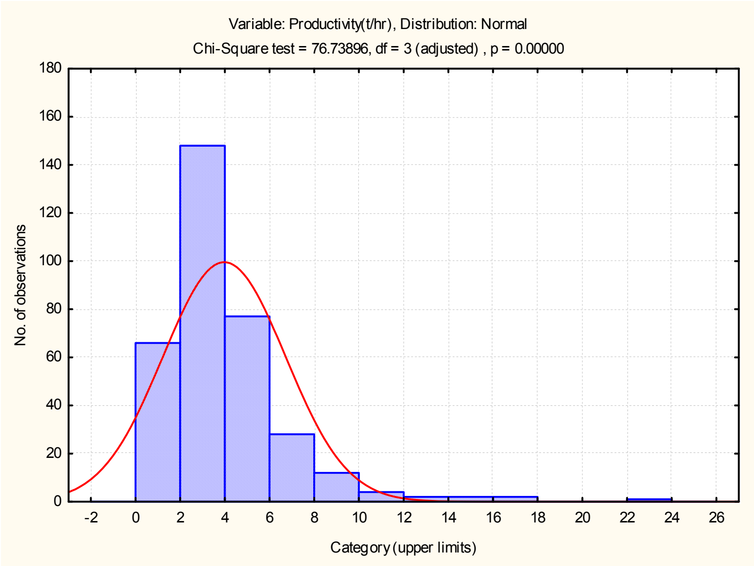
Dependent: **Cycle time(min)**	Median Test, Overall Median = 1.20000; Independent (grouping) variable: **Species** Chi-Square = 34.11750 df = 5 p = .0000			
	Gum 1	Gum 2	Acacia 1	Acacia 2
<= Median: observed	41.0000	18.00000	36.0000	21.0000
expected	30.6733	24.63920	23.1307	31.6790
obs.-exp.	10.3267	-6.63920	12.8693	-10.6790
> Median: observed	20.0000	31.00000	10.0000	42.0000
expected	30.3267	24.36080	22.8693	31.3210
obs.-exp.	-10.3267	6.63920	-12.8693	10.6790
Total: observed	61.0000	49.00000	46.0000	63.0000

Categorized Histogram of the total cycle time variable of three -wheeled loader extraction

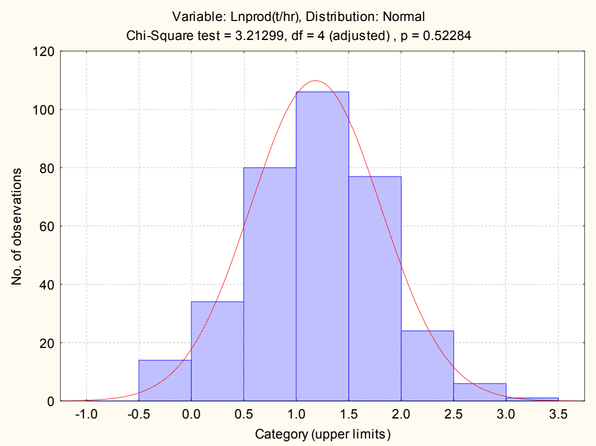


Test of normal distribution of productivity raw data and Lnprod data of the chipper. Prior a Shapiro-Wilk normality test was run on the productivity raw data and the productivity trasformed Ln(prod) data.

```
> shapiro.test(Chipdata$Productivity.t.hr.)
 Shapiro-Wilk normality test
data:  Chipdata$Productivity.t.hr.
W = 0.8026, p-value < 0.001
```



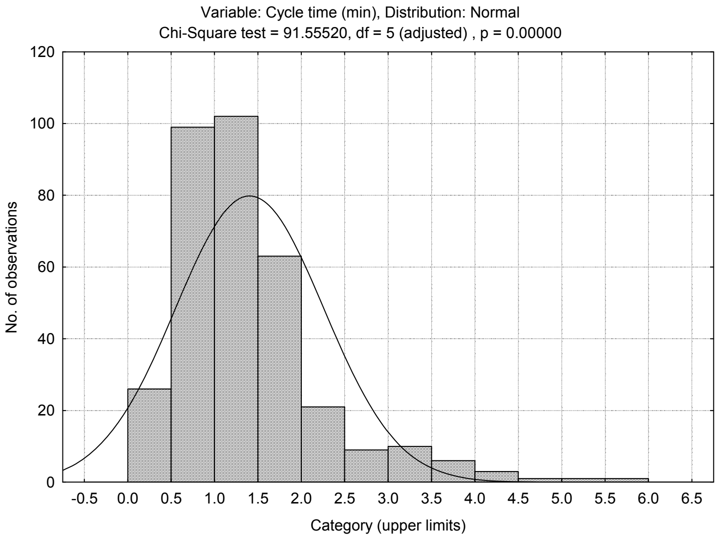
```
> shapiro.test(Chipdata$ Lnprod )
 Shapiro-Wilk normality test
data:  Chipdata$Lnprod
W = 0.9968, p-value = 0.733
```



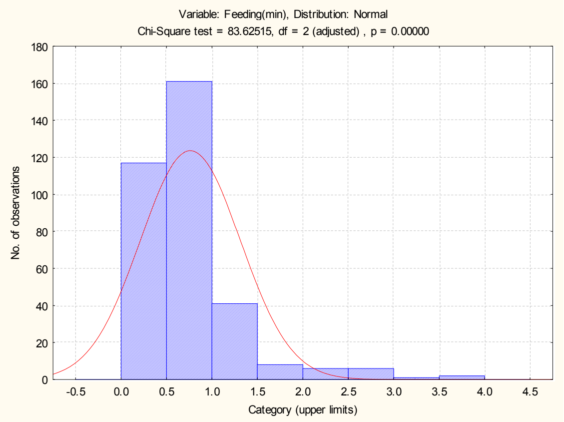
Levene's Test for Homogeneity of Lnprod Variance ANOVA of Squared Deviations from Group Means					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Species	5	3.1327	0.6265	2.18	0.0558
Error	336	96.4562	0.2871		

The test was no significant

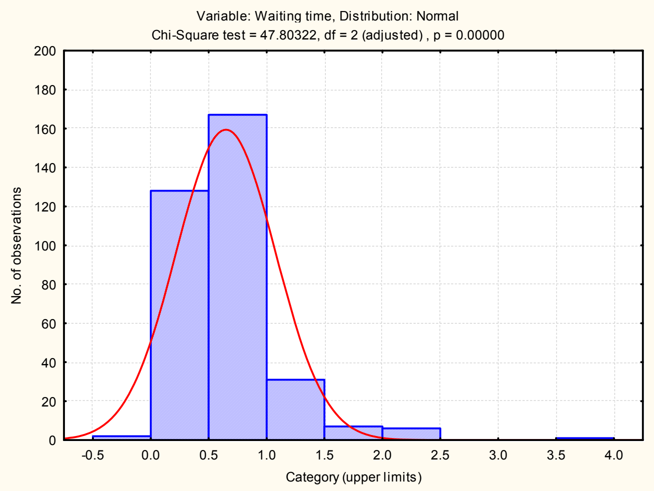
```
> shapiro.test(Chipdata$ Cycle.time.min.)
  Shapiro-Wilk normality test
data:  Chipdata$Cycle.time.min.
W = 0.8502, p-value < 0.001
```



```
> shapiro.test(Chipdata$ Feeding.min.)
Shapiro-Wilk normality test
data:  Chipdata$Feeding.min.
W = 0.7708, p-value < 0.001
```



```
> shapiro.test(Chipdata$ Waiting.time..min. )
  Shapiro-Wilk normality test
data:  Chipdata$Waiting.time..min.
W = 0.8579, p-value < 0.001
```



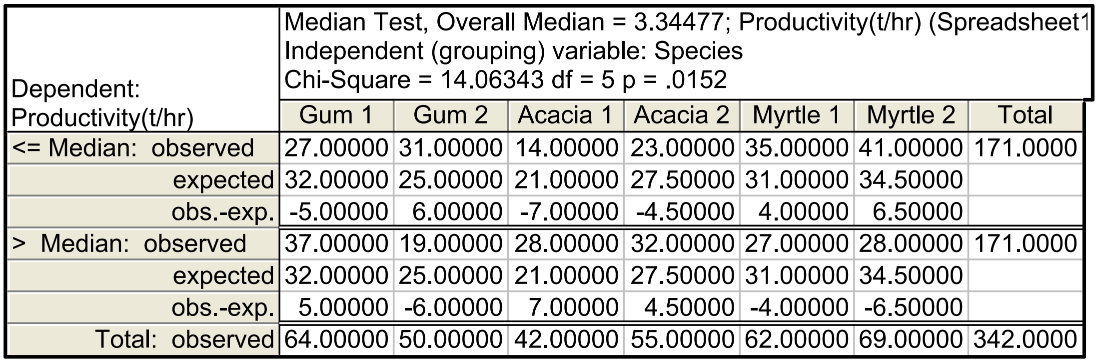
```
> kruskal.test ( Productivity.t.hr. ~Species,data=Chipdata)

  Kruskal-Wallis rank sum test

data:  Productivity.t.hr. by Species

Kruskal-Wallis chi-squared = 24.9779, df = 5, p-value = 0.0001
```

Kruskal-Wallis median test



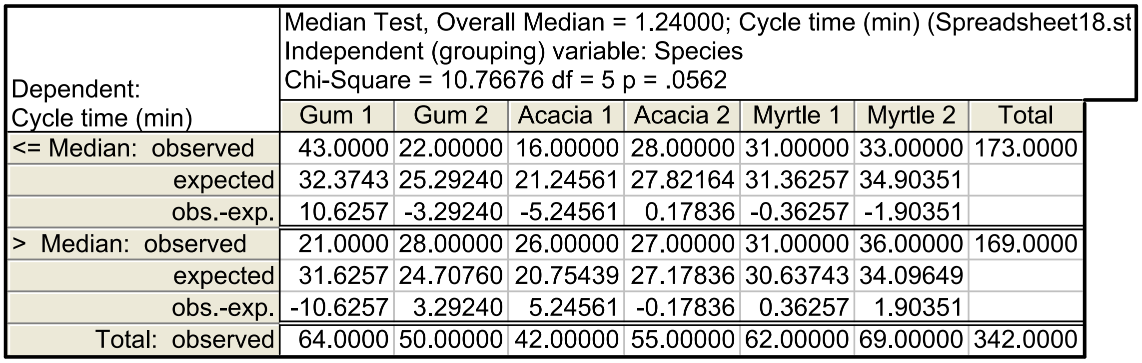
Median Test, Overall Median = 3.34477; Productivity(t/hr) (Spreadsheet1
Independent (grouping) variable: Species
Chi-Square = 14.06343 df = 5 p = .0152

Dependent: Productivity(t/hr)	Gum 1	Gum 2	Acacia 1	Acacia 2	Myrtle 1	Myrtle 2	Total
<= Median: observed	27.00000	31.00000	14.00000	23.00000	35.00000	41.00000	171.0000
expected	32.00000	25.00000	21.00000	27.50000	31.00000	34.50000	
obs.-exp.	-5.00000	6.00000	-7.00000	-4.50000	4.00000	6.50000	
> Median: observed	37.00000	19.00000	28.00000	32.00000	27.00000	28.00000	171.0000
expected	32.00000	25.00000	21.00000	27.50000	31.00000	34.50000	
obs.-exp.	5.00000	-6.00000	7.00000	4.50000	-4.00000	-6.50000	
Total: observed	64.00000	50.00000	42.00000	55.00000	62.00000	69.00000	342.0000

Cycle time of chipper

```
> shapiro.test(Chipdata$Cycle.time.min.)
  Shapiro-Wilk normality test
data:  Chipdata$Cycle.time.min.
W = 0.8502, p-value < 2.2e-16

> bartlett.test(resid(Model1), g = Chipdata$Species)
 Bartlett test of homogeneity of variances
data:  resid(Model1) and Chipdata$Species
Bartlett's K-squared = 99.8968, df = 5, p-value < 2.2e-16
> kruskal.test ( Cycle.time.min.~Species,data=Chipdata)
 Kruskal-Wallis rank sum test
data:  Cycle.time.min. by Species
Kruskal-Wallis chi-squared = 18.6721, df = 5, p-value = 0.002212
```



Median Test, Overall Median = 1.24000; Cycle time (min) (Spreadsheet18.st
Independent (grouping) variable: Species
Chi-Square = 10.76676 df = 5 p = .0562

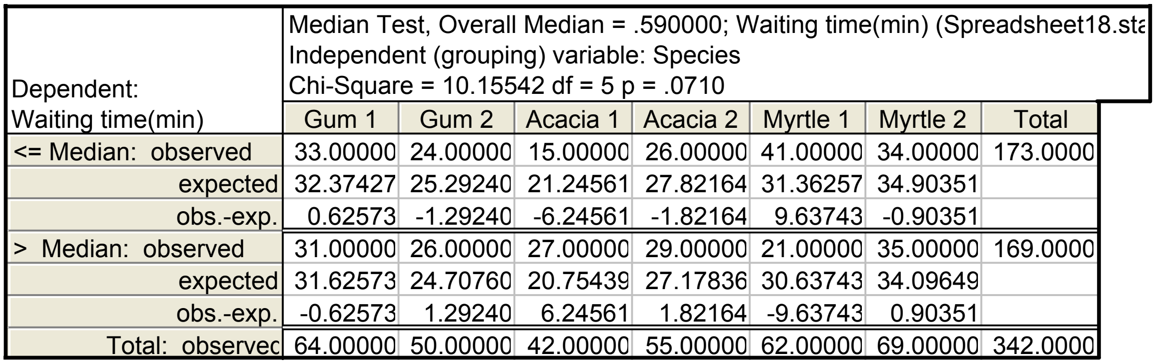
Dependent: Cycle time (min)	Gum 1	Gum 2	Acacia 1	Acacia 2	Myrtle 1	Myrtle 2	Total
<= Median: observed	43.0000	22.00000	16.00000	28.00000	31.00000	33.00000	173.0000
expected	32.3743	25.29240	21.24561	27.82164	31.36257	34.90351	
obs.-exp.	10.6257	-3.29240	-5.24561	0.17836	-0.36257	-1.90351	
> Median: observed	21.0000	28.00000	26.00000	27.00000	31.00000	36.00000	169.0000
expected	31.6257	24.70760	20.75439	27.17836	30.63743	34.09649	
obs.-exp.	-10.6257	3.29240	5.24561	-0.17836	0.36257	1.90351	
Total: observed	64.0000	50.00000	42.00000	55.00000	62.00000	69.00000	342.0000

Waiting time

```
> shapiro.test(Chipdata$ Waiting.time..min.)
Shapiro-Wilk normality test
data:  Chipdata$Waiting.time..min.
W = 0.8579, p-value < 2.2e-16

>  bartlett.test(resid(Model1), g = Chipdata$Species)
Bartlett test of homogeneity of variances
data:  resid(Model1) and Chipdata$Species
Bartlett's K-squared = 78.8328, df = 5, p-value = 1.472e-15
> kruskal.test ( Waiting.time..min.~Species,data=Chipdata)
```

```
Kruskal-Wallis rank sum test
data:  Waiting.time..min. by Species
Kruskal-Wallis chi-squared = 25.6509, df = 5, p-value = 0.0001043
```

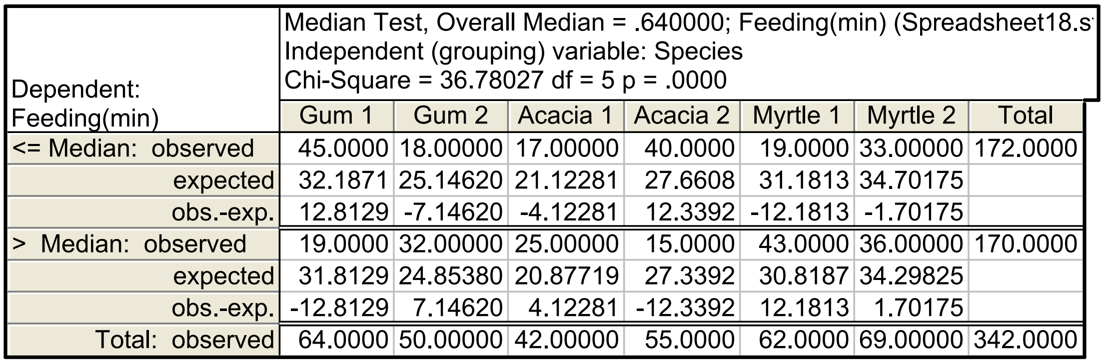


Median Test, Overall Median = .590000; Waiting time(min) (Spreadsheet18.st
Independent (grouping) variable: Species
Chi-Square = 10.15542 df = 5 p = .0710

Dependent: Waiting time(min)	Gum 1	Gum 2	Acacia 1	Acacia 2	Myrtle 1	Myrtle 2	Total
<= Median: observed	33.00000	24.00000	15.00000	26.00000	41.00000	34.00000	173.0000
expected	32.37427	25.29240	21.24561	27.82164	31.36257	34.90351	
obs.-exp.	0.62573	-1.29240	-6.24561	-1.82164	9.63743	-0.90351	
> Median: observed	31.00000	26.00000	27.00000	29.00000	21.00000	35.00000	169.0000
expected	31.62573	24.70760	20.75439	27.17836	30.63743	34.09649	
obs.-exp.	-0.62573	1.29240	6.24561	1.82164	-9.63743	0.90351	
Total: observec	64.00000	50.00000	42.00000	55.00000	62.00000	69.00000	342.0000

Feeding time

```
> shapiro.test(Chipdata$  Feeding.min.)
Shapiro-Wilk normality test
data:  Chipdata$Feeding.min.
W = 0.7708, p-value < 2.2e-16
>  bartlett.test(resid(Model1), g = Chipdata$Species)
Bartlett test of homogeneity of variances
data:  resid(Model1) and Chipdata$Species
Bartlett's K-squared = 159.2827, df = 5, p-value < 2.2e-16
```



Median Test, Overall Median = .640000; Feeding(min) (Spreadsheet18.s
Independent (grouping) variable: Species
Chi-Square = 36.78027 df = 5 p = .0000

Dependent: Feeding(min)	Gum 1	Gum 2	Acacia 1	Acacia 2	Myrtle 1	Myrtle 2	Total
<= Median: observed	45.0000	18.00000	17.00000	40.0000	19.0000	33.00000	172.0000
expected	32.1871	25.14620	21.12281	27.6608	31.1813	34.70175	
obs.-exp.	12.8129	-7.14620	-4.12281	12.3392	-12.1813	-1.70175	
> Median: observed	19.0000	32.00000	25.00000	15.0000	43.0000	36.00000	170.0000
expected	31.8129	24.85380	20.87719	27.3392	30.8187	34.29825	
obs.-exp.	-12.8129	7.14620	4.12281	-12.3392	12.1813	1.70175	
Total: observed	64.0000	50.00000	42.00000	55.0000	62.0000	69.00000	342.0000

```
> shapiro.test(Chipdata$  Feeding.min.)

        Shapiro-Wilk normality test

data:  Chipdata$Feeding.min.
W = 0.7708, p-value < 2.2e-16

> bartlett.test (resid(Model1), g = Chipdata$Species)

  Bartlett test of homogeneity of variances

data:  resid(Model1) and Chipdata$Species
Bartlett's K-squared = 159.2827, df = 5, p-value < 2.2e-16

> kruskal.test ( Feeding.min.~Species,data=Chipdata)

  Kruskal-Wallis rank sum test
```

```
data:  Feeding.min. by Species
Kruskal-Wallis chi-squared = 65.0461, df = 5, p-value = 1.096e-12
```

Appendix 6: Assumptions for machine cost.

General Inputs for the three-wheeled loader	**General Inputs for the chipper**
Number of working days per year: 240 days	Number of working days per year: 240 days
Number of shifts per day: 1shifts	Number of shifts per day: 1 shifts
Work week: 5 days	Work week: 5 days
Scheduled hours per shift: 8 SMH	Scheduled hours per shift: 8 SMH
Machine utilization: 50%	Machine utilisation: 50 %
Estimated productivity: 3.3 tonnes/ PMH	Estimated productivity: 3.1 tonnes/ PMH
Expected economic life: 15000 PMH	Expected economic life: 10000 PMH
Fixed Cost Inputs	**Fixed Cost Inputs**
Replacement value: 450000 R	Replacement value: 420000 R
Salvage value ratio: 10%	Salvage value ratio: 10%
Interest rate: 10%	Interest rate: 10%
Machine license and road user taxes: 0 R/annum	Machine license and road user taxes: 0 R/annum
Insurance: 0R/annum	Insurance: 0R/annum
Annual relocation cost: 0R/annum	Annual relocation cost: 0R/annum
Variable Cost Inputs	**Variable Cost Inputs**
Fuel price: 8 R/Litre	Fuel price: 8 R/Litre
Fuel consumption: 6 Litres/PMH	Fuel consumption: 7.8 Litres/PMH
Oil and lubricant cost: 20%	Oil and lubricant cost: 20%
Maintenance and repair cost: 100%	Maintenance and repair cost: 100%
Cost per front tyre: 10000 R	Number of front tyres on working machine: 2 tyres
Estimated front tyre life: 3000 PMH	Single front tyre cost: 600 R
Cost per rear tyre: 3500 R	Estimated front tyre life: 5000 PMH
Estimated rear tyre life: 2000 PMH	Number of rear tyres on working machine: 0 tyres
	Single rear tyre cost: 0 tyres
	Estimated rear tyre life: 0 PMH

General Inputs for chainsaw
Number of working days per year: 240 days
Number of shifts per day: 1shifts
Work week : 5 days
Scheduled hours per shift: 8 SMH
Machine utilisation: 50 %
Estimated productivity : 1.13 tonnes/ PMH
Expected economic life: 1000 PMH
Fixed Cost Inputs
Replacement value: 6000 R
Salvage value ratio: 0 %
Interest rate: 0%
Insurance: 0 R/annum
Variable Cost Inputs

Fuel price:	8.76/Litre
Fuel consumption:	1.5 Litres
Oil and lubricant cost:	20%
Maintenance and repair cost:	100%
Non-depreciable Items	
Cutting bar life:	125PMH
Cutting bar cost:	250 R
Cutting chain life:	63R
Cutting chain cost :	120 R
Sprocket life:	125 R
Sprocket cost:	40R
Flat File life:	125 PMH
Flat File cost:	20R
Round File life:	125 PMH
Round File cost:	20R
Other non-depreciable item/s cost:	0R