Potentials and Wood Fuel Quality of Logging Residues from Indigenous and Planted Forests in Mozambique

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Abstract

Search for complementary and alternative renewable energy sources is imperative to meet the current growing demand for wood fuel and for diversification of electricity supply sources in Mozambique. Logging residues from timber harvesting operations and whole tree biomass from short rotation coppice (SRC) are available options. The overall aim of this thesis work was to increase knowledge of the potentials and fuel quality of woody biomass from natural forests and SRC plantations as a renewable energy source. The aim also included an assessment of climate effects associated with the replacement of fossil fuels by Eucalyptus pellets for energy production. To estimate the biomass of logging residues species-specific above-ground biomass and stem volume equations were developed for four commercial timber species in Mozambique. The indigenous species included *Afzelia quanzensis* Welm. (Chanfuta), *Milletia stuhlmannii* Taub. (Jambire) and *Pterocarpus angolensis* D.C. (Umbila), while the planted species was *Eucalyptus grandis* W. Hill ex. Maiden (Eucalyptus). Diameter at breast height was the best predictor of biomass, while diameter and height explained the stem volume best. Results on biomass quantification showed that Jambire had the highest dry weight per tree and Umbila had the lowest. The stem had the largest share of the total biomass for Chanfuta, Jambire and Eucalyptus, while branches constituted the major biomass in Umbila. The dry weight proportion of the logging residues relative to the total tree biomass was 77% for Chanfuta, 83% for Umbila, 47% for Jambire and 38% for Eucalyptus. Chemical analyses were carried out to characterize the biomass and evaluate the fuel quality of tree components, stem, branches and leaves. Evaluation parameters, including higher heating value, moisture content, ash content and basic density were used to calculate fuel value index. The stem wood and logging residues of Umbila was ranked as the best fuel with the highest fuel value index, while Eucalyptus ranked lowest. Producing and using wood pellets in a power plant in Mozambique, was more beneficial from a climate perspective than producing it in Mozambique and export to Sweden to be used in a combined heat and power plant. The results indicate that there is a significant amount of biomass with good fuel properties that could be obtained as by-products of logging activities and from SRC for uses such as energy, thus reducing the need for clearing new forests for energy use.

Keywords: Renewable energy, Logging residues, Fuelwoods, Fuel value index, Chanfuta, Jambire, Umbila, Eucalyptus, LCA, Wood pellets

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Dedication

To my husband (Téofilo) and kids (Dylan and Lakisha)

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Mate, R., Johansson, T., Almeida, S. (2014). Biomass equations for tropical tree species in Mozambique. *Forests* 5, 535-556

II Mate, R., Johansson, T., Almeida S. (2015). Stem volume equations for valuable timber species in Mozambique. *Journal of Sustainable Forestry* 34(8), 787-806.

III Mate, R., Anerud, E., Jirjis, R. (2016). Wood fuel quality characteristics of logging residues from indigenous and planted species in Mozambique. To be submitted to *Biomass and Bioenergy Journal* (manuscript).

IV Porsö, C., Mate, R., Vinterbäck, J., Hansson, P.-A. (2016). Time-dependent climate effects of Eucalyptus pellets produced in Mozambique used locally or for export. *BioEnergy Research 9 (3)*, 1-13.

Papers (I, II and IV) are reproduced with the permission of the publishers.

The contribution of Rosta Mate to the papers included in this thesis was as follows:

I. Made an 80% contribution to planning the study and fieldwork, data collection and analysis, and paper writing with the co-authors.

II. Made an 80% contribution to planning the study and fieldwork, data collection and analysis, and paper writing with the co-authors.

III. Made an 80% contribution to planning the study and fieldwork, data collection and analysis. Wrote the paper with input from the co-authors.

IV. Made a 30% contribution to data collection and analysis, particularly on the *Eucalyptus* species production system, and participated in writing the paper.

Abbreviations

A	Ash content
AGB	Above-ground biomass
d.b.	Dry weight basis
DBH	Diameter at breast height
FVI	Fuel value index
GHG	Greenhouse gases
GJ	Gigajoule
GWP	Global warming potential
HHV	Higher heating value
LCA	Life cycle assessment
LHV	Lower heating value
M	Moisture
m^3	Cubic meter
SRC	Short rotation coppice
w.b.	Wet basis

1 Introduction

World-wide, more than 80% of the primary energy consumed in 2013 was fossil based (IEA, 2015). Increased utilisation of fossil fuels has contributed to emissions of greenhouse gases, leading to climate change (Sathre & Gustavsson, 2011). Reducing the dependence on fossil fuels and its associated greenhouse gas emissions constitutes a global priority. Renewable energy sources such as solar, wind, geothermal, dedicated energy crops and woody biomass are among the potential options. Woody biomass is the main energy source for around 12% of the world's population. In Africa, wood accounts for around 27% of the total primary energy supply (FAO, 2014b) and is the main energy source for 81% of households in sub-Saharan Africa (AFREA, 2011). Fuelwood, mainly firewood and charcoal in Africa represented, respectively, 35% and 61% of the global wood fuel production on that continent in 2014 (FAO, 2016; FAO, 2014a). Fuelwood extraction and use have been reported to contribute to deforestation in the tropics (Campbell *et al.*, 2007). Use of logging residues, which are by-products of timber harvesting operations, and biomass from dedicated energy plantations with fast-growing species can contribute to reducing the negative effects of forest clearing for fuelwood extraction. Logging residues and biomass from dedicated short rotation coppice (SRC) energy plantations are commonly used as energy feedstocks in Europe and America, but such use is limited in Asia and Africa.

In Mozambique, around 80% of the population rely on fuelwood to meet their energy needs (Falcão, 2008). The country's fuelwood consumption rate increased from 130,000 cubic metres (m^3) in 1990 (FAO, 2015) to 23.7 million m^3 in 2007 (Sitoe *et al.*, 2007). However, based on official statistics for the sector, the average annual volume of licensed fuelwood in the period 2010-2014 was an estimated 0.74 million m^3 (DNTF, 2014; DNTF, 2011). In contrast, for the same period timber harvesting was estimated to around 0.26 million m^3, representing less than half the volume of fuelwood. It has been reported that only 4% of the fuelwood consumed in Mozambique is licensed (Nhancale *et al.*, 2009), suggesting even higher fuelwood consumption than officially reported. Together, fuelwood extraction and agricultural activities are reported to be responsible for about 0.6% annual loss of forest area and for emitting around 8.6 $MtCO_2$ yr^{-1} (CEAGRE & WinRock International, 2016; Marzoli, 2007).

Another factor is that the Mozambican population increased by 64% from 1997 to 2014 (INE, 2016; INE, 2015). It is estimated that around 61% of the population lived below the poverty line in 2011 (UNDP, 2015), increasing the need for cheap and easily accessible energy sources. In addition, the national average *per capita* consumption of fuelwood is 1.2 m^3 $year^{-1}$ (Sitoe *et al.*, 2007), which represents an increase of 25% on earlier estimates. As a consequence of the population growth, demand for land for agriculture, housing and energy has increased. Shortage of wood fuel in major cities and highly populated areas of Mozambique has been reported (Drigo *et al.*, 2008). Negative impacts, such as forest degradation and deforestation of fuelwood utilisation, are considered to be higher than those associated with selective timber logging operations in Mozambique (Sitoe *et al.*, 2012). High selectiveness in species, geographically scattered production sites and low fuel conversion efficiency in the traditional methods used are among the main challenges of fuelwood use in Mozambique. Considering that, along with the above-mentioned difficulties, fuelwoods will remain the dominant energy source, which poses challenges to sustainable forest resource use in Mozambique. Therefore, assessment of alternative or complementary sources for woody biomass generation to meet the growing energy demand of the country without felling new forests is required. The current timber logging operations in Mozambique are characterised by low timber productivity, resulting in large amounts of residues at felling sites (Fath, 2001). Mozambique has favourable climate conditions and surplus land for establishment of dedicated energy plantations. However, it is as yet unclear to what extent these feedstocks can contribute to reducing the current energy challenges and how suitable they are as fuel, and therefore a thorough assessment of their quality and potential is needed.

2 Objectives

Current developments in the global energy sector show that woody biomass can be a promising option to increase the share of renewable energy sources in the energy sector. For Mozambique, utilisation of logging residues could contribute to meeting energy needs, expanding the country’s revenue sources and reducing the negative impacts of felling forests for fuelwood. The overall aim of this thesis work was to increase knowledge of the potentials and fuel quality of woody biomass from natural forests and short-rotation coppice plantations as a renewable energy source. The aim also included an assessment of climate effects associated with the replacement of fossil fuels by Eucalyptus pellets for energy production. Specific objectives were:

- To develop species-specific equations in order to provide reliable estimates of total above-ground biomass and stem volume for the most widely harvested indigenous and planted tree species in Mozambique.

- To evaluate the potential of different feedstocks available for use as fuel.

- To assess and compare the quality of woody biomass as fuel by evaluating the characteristics of the materials and their fuel value index.

- To assess climate effects of using *Eucalyptus grandis* pellets for electricity production in Mozambique instead of fossil fuels.

2.1 Structure of the thesis

This thesis is based on the work covered in four papers. Quantification methods of woody biomass from indigenous and planted species were covered in papers I and II. The different fractions of logging residues from the selected species were quantified and evaluated in paper III. Paper IV dealt with climate impact of replacing fossil energy by Eucalyptus pellets. A schematic representation of the thesis content is shown in Figure 1.

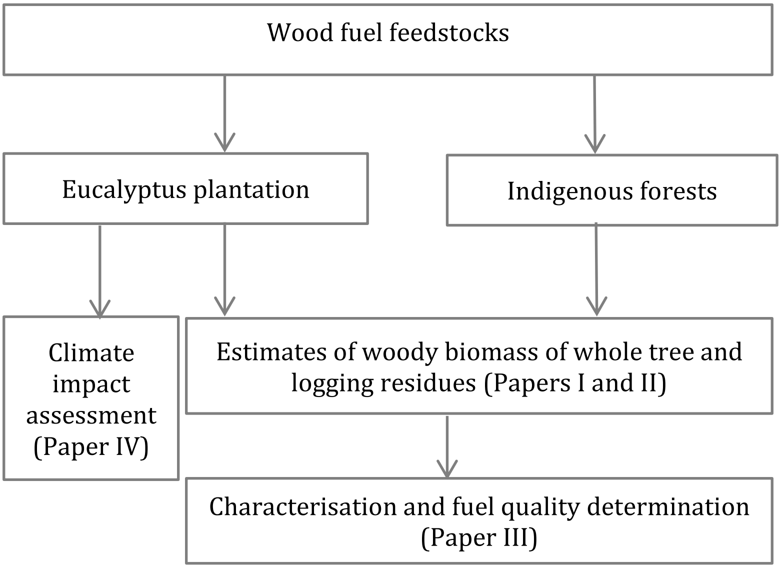

Figure 1. Structure of the work performed in Papers I-IV of this thesis.

3 Background

3.1 Current energy sources and potential

The current Mozambican energy portfolio includes different energy sources such as: biomass (firewood and charcoal), hydropower, diesel, petroleum fuels, natural gas, coal, solar and wind power (ME, 2012; Cuvilas *et al.*, 2010). In the current energy mix biomass is the most dominant source, contributing 82%, followed by electricity with 13% and with hydrocarbons and solar energy accounting for the remaining 5% (ME, 2012).

Biomass has a potential to generate around 2 GW of electricity (EUEI PDF, 2012). In general, biomass and solar energy are mainly used to supply the domestic market (Mahumane & Mulder, 2015). Firewood is mainly for cooking, heating, drying locally made bricks and in small-scale industrial processes such as drying pottery/ceramics and tobacco, cooking and heating in households, hospital buildings, student hostels and bakeries (Sitoe *et al.*, 2012). Charcoal is mainly used for household cooking and heating, and is estimated to represent around 50% of total energy expenditure in urban areas (Mahumane & Mulder, 2015). However, the traditional kilns used for charcoal production in Mozambique are characterised by low conversion efficiency, ranging from 10% to 25% (Pereira *et al.*, 2001). Consequently, more biomass is needed to produce a given amount of energy.

The potential of solar and wind energy is calculated to be about 2.7 GW and 1100 MW respectively (EUEI PDF, 2012). Hydro resources have the potential to produce 19 GW of electricity, but only around 2 GW are exploited at present (ME, 2012). Around 95% of electricity is hydro based and fossil fuels (coal and gas) share less than 1% (UNEP, 2013; IRENA, 2012). Recent discoveries of fossil fuel reserves in Mozambique the share of fossil energy is expected to increase. A report by EDM (2012) lists seven fossil fuels based electricity projects identified so far which will result in 70% from hydropower, 19.3%

from coal and 10.7% from natural gas. However, most of the electricity is intended for export (Mahumane & Mulder, 2015). Electricity and natural gas are currently only accessible to urban households, due to the prevailing high initial investment costs on stoves and limited distribution infrastructure (Atanassov *et al.*, 2012; Falcão, 2008), although a comparative study has revealed that cost-wise, charcoal is more expensive per unit energy than gas and electricity (Egas, 2006).

Liquid fuels such as diesel and kerosene are mostly imported and used for transport, process heat for industries and in small proportions for household cooking and lighting (ME, 2012).

3.2 Forest resources in Mozambique

Around 70% of the land surface in Mozambique is covered by forest and other vegetation types. The most dominant forest type is miombo woodland, which comprises around 67% of the forest area (Marzoli, 2007). Miombo forest occurs in a wide diversity of climates, ranging from tropical wet to dry (FAO, 2005). This type of forest plays an important role in securing the livelihood of 80% of the Mozambican population who rely heavily on forests as a source of employment, income, food, construction material, medicine, energy and other services (Falcão, 2008; Campbell *et al.*, 2007). About 27 million hectares are productive forest with potential for commercial timber production. The available commercial timber stock is estimated to comprise around 1.74 billion m^3, with a permissible annual cut of 516,000-640,000 m^3 (Marzoli, 2007). However, official counts suggests that the annual harvested volume is around 40% lower than the permissible cut limit (Mate, 2014).

The forestry sector is largely dominated by small to medium-scale timber processing industries (Fath, 2001). The sector also provides formal and informal employment to around 600,000 people and accounts for about 9% of Mozambique's gross domestic production (Nhancale *et al.*, 2009).

The natural forests in Mozambique are characterised by a wide diversity of tree species, of which 118 have been identified and classified based on their timber quality (GoM, 2002). There are five classes of timber quality, namely precious and first to fourth class. The species *Afzelia quanzensis* Welw. (locally known as Chanfuta), Millettia *stuhlmannii* Taub. (Jambire) and *Pterocarpus angolensis* D.C. (Umbila) are the most harvested commercial timber species in Mozambique and belong to the first class species (Marzoli, 2007). The fourth class species are mainly used for fuelwood, but limited data exist on their fuel quality properties. The few existing studies performed have focused on the chemical and fuel quality of stem wood of the three most harvested species and other less used timber species (Cuvilas *et al.*, 2014).

Chanfuta, Umbila and Jambire accounted for 78% of total harvested timber in 2004 and around 50% in 2012 (DNTF, 2014; DNTF, 2013; DNFFB, 2004). However, a recent study reported that around 60% of the timber harvest in Mozambique from 2007 to 2012 was unlicensed (Egas *et al.*, 2013). Therefore the real volumes are unknown, but reports suggest that the actual harvested volume is much higher than the reported volume. Other species such as *Combretum imberbe* Wawra (Monzo) and *Colophospermum mopane* (Benth.) J.Léonard (Chanate) contribute significant amounts to the total harvested volume. These species, together with Chanfuta, Umbila and Jambire, constitute the five most harvested species in Mozambique (DNAF, 2016) (Figure 2).

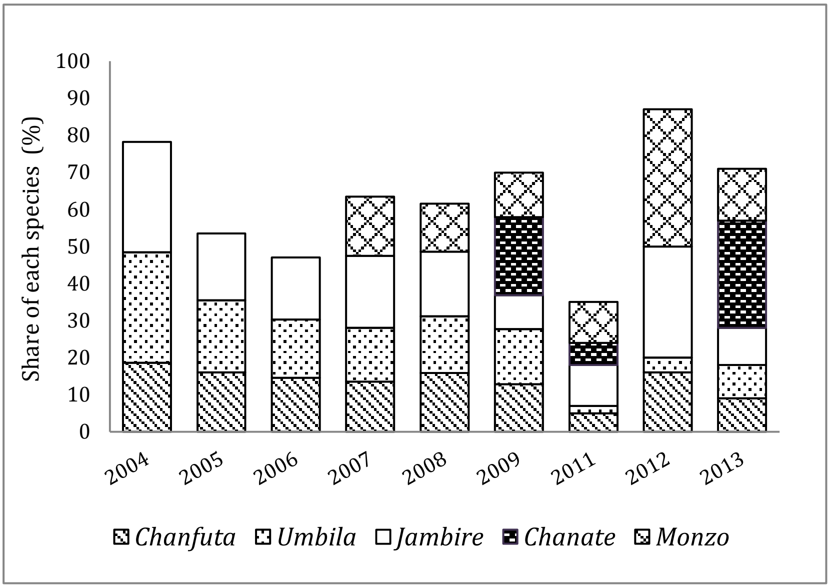

Figure 2. Relative proportions of the five most harvested tree species in Mozambique, 2004-2013.

In Mozambique, timber logging activities take place within forest areas under a simple licence or concession regime. The simple licence consists of a short-term contract awarded for a period of five years and with an annual permissible cut limit of 500,000 m^3. In a concession regime, a long-term contract of 50 years is awarded (GoM, 2012; GoM, 2002). The duration of a simple licence was formerly one year but was recently extended, as a measure to better monitor forest resource use. In both cases, renewal of the contract is dependent upon previous compliance with the provisions of the agreed management plans. The concession regime is the recommended model for sustainable forest management goals (Chitará, 2003; Sitoe *et al.*, 2003). Due to limited technical and resource capacity, the number of forest operators working under a single licence (259) is still high compared with the number licensed under a concession regime (158) (DNAF, 2016). As a consequence of this structure, effective monitoring of harvesting operations is challenging, as a large number of small areas need to be monitored for the simple licence system.

Planted forests cover 0.1% of Mozambique's land surface (FAO, 2015) and are dominated by commercial plantations, mainly consisting of different *Eucalyptus* and *Pinus* species established in central and northern regions of the country. However, the share of dedicated energy forest plantations is unknown. Increased investment in forest plantations has been observed in recent years, but the majority of the trees grown are intended for timber supply rather than as an energy source. Forest plantations offer great potential for regular biomass supply over the rotation period, including biomass from whole tree harvesting in dedicated short-rotation coppice plantations, logging residues from felling, pruning and thinning and wood residues from processing activities. Therefore, plantations could also act as potential feedstock to enlarge the energy supply options and as a source of revenue in Mozambique.

3.3 Above-ground biomass estimation

Biomass is defined as mass of live or dead organic matter. The above-ground biomass of plants encompasses all living biomass above the soil, including stem, stump, branches, bark, seeds and foliage (IPCC, 2003). Available methods for biomass estimation include destructive and non-destructive methods.

The destructive method is a direct way to estimate biomass volume and involves tree felling and separation of different tree fractions such as stem, branches, twigs and leaves, followed by measurement of the fresh and oven-dry weight of these fractions (GTOS, 2009). The advantage of the method is that it produces accurate measurements of biomass in a specific area that can be multiplied up to obtain estimates for a larger area. However, this method is expensive and time-consuming to perform and not practical for large areas or for trees with large diameter at breast height (DBH) and limits the possibility of monitoring biomass growth over time (Vashum & Jayakumar, 2012; Stewart *et al.*, 1992).

The non-destructive methods entail biomass estimation without tree felling (Montès *et al.*, 2000). Tree parameters such as height and diameter are measured and used for development of allometric equations and conversion factors. Despite the fact that these methods are non-destructive, some trees need to be harvested and weighed for method validation, thus limiting assessment of its reliability (Vashum & Jayakumar, 2012). Allometric equations are used for biomass estimates by establishing relationships between different parameters, *e.g*. DBH, height, crown diameter, tree species *etc*. These allometric equations are considered to yield accurate estimates as long they are generated from a representative number of trees for the specific ecosystem or forest type (GTOS, 2009). The resulting estimates can be scaled up to site, regional or global level. Remote sensing data and field measurement biomass data, when combined, provide biomass estimates at stand and landscape level (Case & Hall, 2008). According to Vashum and Jayakumar (2012) remote sensing is cost-effective and is useful for areas that are difficult to access.

3.4 Stem volume estimation

Tree volume is estimated for stand trees based on diameter and height measurements by applying a specific volume equation. Different formula are used, *e.g*. the Smalian, Hubber and Newton formulae (Husch *et al.*, 2003) and the Hohenadl equation (Heger, 1965). The volume can be expressed in cubic metres as a function of DBH, or combined DBH and height (Husch *et al.*, 2003). The precision of the volume estimates obtained can be improved by accounting for the specificity of the population for which the estimates were developed (de Gier, 1992). Three-entry variable equations, where tree form is added to DBH and height, are also commonly used. However, this requires use of a previously determined tree form or knowledge of tree taper (Husch *et al.*, 2003). The development of taper functions and volume equations is an effective tool for managing forests for high yield production (Hjelm, 2013). Unlike coniferous species, taper in tropical tree species is limited due to challenges associated with their irregular and complex shape.

Development of biomass and stem volume estimates is crucial for appropriate forest management (Nur Hajar *et al*., 2010). Several studies have reported stem volume and biomass equations for tropical forests (Adekunle, 2007; Chave *et al.*, 2005; Brown, 1997) and for different *Eucalyptus* species (Crecente-Campo *et al.*, 2010; Zewdie *et al.*, 2009; Saint-André *et al.*, 2005). Despite the apparent validity of existing biomass and volume allometric equations, trees may present different allometric relationships in response to environmental factors (Vieilledent *et al.*, 2012; Chave *et al.*, 2005). Therefore, most of the published findings focusing on generalised models for tropical rainforest species may not be applicable to the deciduous and semi-deciduous species in Mozambique. Moreover, the biomass and stem models currently in use in Mozambique are generic and developed for different vegetation types (Tomo, 2012; Ryan *et al.*, 2011; de Sousa Machoco, 2008; Marzoli, 2007; Tchaúque, 2004). A species-specific volume equation and above-ground biomass formula have been developed for *Androstachys johnsonii* Prain. (Magalhães & Seifert, 2015; Magalhães, 2008). Overall, however, there are limited data on species-specific biomass and stem volume equations for the most harvested commercial species in natural and planted forest in Mozambique. Therefore, development of appropriate allometric equations is needed for the production of accurate biomass and volume estimates in order to support sustainable use of the forest resources in Mozambique.

3.5 Wood fuel quality and fuel value index

Wood fuel characteristics are defined by the inherent physical and mechanical properties of the wood (Wiese, 2013; Pereira *et al.*, 2012). These parameters include heating value, moisture content, volatile matter, ash content and impurities, bulk density, particle size distribution, durability and bridging properties. The most commonly used parameters to assess wood fuel quality include: heating value, moisture content and ash content. Heating value reflects the amount of energy that can be recovered during combustion and it can be expressed as gross calorific value or higher heating value (HHV) and as net calorific value or lower heating value (LHV). The HHV is the absolute value of the specific energy of combustion, in joules, for a unit mass of a solid biofuel burned in oxygen in a calorimetric bomb, where the products are assumed to consist of gaseous oxygen, nitrogen, carbon dioxide and sulphur dioxide, liquid water (in equilibrium with its vapour) saturated with carbon dioxide and solid ash (SIS, 2010). The HHV is a reflection of the total enthalpy of the elemental composition. Therefore, low H:C and O:C ratio increases the HHV, while high concentrations of nitrogen and high ash content decrease the HHV.

The LHV is the absolute value of the specific heat of combustion, in joules, for a unit mass of the biofuel burned in oxygen at constant pressure under such conditions that all the water of the reaction products remains as water vapour and the other products are as for the HHV (SIS, 2010). Thus, the LHV is the energy that can be generated without condensation of vapour and is calculated by deducting the energy used for evaporation of water from the HHV.

Moisture content is defined as the weight percentage of water contained within a lignocellulosic biomass, expressed on a wet weight basis (SIS, 2009). High moisture content reduces the available energy in the biomass and increases emissions during combustion (Van Loo & Koppejan, 2008). In addition, high moisture increases material degradation during storage (Jirjis, 1995). The moisture content, besides affecting the LHV, influences the whole supply chain of biomass, from raw material procurement, processing, storage, transport and utilisation. Thus, monitoring of moisture content is crucial to ensure acceptable fuel quality.

Ash is the remaining residue after combustion (SIS, 2009). It results from unburnable minerals originating from the biomass as salts bound in the carbon structure and from inorganic components present as mineral particles in contaminants, such as soil and dust. High ash content in biomass affects the HHV, therefore not desired. The presence and concentration of certain minerals in the ash affects the ash melting behaviour during combustion and can lead to sintering and clogging problems in combustion plants (Van Loo & Koppejan, 2008). Chlorine (Cl) is an important element for the transportation of alkali metals, and the latter, in combination with chlorine and silica, influences the ash melting temperature, leading to deposit formation and corrosion, fouling and slagging problems (Masiá *et al.*, 2007; Obernberger *et al.*, 2006). Other important characteristics include wood density, which affects energy density, fuel homogeneity and particle size distribution, which affects the fuel feeding process and combustion (Dahlquist, 2013).

There are also interactions between the different parameters mentioned above and thus assessment of the suitability of biomass as a fuel becomes challenging. Fuel value index (FVI), taking into account the main quality properties, has been used with good results to rank wood fuel species in Asia and Africa (Meetei *et al.*, 2015; Cuvilas *et al.*, 2014; Deka *et al.*, 2007; Abbot *et al.*, 1997). The index is based upon parameters including high energy content, high wood basic density, and low ash and moisture contents, as defined by Bhatt and Todaria (1990).

3.6 Climate impacts of wood fuel feedstocks

A commonly used method to assess the environmental impacts of bioenergy systems is life cycle assessment (LCA). Life cycle assessment is a standardised method under ISO 14040/44 (ISO, 2006a; ISO, 2006b) used to assess the impacts of a system or product during its life span, *i.e.* it includes all phases from raw material acquisition to processing, utilisation and disposal (Curran *et al.*, 2011; Cherubini, 2010). There are four interdependent phases within LCA: the first, consist in the definition of the goal and scope of the study. In this stage, information is also provided on the selected functional units, system boundaries, assumptions, allocation methods used, impact categories chosen and study limitations. The second phase is the life cycle inventory analysis (LCI), where all data on resource use and emissions and inventory inputs and output data are collected for all activities within the system boundary. The third phase includes the life cycle impact assessment (LCIA), where the impact of individual emissions and resource use are grouped into defined impact categories and potential environmental impact assessed. Phase four consists of interpretation of the results from LCI and LCIA with regard to the initial goal and scope of the study, the data and impact assessment method used.

The common metric used for climate impact assessment is global warming potential (GWP) (Zetterberg & Chen, 2015; Fuglestvedt *et al.*, 2003). The GWP expresses the integrated radiative forcing (RF) of a gas compared with the integrated RF of a reference gas (carbon dioxide) over a chosen time horizon (Ericsson *et al.*, 2013). The RF (W m^{-2}) which describes the energy imbalance on Earth due to altered GHG concentrations, positive results describe a warming climate response and negative results a cooling climate response (Myhre *et al.*, 2013). The GWP is calculated for time horizon of 100 years (GWP_{100}), expressed as CO_2-equivalents (CO_2-eq.).

Forests play an important role as carbon sinks as well as a source of biomass for other uses such as energy. Replacing fossil fuels with woody biomass can help to reduce greenhouse gas emissions. In several studies, bioenergy systems have been considered carbon neutral (Masiá *et al.*, 2007; Gan & Smith, 2006), *i.e.* assuming the same amount of CO_2 is released when biomass is combusted as sequestered during biomass growth. However, this assumption has been criticised for not accounting for temporal changes in carbon stocks in the system (Zanchi *et al.*, 2012). To account for the dynamics of carbon fluxes not captured by the conventional LCA, time-dependent LCA methodology is needed (Agostini *et al.*, 2013; Ericsson *et al.*, 2013).

4 Materials and methods

4.1 Characterisation of study areas

The work reported in this thesis was carried out in southern and central regions of Mozambique (Figure 3). The choice of study areas was based on the current and future wood fuel demand and supply projections in Mozambique (ME, 2012). Sofala province (central region) is expected to be at high risk of wood fuel shortage by 2020 and was selected for study for this reason. In addition, Sofala province is among the three major contributor's provinces to available commercial timber stock in Mozambique. Manica province, also located in the central region, is at low-medium risk of wood fuel shortage and was included due to its high potential for forest plantations as a result of good climate conditions (Nhantumbo *et al.*, 2013). A third site, Inhambane, which is already under wood fuel scarcity, was included in 2013 due to logistical constraints in accessing sampling sites in Sofala.

Inhambane (23°52'S, 35°23'E) is characterised by a tropical savannah climate with mean annual rainfall ranging from 500 to 800 mm year^{-1} and the soils are mainly deep sand types (MAE, 2005b). The stands visited were located in Funhalouro district, in Tome and Mavume localities, and were under the management of the provincial Forestry Authority.

The Sofala study site (18°58'S, 34°10'E) is characterised by a rainy tropical savannah climate with mean rainfall ranging from 1000 to 1100 mm year^{-1}, with the soil type in the area predominantly characterised by clay to sandy soils (MAE, 2005a). The stands studied in Sofala were located within two 'forest concession' areas in Cheringoma District, Inhaminga locality.

The Manica site (18°56'S, 32°43'E) is characterised by a temperate humid climate with mean annual rainfall ranging from 1000 to 1020 mm and deep clay soils (MAE, 2005c). The stands visited in Manica were within the plantation area under the management of the Faculty of Agronomy and

Forestry Engineering Research Centre (CEFLOMA), located in Manica District.

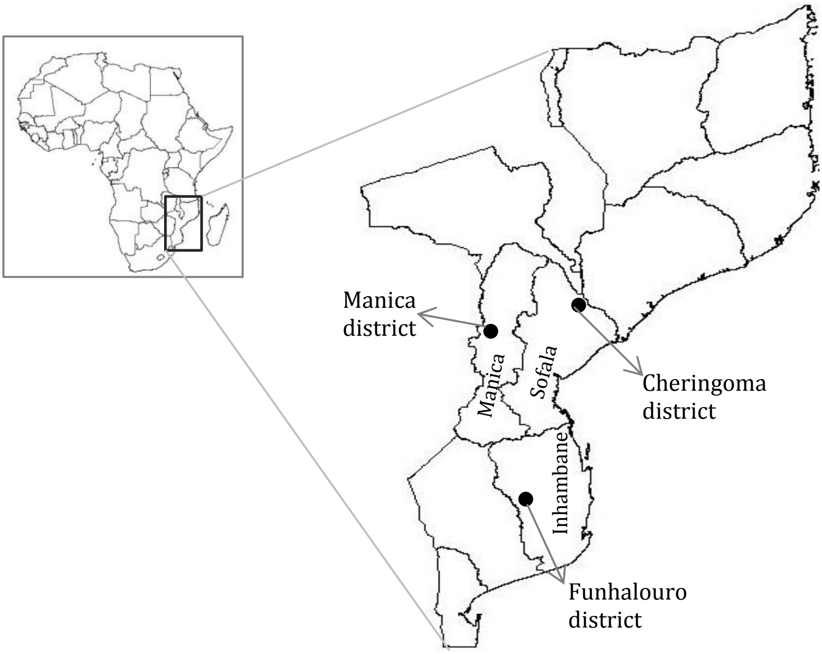

Figure 3. Geographical location of the study areas in Mozambique: Cheringoma in Sofala province, Manica in Manica district and Funhalouro in Inhambane province.

4.2 Characteristics of studied species

In this thesis three indigenous valuable timber species and one of the most widely planted exotic species were studied (Figure 4). The indigenous species were: *Afzelia quanzensis* Welw. (Chanfuta), *Millettia stuhlmannii* Taub. (*Jambire*) and *Pterocarpus angolensis* D.C. (Umbila). The exotic species was *Eucalyptus grandis* W. Hill ex. Maiden (Eucalyptus). Throughout the remainder of this thesis, the species are referred to by their common names indicated above in brackets. The summary of characteristics of the species studied in this thesis is presented below.

Chanfuta is a medium to large deciduous tree from the Fabaceae-Ceasalpinioideae family, growing in dry forests, lowland thickets or dry miombo woodlands (DFSC, 2000). Tree height usually ranges from 12 to 15 m but can reach 35 m. The wood is hard, heavy and durable, with basic density ranging from 692 to 781 kg m^{-3} (Mate *et al.*, 2014; Bunster, 1995) and minimum over bark (ob) stem DBH over bark (DBH_{ob}) at felling of 50 cm (GoM, 2002). Total available commercial stock in Mozambique is estimated at 2,514,000 m^3 (Marzoli, 2007).

Umbila is a medium-sized to large tree from the Leguminosae-Papilionoideae family. Height usually ranges from about 10 m to 20 m but can reach 28 m (Van Wyk & Van Wyk, 1997). Wood basic density ranges from 636 to 640 kg m^{-3} (Mate *et al*., 2014; Bunster, 1995) and permissible minimum DBH (ob) at felling is 40 cm (GoM, 2002). Total available commercial stock in Mozambique is 5,620,000 m^3 (Marzoli, 2007).

Jambire is a medium to large deciduous tree from the Leguminosae-Fabaceae family. Height ranges between 15 m and 25 m (ECCM, 2009). The wood is moderately hard and very durable, with basic density ranging from 841 to 1000 kg m^{-3} (Mate *et al*., 2014; Bunster, 1995). In Mozambique the species is also known as *panga panga*. Total available commercial stock is 4,200,000 m^3 (Marzoli, 2007) and permissible minimum DBH (ob) at felling is 40 cm (GoM, 2002).

Eucalipto is a tall to very tall tree from the Myrtaceae family reaching 45 to 55 m in height and with DBH (ob) reaching up to 2 m. It prefers an altitude of 600-1100 m and annual rainfall of 1000-3500 mm (McMahon *et al.*, 2010). It is originally from Australia and introduced in Mozambique, with an annual growth rate around 20 to 25 m^3 ha^{-1}. Wood basic density varies from 452 to 788 kg m^{-3}. Data on available stock of this species are lacking.

Figure 4. General appearance of the three indigenous Mozambican timber species and the commercial Eucalyptus species.

4.3 Sampling design

A total of 90 plots were allocated randomly for sampling of Chanfuta, Umbila and Jambire. However, only 57 plots could be surveyed due to limited road infrastructure that resulted in long walking distances with heavy equipment. Fieldwork was also constrained due to logistics problems arising from the data collection being carried out mostly during the rainy season. The sampled trees were encountered in only 48 plots. For stands within forest concessions, the sampled tree number was kept to one individual per species due to limits set by private entities managing the forests and also due to the fact that they were not licensed for all species of interest in this study. In contrast, for Umbila, which was mostly sampled in government-managed areas there was no restriction on sampling number. The plots, with dimensions 100 m × 20 m, were established and demarcated using sticks and ropes following applied forest inventory methodology in Mozambique (Cuambe & Marzoli, 2006). In the case of the forest plantation of Eucalyptus, the stands were previously identified by the staff at CEFLOMA and one plot per stand was allocated. A total of five plots, each measuring 50 m × 20 m, were surveyed in the Eucalyptus stands. The sampled area was 11.4 ha in natural forests and 0.5 ha in Eucalyptus plantations. The low density and scattered location of indigenous tree species at the sites, along with mentioned difficulties in sampling these species, limited the number of trees sampled.

4.4 Plot survey

Within demarcated plots all trees found were surveyed, measured in terms of their DBH (ob), height (total and commercial) and their local names were recorded to enable identification to their scientific names. The DBH was measured using callipers, while height was measured using a hypsometer. The minimum DBH considered was 10 cm. All information per surveyed tree was recorded in a numbered field form.

For the indigenous species, four diameter classes from 10 to 70 cm (10-30, 30-50, 50-70 and >70 cm) were established and during tree sampling attempts were made to allow representation of all defined classes. However, due to the limited number of trees per plot, it was not possible to get equal numbers of trees in each diameter class. In total, 58 trees of indigenous species were sampled throughout the plots, which consisted of 24 trees of Chanfuta, 19 of Umbila and 15 of Jambire. The number of selected trees per plot of these three species was based on species abundance, mean DBH and stem quality. All sampled trees were healthy, undamaged, with fairly straight stems and non-forked. For Eucalyptus, five trees per plot were randomly selected, resulting in a total of 25 sampled trees. Age was not considered as a variable in this thesis work, due to the difficulties related to ring identification and/or the need for advanced age determination methods. Existing studies suggest that the age of the trees surveyed ranged from 19 to 260 years for Chanfuta, 15 to 100 years for Umbila and 69 to 92 years for Jambire (Mate, 2014). Eucalyptus stands were aged 3.5 to >20 years (A. Esequias, pers. comm. December 2014). Logging residues are heterogeneous in terms of size of the material and its composition. Therefore consideration of different tree sizes and ages was used to approximate the composition of potential logging residues.

4.5 Biomass and stem volume measurements

Destructive methods were used to obtain the biomass and stem data. For the trees selected for measurements, stump height was defined at 20 cm above-ground before the tree was felled. In addition, the main stem was distinguished from the wide crown and branches were separated from the felled tree. Stem identification was problematic for indigenous species due to the umbrella-shaped crown without a clear natural top. To reduce the effect on the stem estimates, the direction of the main stem below the first branching point was followed, assuming a fairly straight line to the top following the larger diameter part was considered in the analysis. A similar method has been applied for estimating logging residues for bioenergy use in southern Africa (Ackerman *et al.*, 2013). Finally, all above-ground biomass components (stems, branches and leaves) were separated (Figure 5). Sample discs (10-15 cm thick) in each mid-section of the stem, at DBH and from branches (three per tree from the middle crown), and 100-300 g leaves from different parts of the crown were weighed fresh and taken for determination of moisture content and dry weight. The stump component was not accounted for in the measurements, since coppice management is recommended practice in Mozambique. In general, miombo woodland species (indigenous) are reported to respond well to wood harvesting by coppice management (Frost, 1996). Sampling for component-based biomass determination in the field was laborious, time-consuming and demanded complex logistics. Average of three trees was felled for measurements per day during the field data collection for the present thesis. The stem wood basic density was determined by the water immersion method following standard methods (Papers I and III).

a) Stem identification b) Sectioned stem sections

c) Branches d) Leaves

Figure 5. *Images of measured above-ground components.*

The total stem length was recorded and the stem divided into five sections proportionally to its total length (10, 30, 50, 70 and 90%) (Figure 6), following Hohenadl's method (Heger, 1965). This model allows uniform positioning of the section depending on stem length. For the stem volume estimates, the bottom and top diameter and length of each section were measured to enable calculation of individual section volume using the Smalian formula. Diameter at the base of the tree and at breast height (DBH) was also measured. Volume of the tree top section (90-100%) was estimated using the formula for a cone (Husch *et al.*, 2003). The total over bark (ob) stem volume was accurately determined by adding together data for each individual stem section determined. Full details of the formulae used to calculate the various parameters referred to above are provided in Papers II and III.

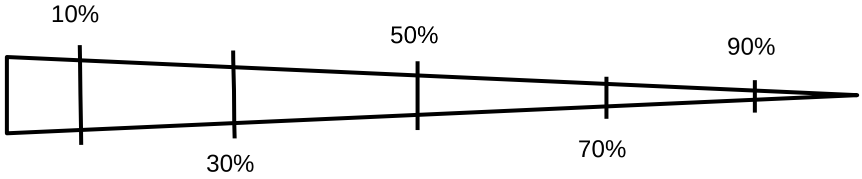

Figure 6. Representation of stem sections and sampling points.

4.6 Fitting and selection of biomass and stem equations

To accurately estimate the above-ground biomass, equations were fitted for each component using dendrometric parameters (DBH and height) as well as wood basic density. A stem volume equation was developed to assist in estimation of the un-merchantable stem part. Non-linear power equations performed well (Table 1) and therefore were further investigated. Good performance of similar non-linear equations has been reported for above-ground biomass estimates (Návar-Cháidez *et al.*, 2013; Návar, 2010; Kittredge, 1944) and stem volume estimates (Tewari *et al.*, 2013; Lumbres *et al.*, 2012; Cao *et al.*, 1980).

Table 1. *Fitted above-ground biomass and stem volume equations used in Papers I-III*

Above-ground biomass (AGB)		*Stem Volume*	
$AGB = \beta_0 D^{\beta_1}$	*(Equation 1)*	$V = \beta_0 + \beta_1 D^{\beta_2} + \varepsilon_i$	*(Equation 5)*
$AGB = \beta_0 D^{\beta_1} \beta_2 Bd$	*(Equation 2)*	$V = \beta_0 + \beta_1 D^2 H$	*(Equation 6)*
$AGB = \beta_0 (BdDH)^{\beta_1}$	*(Equation 3)*		
$AGB = (\beta_0 + \beta_1 Bd) D^{\beta_2}$	*(Equation 4)*		

where AGB = above-ground biomass (kg dry weight tree^{-1}), D = diameter at breast height over bark (DBHob, mm), Bd = wood basic density (g cm^{-3}), H = tree height (m), V = stem volume (m^3 tree^{-1}), β_0, β_1 and β_2 are parameters, and ε_{i} = residual $E(\varepsilon_i \mid \chi_i) = 0$.

4.7 Estimation of potential of logging residues

The logging residues were considered to be constituted of branches, leaves and un-merchantable stem part. Biomass of branches and leaves were calculated from its proportional share of the total dry weight of the tree (Paper I). To estimate the stem un-merchantable volume, the merchantable volume ratio data for the studied species was needed. The estimate of merchantable volume ratio is based on top diameter and height limits (Barrio Anta *et al.*, 2007; Alemdag, 1988; Burkhart, 1977). Taper equations are also used as an alternative method to predict a diameter at any stem height. In Mozambique neither the volume ratio nor the taper function for the studied species exist. Data on dimensions of harvested logs of Chanfuta, Jambire and Umbila between 2004 and 2011 by forest operators at two concession areas in Sofala Province was used (Paper II). For Eucalyptus dimension of commercial products such as poles and construction material were used. Computed the average dimensions of logs (diameter and height) were compared to average values from direct measured data. Separate expressions for estimating potential un-merchantable volume were developed for the indigenous species (Paper II) and Eucalyptus (Paper III).

Estimates of the potential availability of logging residues (Paper III) was combined with data on total standing volume of the studied species (Marzoli, 2007) and weighted HHV (Paper III) to calculate the potential recoverable energy. Recoverability rate was set to 50% for indigenous species and 70% for Eucalyptus, based on ranges (50-75%) given by Yamamoto *et al.* (2001); Johansson *et al.* (1992). For Eucalyptus, available data on the stock volume was limited and it was therefore calculated assuming 80% cover in the total planted area and an average stem volume of 0.6 m^3.

4.8 Fuel quality and fuel value index

Samples of individual above-ground biomass components (stem, branches and leaves) were analysed for HHV, ash content, moisture content, basic density and chemical composition. The HHV and ash content analyses were performed at SLU-Sweden, while the moisture content and basic density were determined at UEM-Mozambique. The chemical analyses were carried out at an accredited commercial laboratory in Sweden. All determinations were performed according to the standard methods presented in Table 2.

Table 2. *Standards methods used for chemical and fuel quality analysis*

Parameter	**Units**	**Standard method/s**
Higher heating value (HHV)	MJ kg^{-1} d.b.	SS-EN 14918:2010
Ash content (A)	% dry weight basis (wt-% d.b.)	SS-EN 14775:2009
Moisture content (M)	% wet weight basis (wt-% w.b.)	SS-EN 14774-2:2009
Basic density (Bd)	kg m^{-3}	ISO 3131-1975
Concentration of elements (Ca, K, Mg, Na)	wt-% d.b.	NMKL 161 1998 mod. / ICP – AES
Silicon (Si)	wt-% d.b.	EN 14385 / ICP – AES
Chlorine (Cl)	wt-% d.b.	EN 15289:2011/EN 15408:2011/SS
Volatile matter (Vm)	wt-% d.b.	EN 15148:2009 / EN 15402:2011
Elemental analysis (C-H-N)	wt-% d.b.	EN 15104:2011 / EN 15407:2011
Aluminium (Al)	wt-% d.b.	NMKL 161 1998 mod. / ICP – MS

Chemical composition and fuel quality parameters were used to rank the woody biomass samples using the fuel quality index (FVI). The parameters considered were: HHV, moisture content, ash content and wood basic density (only for stem wood). The equations used for the FVI were:

$$FVI = \frac{HHV}{A * M} \quad \text{Equation 7} \qquad FVI = \frac{HHV}{A} \quad \text{Equation 8}$$

$$FVI = \frac{HHV * Bd}{M * A} \quad \text{Equation 9} \qquad FVI = \frac{Bd}{A} \quad \text{Equation 10}$$

where HHV is higher heating value (MJ kg^{-1} d.b.), M is moisture content (wt-% w.b.), A is ash content (wt-% d.b.) and Bd is wood basic density (kg m^{-3}).

4.9 Assessment of climate impacts

In Paper IV, an attempt was made to assess the climate impacts of Eucalyptus pellets combusted for electricity and or heat production using LCA methodology (Paper IV). Due to limited data on indigenous species, inclusion of these in the assessment was impossible. In the LCA study, a short-rotation coppice (SRC) Eucalyptus was assumed to be located on surplus land in Manica province. The SRC plantation was considered to be established for a life time of 50 years. The rotation length was 20 years, with five four-year coppice cycles. All activities from plant establishment to management and harvest of the plantation, raw material transport to the pellet plant, pelleting, pellet transport to the end user and final use of the pellets were included in the assessment. The systems studied consisted of the pellet system and a fossil reference system (using coal and natural gas), both producing equal amounts of heat and power (Figure 7).

Emissions from all input sources to the system from fossil energy, N_2O from soil, carbon changes in soil and biomass during the life time of the plantation were accounted for. The functional unit for assessing GWP was 1 GJ pellets delivered to a combined heat and power (CHP) plant in Sweden, or alternatively used in a power plant in Mozambique. In addition, when expressed in temperature change including annual changes in biogenic carbon fluxes from biomass and soil carbon pools, the functional unit of 1 ha of cultivated SRC of Eucalipto was used.

The climate impact of the system was expressed as GWP, considering the main greenhouse gas contributors: CO_2, CH_4 and N_2O. The characterisation factors used to calculate the emissions in carbon-dioxide equivalents (CO_2-eq.) was 28 for CH_4 and 265 for N_2O (Myhre *et al.*, 2013). To account for time-dependent temperature effects, LCA methodology developed by Ericsson *et al.* (2013) was used. The climate impact was expressed as global mean surface temperature change at a given point in time.

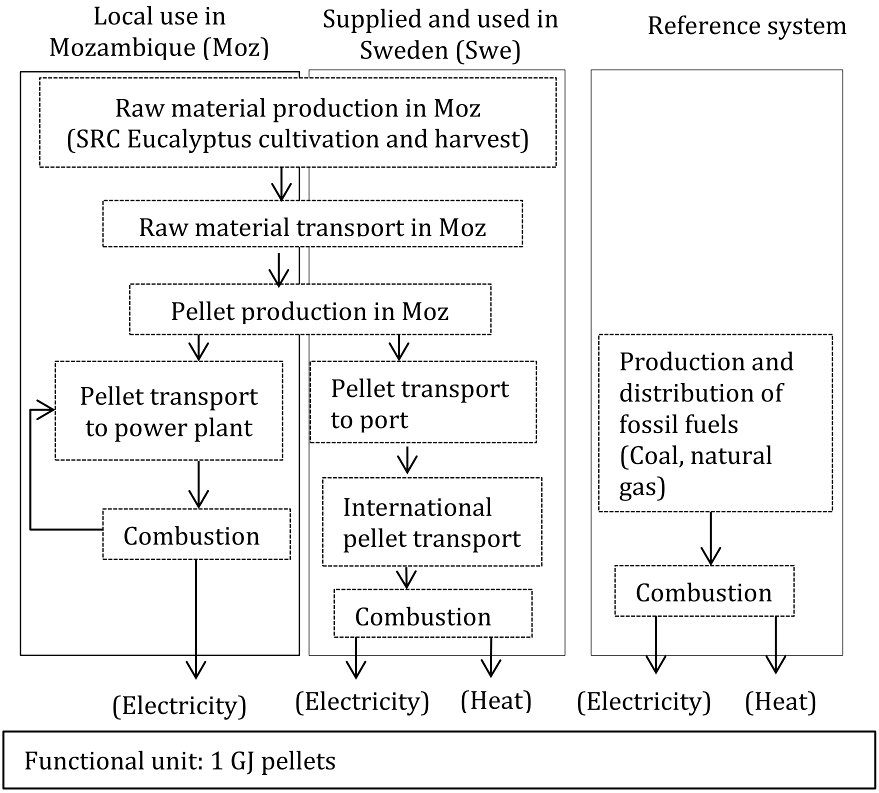

Figure 7. System description of the short-rotation coppice (SRC) Eucalyptus and reference fossil systems considered for producing electricity in Mozambique and heat and electricity in Sweden. Full lines indicate system boundaries.

4.10 Statistical analysis

Non-linear regression procedure in the SAS/STAT system for personal computers (SAS, 2006) was used for statistical analysis of biomass and stem volume equations for the indigenous species (Papers I and III). Various methods exist for selecting the best model. Assessment of best fit biomass equations was based on the coefficient of determination (R^2), average bias, average absolute bias (AAB), root mean square error (RMSE) and residual plots (Zar, 1999; Parresol *et al.*, 1987). Additional parameters used for stem volume equations were residual standard error (RSE) and second-order variant Akaike information criterion (AIC_c) (Chave *et al.*, 2005; Burnham & Anderson, 2002) (Papers II and III). The AICc is an AIC adjusted to small samples (Hurvich & Tsai, 1989). The best model should be of minimal AICc values (Burnham & Anderson, 2002). The AICc was computed using the MuMIn function in the R package (R Core Team, 2014).

The detected heteroscedasticity by visual inspection of the residual plots, showed that the White-Pagan's test was not able to detect that problem and other analysis were needed to deal with the problem. Heteroscedasticity was detected and estimated parameters were corrected by adding the argument "weights=varPower()" in the nonlinear generalised least squares function (gnls) in R package (R Core Team, 2014). The gnls function with statement of weight to model the variance was used. As the data set was separated by species, the group variance was eliminated, and only within-group variance had to be accounted. By the varPower() function in gnls procedure in R which considers the variance to increase with a power of the absolute fitted values, and also allows correlated or unequal variances (Turner & Firth, 2007). Similar procedures were used when analysing the Eucalyptus biomass and stem volume equations (Paper III).

For the fuel parameters (Paper III), the data were analysed in R statistical package. Variations in element composition, minerals, ash, volatile matter and HHV were analysed using analysis of variance (ANOVA). Significant effects were then further analysed using a Tukey test at 95% confidence level.

5 Results

5.1 Characteristics of studied stands and species

In the natural forest areas a total of 1116 trees were measured and were found to represent around 48 different species. The target species for this thesis represented only 14% of the total recorded species, with Chanfuta, Jambire and Umbila being represented by 48, 55 and 52 trees, respectively (Paper I). The studied species occurred in different forest and vegetation types, including dense closed and open deciduous forests, thickets, shrubby areas and grasslands. For the Eucalyptus plantation, a total of 389 trees were measured in the plots (Paper II).

Differences were found in stem density in the study areas. Plots located in Tome locality in Inhambane province had the highest stem density, 147 stems ha^{-1}, compared with 119 stems ha^{-1} in Inhaminga (Sofala) and 104 stems ha^{-1} in Mavume locality (Inhambane). At species level, Jambire had the highest stem density, 17 stems ha^{-1}, compared with 13 and 12 stems ha^{-1} for Chanfuta and Umbila, respectively (Paper I). Some variability was also observed in the occurrence of the three species. For instance, Chanfuta and Umbila trees were found at the Inhambane and Sofala sites, while Jambire was only found at the Sofala site. Moreover, tree size differed, with trees in Sofala having larger mean DBH and height compared with the Umbila mostly sampled in Inhambane (Paper I). For the Eucalyptus, a stem density of 778 stems ha^{-1} was found (Paper III).

The sampled trees also differed in terms of their characteristics, *e.g.* average DBH, height, stem volume, above-ground biomass, basic density and moisture content (Table 3). Jambire and Chanfuta had the largest mean DBH, while Eucalyptus the largest mean height. At tree level, Jambire had the highest average total above-ground biomass and wood basic density, followed by Chanfuta, Umbila and Eucalyptus. However, the basic density of Jambire was not significantly different from of Chanfuta, but both were significantly higher than Umbila and Eucalyptus. Moreover, the basic density of Umbila is significantly higher than in Eucalyptus. The average moisture content expressed on a wet weight basis ranged from 49 to 52 % in indigenous species (Paper I) and was around 54% in Eucalyptus. In general, a very large range of values was found for the sampled trees (Table 3), suggesting high heterogeneity in their characteristics.

Table 3. *Mean and range values of diameter at breast height, commercial and total heights, total stem volume, total above-ground biomass, wood basic density and moisture content of the different species of trees sampled (standard deviation shown in brackets)*

Parameter		Chanfuta	Umbila	Jambire	Eucalyptus
Diameter at breast height, cm	Mean	33.8 (12.6)	27.0 (9.5)	34.8 (8.2)	22.1 (12.5)
	Range	13.5 – 61.1	14.0 – 46.5	21.0 – 52.2	7.3 – 50.0
Total height, m	Mean	17.0 (3.3)	11.3 (2.4)	16.3 (4.9)	23.0 (11.5)
	Range	9.5 – 22.1	6.5 – 14.8	7.3 – 25.8	7.3 – 43.9
Commercial height, m	Mean	9.1 (3.3)	5.1 (1.4)	9.7 (3.5)	14.6 (7.6)
	Range	4.4 – 14.8	3.0 – 8.5	5.1 – 18.8	2.1 – 28.2
Stem volume, m^3	Mean	0.9 (0.6)	0.4 (0.3)	0. 9 (.5)	0.6 (0.8)
	Range	0.2 – 2.5	0.1 – 1.2	0.2 – 1.7	0.01 – 3.0
Above-ground biomass, kg $tree^{-1}$	Mean	864	321	1016	308
	Range	107–2018	52–1121	411–2086	17–309
Wood basic density, kg m^{-3}	Mean	781	636	841	582
	Range	606 –952	500 –769	786 –889	452 –788
Moisture content, wt-% d.b.	Mean	51.5	49.3	50.5	54.2
	Range	29.8 – 86.4	40.0 – 57.7	27.8 – 80.8	21.4 – 65.0

Moreover, total dry weight and stem and branch dry weight increased with an increase in tree DBH for the trees sampled. In contrast, leaf dry weight of sampled indigenous species showed minimal variation in relation to DBH (Paper I) compared with Eucalyptus (Figure 8).

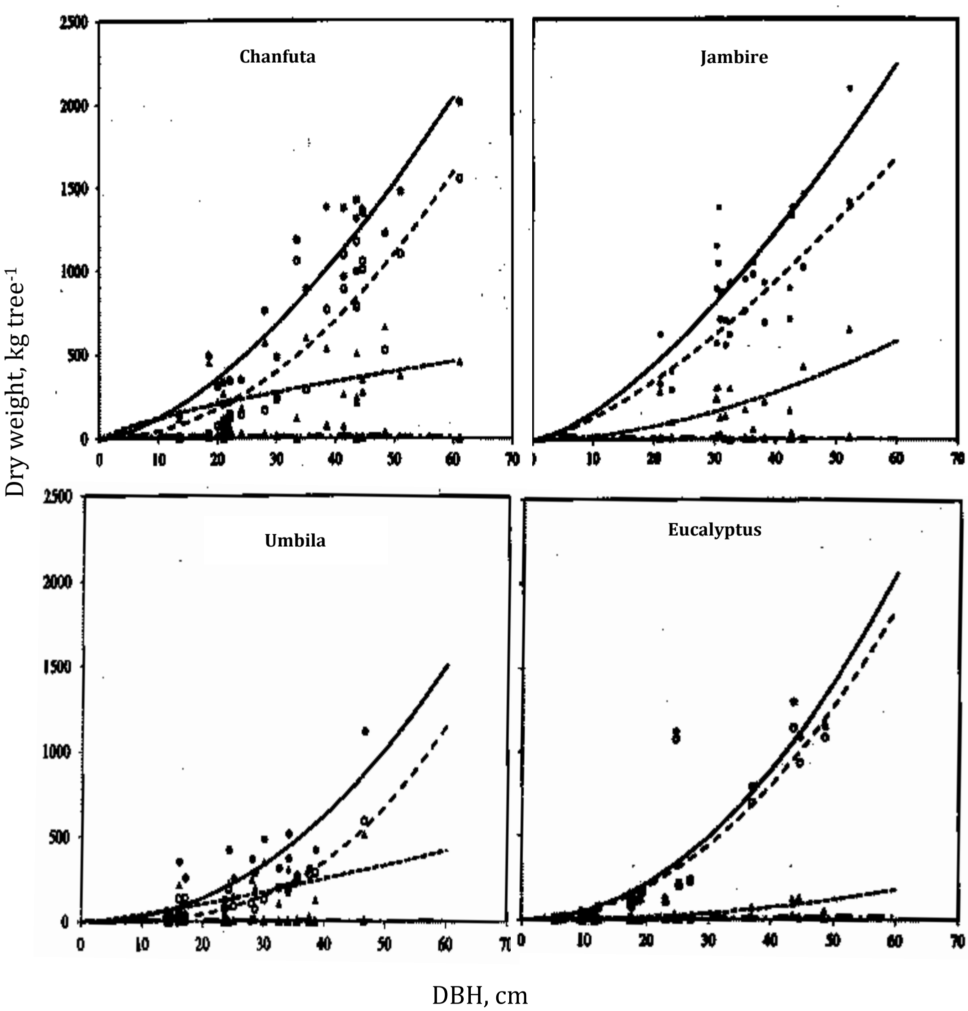

Figure 8. Total (—●), stem (– – - ○), branch (---▲) and leaf (— · △) dry weight (kg tree^{-1}) distribution as a function of diameter at breast height (DBH) for samples of the four species studied in Mozambique.

5.2 Above-ground biomass equations

Power equation 1 (Table 1), with only DBH as the explanatory variable, best fitted the biomass data (Table 4). A relatively high coefficient of determination (R^2) was obtained for total above-ground biomass and stem biomass (range 0.89-0.97). However, lower R^2 was found for branch and leaf biomass of the indigenous species (0.40-0.79) than for similar components of Eucalyptus

(0.87-0.96). Low average absolute bias (AAB) was obtained for branches and leaves, indicating that the fitted model performed well in terms of predicting total above-ground biomass and stem biomass. Larger differences in AAB and RSME were obtained for components of Chanfuta compared with other species, revealing large variations in error in the estimates obtained for the sampled trees. The best fit model for Eucalyptus had lower AAB and RMSE than the models for all other species. Statistical parameters for the three indigenous species and Eucalyptus are shown in Table 4.

Table 4. *Statistical parameters for the fitted above-ground biomass equation 1 for the four trees species studied: Chanfuta, Jambire, Umbila and Eucalyptus. AB = average bias, AAB = average absolute bias, R^{2} = coefficient of variation, RSME = root mean square error*

Components	Parameters	AB	AAB	R^2	RMSE
Chanfuta					
Total	$3.1256 \times D^{1.5833}$	−10.6	160	0.97	194
Stem	$0.4369 \times D^{2.0033}$	−20.0	172	0.91	228
Branches	$22.7577 \times D^{0.7335}$	−0.1	15	0.79	168
Leaves	$19.9625 \times D^{-0.0836}$	2.1	13	0.40	19
Jambire					
Total	$5.7332 \times D^{1.4567}$	49.5	250	0.95	257
Stem	$4.8782 \times D^{1.4266}$	43.5	218	0.94	220
Branches	$0.3587 \times D^{1.8091}$	10.3	91	0.78	142
Leaves	$77.0114 \times D^{-0.5511}$	−0.7	6	0.72	4
Umbila					
Total	$0.2201 \times D^{2.1574}$	9.6	104	0.89	141
Stem	$0.0083 \times D^{2.8923}$	−1.6	23	0.95	51
Branches	$2.3596 \times D^{1.2690}$	3.7	96	0.69	121
Leaves	$4.0400 \times D^{0.1680}$	0.0	3	0.71	5
Eucalyptus					
Total	$0.2195\times D^{2.2483}$	-9	59	0.95	95
Stem	$0.1491\times D^{2.3067}$	-7	49	0.95	79
Branches	$0.0880 \times D^{1.9472}$	-2	12	0.87	20
Leaves	$0.0072 \times D^{2.1696}$	0	1	0.96	2

5.3 Stem volume equations

Diameter and height together best explained the volume variation for all four species studied, with R^2 ranging from 90 to 95% (Table 5). The selected non-linear power equation 6 (Table 1) gave low AAB and the lowest AIC_c values for all species studied. Low positive absolute bias was obtained for all three indigenous species, indicating that the predictor equation slightly underestimated the stem volume (Paper II). For Eucalyptus low, negative absolute bias was found, suggesting slight overestimation of stem volume by the model (Paper III). A summary of estimated parameters for the best fit equations is provided in Table 5. Non-linear equations with DBH alone explained between 84 and 90 % of the variation in stem volume. However, higher error (RMSE) and bias (AAB) and higher AIC_c values were obtained for the indigenous species (Paper II) than for Eucalyptus (Table 5).

Table 5. *Estimated parameters for the best fit total stem volume equation (equation 6, see Table 1) for the four species studied. SE = standard error, R^2 = coefficient of variation, RSME = root mean square error, AB = average bias, AAB = average absolute bias, AIC_c = second-order variant Akaike information criterion*

Parameter		SE	R^2	RMSE (m^3)	AB (m^3)	AAB (m^3)	RMSE[1] (m^3)	AIC_c
Chanfuta								
β_0	0.120	0.102	0.95	0.124	0.004	0.095	0.126	-21.7
β_1	1.900E-4	2.300E-4						
β_2	2.160	0.295						
Jambire								
β_0	0.118	0.042	0.92	0.113	-0.019	0.098	0.114	-9.8
β_1	2.019E-6	3.00E-6						
β_2	2.738	0.380						
Umbila								
β_0	0.016	0.009	0.92	0.045	0.002	0.028	0.045	-71.1
β_1	3.470E-4	1.872E-4						
β_2	2.050	0.156						
Eucalyptus								
β_0	-0.002	0.002	0.90	0.312	-0.01	0.116	0.310	-70.9
β_1	8.000E-5	3.495 E-5						
β_2	1.718	0.141						

1) Cross-validation "leave-one-out" procedure

5.4 Biomass distribution and logging residues composition

On applying the biomass equations developed, differences were observed in terms of contribution of each species to the total biomass per unit area. The total above-ground biomass was estimated to be around 180.6 tons ha^{-1} dry weight, to which the three indigenous species together contributed 35.6 tons ha^{-1} (Paper I) and Eucalyptus 145 tons ha^{-1} (Paper III). There was a clear difference in the contribution of the different species to total above-ground biomass, with indigenous species making the lowest contribution per unit area. Of the indigenous species, Jambire was the greatest contributor to the total biomass per unit area and at tree level, while Umbila contributed the least

(Paper I). Differences were also observed in the allocation of above-ground biomass between different tree components (stems, branches and leaves). These differences influenced the quality characteristics of the logging residues (Paper III).

The residual stem contribution was found to be dependent on the stem timber quality, which defined the proportion of commercial height to total height (Papers II and III). The share of un-merchantable stem dry weight was 50% for both Chanfuta and Umbila, 30% for Jambire and 35% for Eucalyptus. The final share of total residues from the total tree biomass was 77% for Chanfuta, 83% for Umbila, 47% for Jambire and 38% for Eucalyptus. The stem component was the major constituent of logging residues from Chanfuta and from Eucalyptus. Jambire had similar contributions of stem and branches, while for Umbila branches contributed the most. The contribution of the leaf component ranged from 0.1 to 0.4 ton ha^{-1} for the indigenous species and 3.7 ton ha^{-1} for Eucalyptus (Figure 9). However, stem and branches are the major fractions of the final logging residue mix and their characteristics define the wood fuel quality of the logging residues (Paper III).

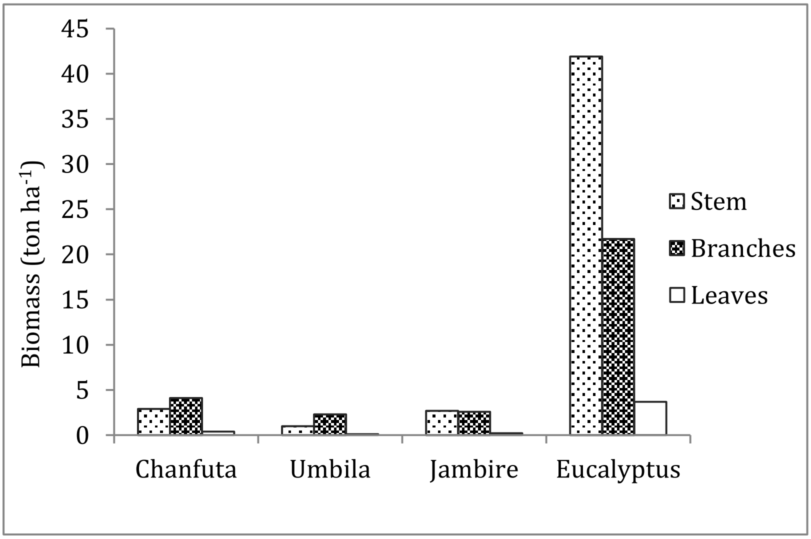

Figure 9. Proportion of individual tree components (stem, branches, leaves) in logging residues of the four species studied

5.5 Wood fuel quality properties

Analysis of the different tree components of the four species studied revealed some variations with regard to the main fuel quality parameters, *i.e.* HHV, ash content and moisture content (Paper III). However, it should be mentioned that the effect of geographic location of the sampled trees on the biomass properties was not significant ($P>0.05$).

5.5.1 Higher heating value

The average HHV of stem wood varied from 20.0 to 20.8 MJ kg^{-1} for the three indigenous species, while Eucalyptus had 18.4 MJ kg^{-1} (Figure 10). Results showed that the stem of Jambire had the highest HHV, followed by both Chanfuta and Umbila with similar values, and Eucalyptus which had significantly lower HHV. However, no significant difference was found between the HHV for branches from the four studied species, which varied between 18.8 to 19.8 MJ kg^{-1}. In the leaves component, the range for the average HHV was from 19.7 to 22.3 MJ kg^{-1}, and it was significantly higher in leaves of Chanfuta and Eucalyptus.

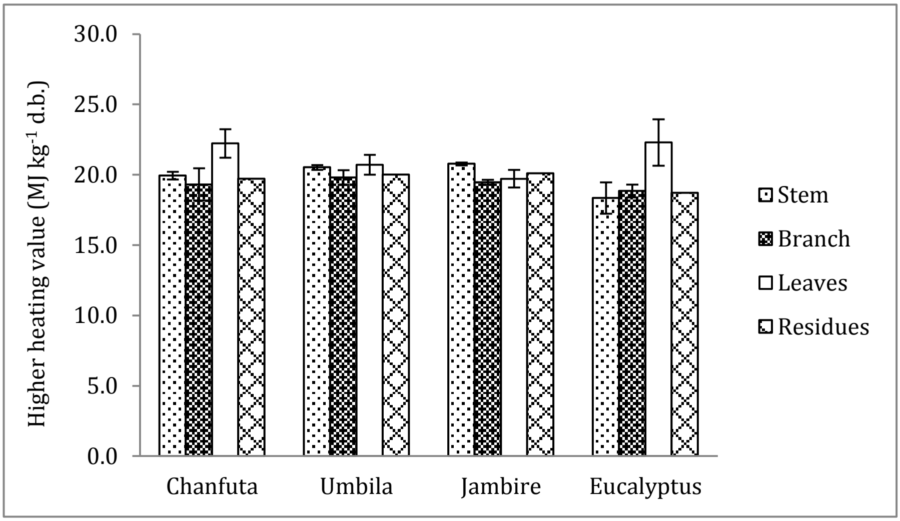

Figure 10. The higher heating values of the individual tree components (stem, branches and leaves) and logging residues from the indigenous and planted species studied. Bars indicate 95% level of confidence.

At species level, stems of Umbila and Eucalyptus had similar HHV as their branches, while the stems of Chanfuta and Jambire species had higher HHV compared to the branches. However, significant difference was only found between stem and branches of Jambire. The HHV of the leaves of Chanfuta was significantly different from Jambire, but not from Eucalyptus. For the logging residues, the weighted HHV varied from 18.7 to 20.1 MJ kg^{-1}, with Eucalyptus showing the lowest value.

More pronounced differences between the HHV of the components were observed when HHV was calculated on dry ash free basis ($HHV_{daf.}$), with pattern similar to that shown in Figure 10. In addition, the amount of carbon explained the variations in the $HHV_{daf.}$ (R^2 = 0.79). The leaves component had significantly higher HHV_{daf} compared with stem and branches of the same species. Moreover, the HHV_{daf} of leaves of Umbila were similar to Jambire, and not significantly different from Eucalyptus.

In Mozambique, based on the total availability and wood fuel quality around 84.5 PJ can be recovered from utilization of logging residues.

5.5.2 Moisture and ash content

The average moisture content of the tree components of the four species varied slightly, where it was 51% for the indigenous species and 54% for Eucalyptus. Large variations in moisture content were observed in the leaf component in all species except for Umbila (Paper III).

With regard to ash content, all the indigenous species had similar trend with the stem component showing values ranging from 0.8 to 3.1%, followed by branches (2.5 to 5.3%) and leaves (6.4 to 10.8%). The branches of Eucalyptus had the lowest ash content (2.5%) compared to the stem (3.5%) and the leaves (5.5%). The lowest ash content (0.8%) was measured in the stem of Umbila, while the highest concentrations (9.8-10.8%) were obtained in the leaves of Jambire and Chanfuta. In general, the leaves component had the highest ash content compared to stem and branches of all the studied species. The stem and branches of Chanfuta and Jambire had higher ash content than Umbila. Moreover, stem wood of Chanfuta had the highest ash concentration among the indigenous species. Ash content in the branches of Umbila and Eucalyptus were significantly lower than that of Chanfuta and Jambire (Figure 11).

Considerable variations were measured within the samples of each component of Chanfuta trees as well as in the leaves of Umbila and Jambire and in the stems of Eucalyptus. For the logging residues fraction, a trend similar to that of the stem wood was clear in all the four species. The logging residues of Umbila had the lowest weighted average ash content (2.2%), which was less than half the value obtained for Chanfuta (4.7%). The ash content in logging residues of Jambire and Eucalyptus was 3.3%.

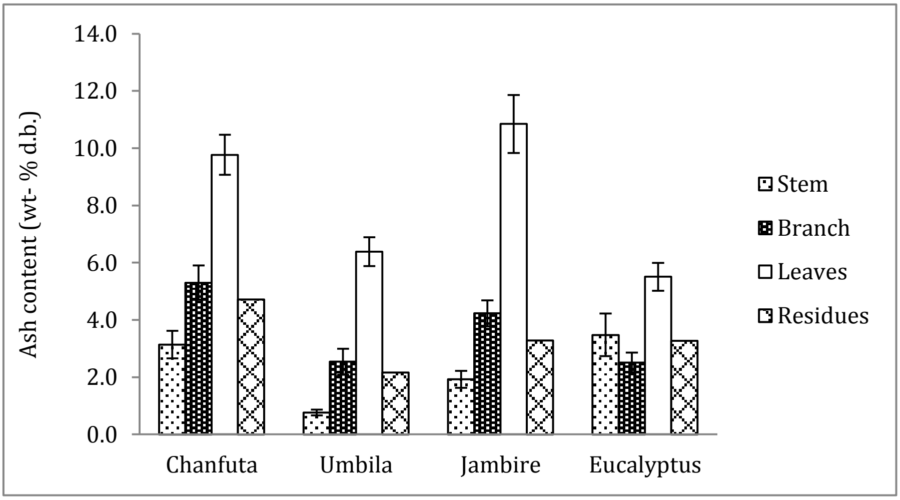

Figure 11. Ash content in different biomass fractions (stem, branches, leaves) and mixed logging residues of the indigenous and planted species studied. Bars indicate 95% level of confidence.

The composition of the minerals in the biomass and in ash of the studied species was dominated by calcium, followed by potassium and magnesium, chlorine (Cl), sodium, silicon (Si) and aluminium. However, all minerals were at very low concentrations, except for Cl in Eucalyptus (Paper III). Analysis of Si and Cl, which can influence the use of the biomass as fuel showed that their concentrations were higher in leaves compared to other components. The logging residues of Chanfuta had the highest Si content (0.17%) compared to other species, with leaves component containing (2.5%). The leaves of Eucalyptus had the highest Cl content (0.39%). In general, Cl contents in indigenous species were lower compared to Eucalyptus. The elemental composition of the studied wood fuels was typical for woody biomass (Paper III).

5.6 Fuel value index

Stem wood of all four species studied, regardless of the quality parameter used to calculate the FVI, showed a similar ranking to logging residues (Table 6). Stem wood of Umbila was ranked as the best fuel of the tree species, followed by Chanfuta, with Eucalyptus the least. With regard to FVI rank for the logging residues, the logging residues of Eucalyptus ranked better than those of Chanfuta.

Table 6. *Ranking of stem wood and logging residues (1 being the best) using the fuel value index (FVI) based on different parameters (HHV = higher heating value, M = moisture content, A = ash content, Bd = basic density). Tree species: Chan = Chanfuta; Umb = Umbila, Euc = Eucalyptus*

FVI	Parameters used	Stem wood			Logging residues		
		Chan	Umb	Euc	Chan	Umb	Euc
Eq.7	HHV, M, A	2	1	3	3	1	2
Eq.8	HHV & A	2	1	3	3	1	2
Eq.9	HHV, Bd, M, A	2	1	3			
Eq.10	Bd & A	2	1	3			

5.7 Climate impact of Eucalyptus-based pellets

The total global warming potential (GWP_{100}) associated with short-rotation coppice Eucalyptus feedstock upgraded to pellets was 9 kg CO_2-eq. GJ^{-1} pellets when used in Mozambique for electricity production and 12 kg CO_2-eq. GJ^{-1} when exported for use in a combined heat and power plant in Sweden (Figure 12). The fossil reference scenario with use of coal or natural gas resulted in high GWP of 107 and 70 kg CO_2-eq. GJ^{-1} fuel, respectively (Paper IV). Thus use of pellets resulted in much lower GWP compared with use of fossil fuels regardless of the end destination of the pellets (Mozambique or Sweden).

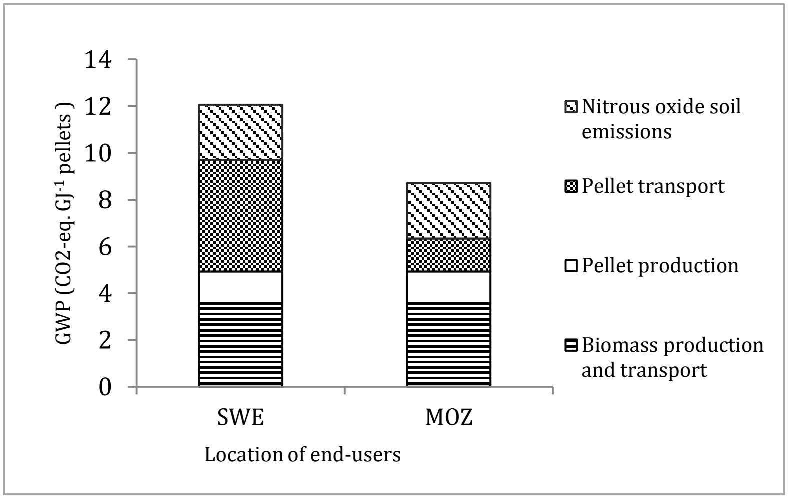

Figure 12. Global warming potential (GWP) from the different processes involved in production and transport of Eucalyptus-based pellets.

The temperature effects of the pellet systems due to GHG emissions associated to the production system differed depending on the end-use of the pellets, but with a continuous warming temperature effect increase over time (Paper IV). Comparatively, the temperature effect due to biogenic carbon fluxes from biomass and soil was the same regardless the final use of the pellets. The carbon stock in biomass increased from 10 Mg ha^{-1} to 36 Mg ha^{-1} at the first harvest (4 years) and 43 Mg ha^{-1} for subsequent harvests, while carbon stock in soil increased more or less regularly over time, from 45 Mg ha^{-1} to 58 Mg ha^{-1} at the end of the rotation period (Paper IV). An overall cooling effect on the temperature resulted from the increased carbon stocks in both soil and biomass. Removal and combustion of the vegetation before plantation establishment resulted in initial temperature warming effect in the pellet scenarios. The warming effect was higher for pellets delivered to and used in Sweden compared to when used in Mozambique (Paper IV).

Results showed that both pellet systems contributed to an initial cooling effect on the temperature, which declined over time (Figure 13). A longer cooling period (39 years) was observed when pellets were used in Mozambique compared to when delivered and used in Sweden (27 years). However, for the fossil fuel scenario, a continuous warming effect increase resulted during the whole period (50 years) regardless the end-use. Replacement of coal based electricity production by pellets contributed to larger temperature cooling effect than when natural gas was replaced (Paper IV).

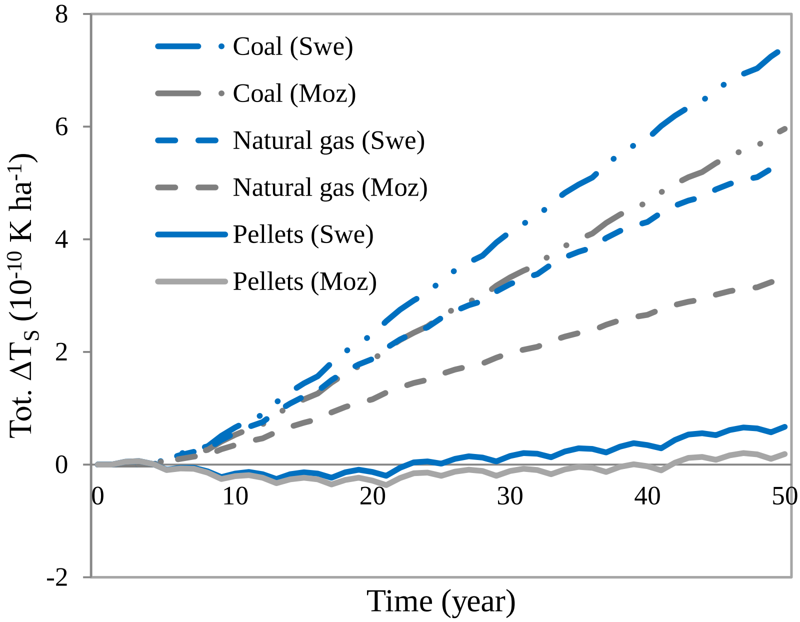

Figure 13. Comparative temperature effects (ΔT_S) of combustion of Eucalyptus pellets from 1 ha of plantation, comparing end use in Sweden (Swe) and Mozambique (Moz).

6 Discussion

To gain better knowledge of the potential of woody biomass as fuel, accurate estimation of available amounts and quality is crucial. In addition, assessment of the climate impact that could be associated with use of a feedstock provides a useful guide for the choice of energy source. The findings of the evaluations performed in this thesis are discussed below.

6.1 Biomass and stem volume estimates

In this thesis, results obtained by using developed equations showed that DBH alone explained the variation in above-ground biomass for the studied species. Similar biomass equations have been reported for other tropical and Eucalyptus species (Guedes, 2016; Chave *et al.*, 2005; Zianis & Mencuccini, 2004; Brown, 1997). Other studies have found that inclusion of wood basic density as a parameter improves the biomass prediction for tropical species and that inclusion of height improves the biomass prediction for Eucalyptus (Návar-Cháidez *et al.*, 2013; Zewdie *et al.*, 2009). In this thesis, when wood basic density was added to the models an increased coefficient of determination was obtained for total above-ground biomass estimates for the Umbila tree species (Paper I), but due to high average bias such models were not considered. In addition, determination of wood basic density requires use of destructive methods that are costly, laborious and time-consuming, which can limit the applicability of such models. The addition of tree height into the models improved the R^2 and reduced the errors of volume estimates for the four studied species. However, concerns have been raised regarding height measurement accuracy and the time investment required to obtain reliable data (Zewdie *et al.*, 2009; Kanime & Laamanen, 2002). In this thesis, inclusion of height was considered not to have an effect, as length of the stem was also directly measured from felled trees. Other possibilities to improve model predictions taking into consideration site-specific variables (*e.g*. precipitation, climate, soils) have been suggested by Henry *et al.* (2010). In the present thesis such assessments were not undertaken due to the low representation of sampled trees. However, use of DBH as the sole parameter proved to provide accurate estimates of the above-ground biomass for the studied species. Moreover, models with only DBH are easy to construct, DBH measurements can be made with high accuracy and the field measurements are practical and less time-consuming. However, low model stability has been reported for short-lived branches and leaves of other tropical species (Navar, 2009), a finding confirmed in this thesis. Sampling of biomass during the dry season (August-October) is recommended to minimise the variation in tree components (Chidumayo, 1990). However, due to logistical limitations, data collection for indigenous species in this thesis was performed during the rainy season in Sofala province (December 2012) and the dry season in Inhambane province (April 2013). As a result of seasonal variation, a wide range was obtained in the estimates produced. In contrast to the approach used for indigenous species, sampling for Eucalyptus was performed during the wet season, a period of peak foliage, which reduced the variations between sampled trees.

In the present thesis, use of Hohenadl's relative height positions (Heger, 1965) with several diameter measurements along the stem length led to reliable total stem and residual stem volumes. The relative height method proved to be suitable also for multi-branched crowns, but was laborious, time-consuming and required complex logistics. Combined DBH and height together explained the variation in stem volume data of the studied species (Papers II and III). The selected stem volume model is consistent with findings of previous studies for tropical species (Khan & Faruque, 2010; Brown *et al.*, 1989) and Eucalyptus spp. (Zianis *et al.*, 2005). Different results can be achieved depending on parameters considered (Burnham & Anderson, 2002). In this thesis, considering the AAB (Parresol *et al.*, 1987) and AICc (Hurvich & Tsai, 1989) a similar best candidate stem volume model was obtained as when solely the AICc was considered. The AICc accounts for both model errors and complexity (Chave et al., 2005). Therefore, in this thesis the AICc was considered to be sufficient to support the model selection. The developed stem volume model predicted more accurately the stem volume than the commonly used generic equation for indigenous species in Mozambique as recommended by Marzoli (2007).

The equations developed have the advantage of being species-specific. Species-specific volume estimates are crucial for sustainable utilization and planning of existing volume stock for specific uses (Geldenhuys, 1990). Considering the sampling location, the equations developed for the indigenous species Chanfuta and Umbila can be regarded as species-specific, while for Jambire and Eucalyptus they are species-site-specific. However, it has been reported that absence of species-specific allometric models is one of the major sources of uncertainty in timber and carbon stock estimates for tropical forests in Africa (Guendehou *et al.*, 2012). The provided species-specific biomass and stem volume equations in this thesis contributes to a possibility to reduce the limitation of prediction of biomass by only using stem volume, disregarding the biomass of the crown component and the un-merchantable stem part. The estimates provided in this thesis should be regarded as an indicator of the conditions encountered at the studied sites and of the nature of the different tree species.

6.2 Assessment of wood fuel potentials

Through applying the equations developed, it was found that the contribution of the indigenous species to total amount of logging residues was 16 ton ha^{-1} compared with 67 ton ha^{-1} for Eucalyptus species. Stand density was found to determine the amount of biomass and logging residues for the studied species. Chanfuta, Umbila and Jambire species represented 155 trees out of 1116 surveyed trees in the studied stands. Moreover, the low density of the studied stands was due to the fact that that stands have been harvested earlier and were composed mainly by smaller diameter trees. On the other hand, the three indigenous species account for 12.3 million m^3 out of 1.74 billion m^3 total available timber stock in Mozambique (Marzoli, 2007). Low density of valuable timber species is also a common feature of miombo woodlands (Dewees *et al.*, 2011). These is also the case of Mozambique where value timber species account for only 7% of the total standing wood volume (Marzoli, 2007). The Eucalyptus stands studied had high density (778 stems ha^{-1}) compared with the 250 stems ha^{-1} expected in mature stands grown for the purpose of timber production (Orwa *et al.* (2009). Limited thinning has been performed in the Eucalyptus stands since their planting (A. Esequias, pers. comm. December 2014), which explains the high density.

It was also found that stem and branch fractions were the major contributors to the total amount of logging residues for the four studied species, but differences were found in how much each fractions contributed between the studied species depending on site condition and stem timber quality. Branches were the major contributors for Chanfuta and Umbila and stems for Eucalyptus. For Jambire, an equal proportion was obtained from stem and branches. According to previous studies by Geldenhuys and Golding (2008) miombo woodland species allocate around 50% of their biomass to the crown part (branches, twigs and leaves). However, competition for light and space is reported to limit the development of large branches more in dense forest than in open and shrub forest types (Segura & Kanninen, 2005). These findings were confirmed in this thesis, where Chanfuta and Umbila sampled in open forests had more branches contribution compared to Jambire sampled in dense deciduous forests. The high stem density in Eucalyptus stands resulted in less branch biomass obtained. Regarding the stem timber quality it was found that un-merchantable stem volume ranged from 30-50% for the studied species. Similar range values (32-70%) have been reported for tropical species in Mozambique and elsewhere as result of inefficient felling methods and obsolete machinery deployed during logging operations (FAO, 2008; Fath, 2001; Eshun, 2000). For plantation forests large proportion of logging residues 38% was estimated in this thesis compared to 10 to 20% reported elsewhere (FAO, 2008). From this thesis, it can be concluded that site conditions and stem timber quality are important factors that define the potential amount of logging residues. Based on the above-mentioned factors and available stand stock in Mozambique, apart from Eucalyptus, the Umbila species are likely to contribute more to the logging residue resource among the indigenous species. Umbila species represented an average of 20% of the harvested timber volume during 1998 to 2013 and 25% up to March 2016 (DNAF, 2016). In addition, Umbila species represented the largest standing volume stock and had the largest dry weight of branch component. Consequently, Umbila offered the largest proportion of logging residues per tree (83%) and had the best fuel quality among all the studied species.

6.3 Wood fuel quality characteristics

HHV is one of the most important parameters used to compare different species as fuel since it provides the amount of energy that could be recovered from specific biomass. Based on their HHV, it could be stated that Jambire and Umbila were better wood fuels than Chanfuta and Eucalyptus feedstocks. The HHV values obtained for stem wood of the studied species were comparable to values reported for similar species (Cuvilas *et al.*, 2014; Obernberger *et al.*, 2006). Contents of lignin and extractives in biomass are known to influence the HHV (White, 1987). Extractives concentrations as high as 15% in some tropical species were reported (Zhang *et al.*, 2007), while Eucalyptus species were reported to contain between 2.7 to 7.6% (Morais & Pereira, 2012; Gominho *et al.*, 2001). Lignin content in Eucalyptus was reported to be around 29.8%, which is lower than the average value (33.8%) for indigenous species in Mozambique (Cuvilas et al., 2014; Dutt & Tyagi, 2011). These reported lignin and extractives contents can explain the high HHV found in the indigenous species.

In general, the leaves component had high HHV compared to stem and branches. This could partly be explained by the highest content of extractives which influences positively the HHV (Yang & Jaakkola, 2011; White, 1987). However, the high HHV in leaves of Chanfuta and Eucalyptus can likely be explained by their high carbon content. Another possible reason for variations in HHV is the ash content in the biomass which affects the HHV negatively. However, comparing the HHV calculated on ash free basis did not explain the obtained results. Our results showed that leaves of all the studied species contained the highest ash content compared to the other components, which could be related to the high Si concentration in this component. The ash content in the logging residues of the studied species, except for Umbila, were higher than 3%, which is the maximal allowed concentration according to the standard ISO 17225-4:2014 (ISO, 2014). Earlier reported study showed similar ash content for Umbila, but lower ash content in stems of Chanfuta and Jambire (Cuvilas *et al.*, 2014). Ash content in stem of Eucalyptus was higher than previously reported (Dutt & Tyagi, 2011). Based on the findings of this thesis, measures to reduce the ash content in Chanfuta and Eucalyptus should be considered to improve their fuel quality. During the collection of logging residues, the material is usually exposed to potential contamination with soil and sand during collection, handling and storage in the field, which can increase ash contents in the material.

Other important characteristic of a fuel is moisture content, as high moisture content lowers the net energy content, increases operational costs and emissions during combustion (Van Loo & Koppejan, 2008). The samples were collected in both wet (Sofala and Manica) and dry (Inhambane) climate conditions. However, the variations in moisture content between and within the different species were not significant. The moisture contents were within the ranges reported for woody biomass (Vassilev *et al.*, 2010). Natural air drying commonly facilitates reduction of moisture content in harvested biomass and can also lead to detachment of leaves component. The duration of rainy seasons varies from December to April (Inhambane and Sofala) and November April (Manica). Felling activities in natural forests, are not allowed during these period to enable tree regrowth (GoM, 2012) and activities are planned accordingly. Storage of biomass should be considered to ensure continuous supply as it is already practised for timber production. Therefore, air drying can be an option in Mozambique, thus reducing operational costs. Drying can result in higher HHV and lower ash content, due to leaves detachment, but it leads to biomass loss. On the other hand, this loss will contribute to soil nutrient recycling.

Fuel quality parameters showed to be interconnected, therefore, calculation of FVI in which these parameters were considered showed that stem wood and logging residues of Umbila were a better fuel than Eucalyptus feedstock. A similar ranking for stem wood of indigenous species has been reported in earlier studies (Cuvilas et al., 2014). Studies focusing on quality properties of Eucalyptus growing in Mozambique are scarce and therefore no comparison is possible. In contrast, logging residues of Eucalyptus ranked as better fuel compared to Chanfuta, which was the opposite to the results obtained for its stem wood. The relatively high moisture and ash content in Chanfuta stem and branches which are the major components in the logging residues justifies the obtained rank. Therefore, considering the fact that HHV and ash provided the same ranking as when all parameters (HHV, wood basic density, moisture content, ash content) were considered, it was concluded that HHV and ash content showed to give sufficient basis for fuel ranking.

It was found that components of indigenous species had threefold the amount of nitrogen present in Eucalyptus. A recent study showed that the nitrogen content was higher in soils where Eucalyptus plantations were established compared with in soils under natural miombo forest (Guedes, 2016). Miombo woodland soils where the studied indigenous species grow are characterized by low nitrogen content (Frost, 1996). In addition, the mineral content in the studied feedstocks was low, except the high content of chlorine in Eucalyptus biomass. Therefore, considering the low concentrations of heavy metals reported for the indigenous species in Mozambique (Cuvilas *et al.*, 2014) and poor soil quality (Frost, 1996), ash recycling can contribute to improve the soil quality in miombo forests.

The majority of the values obtained in this thesis for chemical composition and wood fuel quality of the four species studied were within the range of values for woody biomass reported in earlier studies (Vassilev *et al.*, 2010; Obernberger *et al.*, 2006). Differences in chemical composition are reported to exist between tree components and species (Nguyen *et al.*, 2016). However, the differences found in this thesis were generally not statistically significant, particularly between stem and branches. In addition, few and un-even number of samples of the indigenous species per site limited the assessment of geographical location effect on the chemical composition. The reasons behind the limited number of samples include the restrictions set by forests companies, practical difficulties and limited project resources. The scattered locations of sampling plots with limited road infrastructure hindered the accessibility to the plots. In addition, only a small number of selected species were found in the plots because of harvesting operations.

Results of performed assessment showed a potential to recover up to 84.5 PJ from utilization of logging residues in Mozambique. However, an earlier study reported a potential of 2.7 PJ (Batidzirai *et al.* (2006). Differences in the estimates could partly be explained by differences in methodology used in the two studies as well as consideration of the crown biomass in our study. However, the estimated biomass potential availability should be regarded as representing the theoretical recoverability and further research is needed to define the actual recoverability rate by accounting for the technical, ecological and social implications of logging residue extraction.

6.4 Climate benefits of Eucalyptus pellets used for energy production

Use of LCA methodology to assess climate impacts of alternative bioenergy systems is very limited in Mozambique. Therefore, an attempt was made and results showed that use of SRC Eucalyptus pellets for electricity production in Mozambique resulted in lower GWP compared to when pellets were delivered and used in Sweden. With regard to GWP associated with export of pellets, results obtained were consistent with reported values in earlier studies (Batidzirai *et al.*, 2014; Magelli *et al.*, 2009). It was also shown that local use of pellets in Mozambique resulted in a longer temperature cooling effect than when delivered to Sweden, due to transport distance and differences in assumption related to energy use in the system. Both pellet systems showed to be more beneficial from a climate perspective than the fossil fuels which are being considered as potential options to diversify electricity production in Mozambique. However, for the Swedish scenario, the difference in efficiency of pellets compared to fossil reference in a CHP was small leading to larger climate benefit. The low conversion efficiency of the pellets in a power plant would require more biomass to produce similar amount as the fossil fuels. With regard to carbon fluxes, results indicated an increase on carbon stocks in soil and biomass associated with the SRC Eucalyptus plantation. A similar trend in carbon fluxes in Eucalyptus plantations was recently reported (Guedes, 2016).

Factors such as population growth, demand for food, crop yields, natural forest growth and wood production from plantations are among the key factors that determine the potential of bioenergy production (Smeets et al., 2004). Land use changes related to establishment of large plantations of dedicated energy crops are highly debated. In the present assessment, land was assumed to be available and therefore no land use impacts were considered (Paper III). On other hand, around 80% of Mozambican population rely on the forests for their livelihood. Existing studies have reported that increased population, urbanisation, agricultural expansion, conservation and other needs can increase the pressure on the remaining land in Mozambique (Sitoe *et al.*, 2012; Overbeek, 2010). Therefore, the above mentioned factors, along with increased attractiveness of bioenergy markets may further increase pressure on land, and indirect land use changes may occur. Indirect land use changes from biofuel feedstocks production have been reported to be associated with large climate impact (Tilman *et al.*, 2009). Therefore, it could be interesting to study the impacts of land use changes, as there was an increase in forest plantation investment projects in the past years in Mozambique.

6.5 Possibilities of wood fuels utilization

The potential availability and wood fuel quality were evaluated. However, questions related to reliability of biomass supply, accessibility as well as technical, ecological or economic restrictions need to be addressed. The logging residues from natural forests showed to be geographically scattered and at low stand density, which may negatively affect their availability and reliability as well as challenge efficient logistics. Assessment of possibilities of integration of logging residues extraction in the current timber harvesting systems can contribute to lowering the operational costs and create opportunities for income diversification. Other factors such as changes in timber species demand result in different composition of potential sources of logging residues affecting the reliability on biomass from some species. Use of logging residues from timber harvesting operations for energy purpose is defined in the article 24(1) of the Mozambican forest regulation (GoM, 2002), but not yet applied. Limited market, lack of technical guidelines, tracking and verification systems to avoid whole tree felling of valuable species, limited resource and technical capacity for monitoring by forest authorities are among potential reasons. The use of logging residues can probably be applicable in short term for biomass supply for household domestic use, drying of wood in sawmills, of ceramics and tobacco, which are the major consumers of fuelwoods. Consideration of establishment of community based enterprise specialized in collection and handling and trade of logging residues can create self-employment opportunities and serve as an incentive to local people to participate in forest management, which today is still limited in the country. In addition, removal of logging residues may also be regarded as management practice, as it prevents excessive biomass accumulation that may contribute to occurrence of natural forest fires, which threaten species diversity of miombo woodlands.

Logging residues can also be obtained from mature plantations. Possibility for whole tree harvest also increases the potential availability of biomass from planted forests. For SRC Eucalyptus, climate conditions, technical production system and choice of species could be the most influencing factors and can be easily accounted for when establishing the plantations. It was concluded that Eucalyptus plantation has great potential for biomass supply, but the feedstock was ranked as the lowest quality fuel. Upgrading to briquettes and pellets can improve the fuel quality properties of the Eucalyptus feedstock. To further explore the existing potential, the possibility of upgrading to pellets was considered as an option for fuel homogeneous in size, with high energy density, easy to store, handle and transport. It should be pointed out that use of wood pellets is not currently practised in Mozambique. Pellets are not yet traded in the country and a conversion system not available today. However, great acceptability of wood pellets for household cooking in Mozambique has been reported (Tabrizi, 2014; Vesterberg, 2014). In order to attract the major consumers of fuelwoods, the pellets and its conversion technology should be economically accessible. Use of pellets from well-managed forests can help to reduce the negative impacts of fuelwood extraction in Mozambique. In addition, pellets are products of high demand especially in Europe to meet the 2020 environmental target with regard to reduction of greenhouse emissions and increase share of energy from renewable energy sources. Therefore, pellets have the potential for both small and large-scale applications, which can allow a shift to more efficient energy fuels and diversification of renewable electricity sources, which can lead to improved security of electricity supply limited today. In addition, use of pellets can as well allow increasing the country’s revenue from pellets and electricity exports.

7 Conclusions

Species-specific equations for predicting the above-ground biomass and stem volume of three of Mozambique's most valuable native tree species (Chanfuta, Jambire and Umbila) and one widely planted species (eucalyptus) were developed. These equations represent a valuable novel contribution of the thesis work, since apart from allowing estimation of total biomass available for energy, they can also be used to predict merchantable volumes, estimate the national forest resource and carbon stocks, and thus support development of appropriate management strategies. However, the estimates of actual available amounts of logging residues should account for technical, ecological and economic restrictions before utilization of logging residues is considered. Logging residues represent potential biomass source with good fuel properties as far as quality is concerned. The main conclusions of this thesis work were:

- Diameter at breast height was the best predictor of above-ground biomass, and both diameter and height best predicted the total stem volume for all species studied.
- Biomass allocation differed between the species studied. The stem fraction was found to be the major contributor to total above-ground tree biomass for Chanfuta, Jambire and Eucalyptus, while branches were the main contributor for Umbila.
- Umbila can be a high quality, potential energy source of logging residues among the indigenous species. On the other hand Eucalyptus had the lowest fuel quality but the e largest amount of logging residue compared to other species.
- LCA analysis showed that using wood pellets for energy production in Mozambique resulted in less emissions connected with pellet transport compared to when pellets are exported and used in Sweden.

- Both pellet scenarios contributed to less global warming than the reference scenario using fossil fuels. This indicates that SRC of Eucalyptus has a potential to contribute to mitigation of climate impacts associated with the use of fossil fuels.
- The potential availability of logging residues can be affected by the abundance of the target species in the stands, the share of un-merchantable stem and the proportion of the crown biomass.

8 Future research

Different factors influence the use wood biomass as fuel. Availability and acceptable fuel quality are some of the aspects to be dealt with when use of wood fuel is intended. Issues such as geographic location, accessibility, security of supply or other logistical problems may pose challenges for the use of logging residues as fuel. Some of the major concern that needs to be addressed to the future research may include:

- Assessment of the potentials from existing variability of trees species including non-timber species, discarded logs during felling and sawmill processing.
- Development of guidelines for logging residues uses based on the technical, ecological or economic restrictions. It should also include the institutional arrangements that can support the implementation.
- Assessment of the feasible logistics chains for logging residues and identification of strategies to integrate it with timber production.

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