TREES AND WOODLOTS IN RWANDA AND THEIR ROLE IN FUELWOOD SUPPLY

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This thesis is dedicated to my wife and sons

Abstract

Trees and woodlots on farms are prominent features of agricultural landscapes worldwide. For developing countries such as Rwanda where fuelwood is the main sources of energy for cooking, the contribution to total energy supply is important. However, little is known about their role in meeting the household demands of fuelwood under conditions of high population density, small forest cover per capita, heavy reliance on forests for fuelwood, and subsistence farming. The main focus of this study was to quantify the role of trees and woodlots on farms in fuelwood supply in Rwanda, by analysing the fuelwood demand and supply, identifying the determinants of the farmer's choice of fuelwood sources and the reasons why and when farmers are keeping trees and woodlots on their farms. Biomass stocks on individual farms and in the agricultural landscape were assessed, and the contribution of woody biomass on agricultural land to fuelwood supply was determined. The study showed that households with higher socio-economic status obtained fuelwood from their farms and markets rather than collecting it from nearby forests. Indeed, many trees and woodlots were mainly kept for economic benefits, including fuelwood. The household decision to have trees and woodlots on farms in three altitude regions was affected by different sets of socio-economic and location variables, implying that interventions to promote tree and woodlots must be region specific to account for the socio-economic and biophysical environments. The woody biomass survey on the agricultural land indicated that about 80 % of total standing biomass in trees and woodlots was useable biomass for fuelwood. It was estimated that for Rwanda, the amount of fuelwood on agricultural land

was higher than in forest plantations. Increasing sustainable woody biomass production on farms could potentially meet the fuelwood demands by the households; even a surplus is possible in the future. This, however, is only achievable if sustainable tree and woodlot management are promoted and implemented, and the socio-economic and policy environments improved.

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Chapter 1 General Introduction

1.1 Background

Woody sources account for a large share of all biomass used globally for energy. The overwhelming majority of the consumption of biomass energy is based on the use of firewood and charcoal in developing countries. According to FAO (2010a), fuelwood and charcoal account for 74 % of energy consumed globally, nearly all of which is used for cooking and heating in developing countries. The remaining proportion of energy is used in industrialized countries for industrial applications and for the heating purposes of the private sector (Heinimö *et al.* (2007).

The majority of households in the developing countries rely on biomass for cooking; the share is highest in sub-Saharan Africa, at 76 % (IEA 2009). Many households in Africa, South and East Asia use energy from a combination of fuelwood, crop residues and dung (Fig.1-1). The reasons for doing so include cultural preferences, availability and economic factors (Sanchez 2010). In the developing countries, fuelwood is estimated to account for 80 to 100 % of biomass use, although the percentage is lower in East and South Asia, where the use of agricultural residues is 0.3 and 0.08 billion m^3, espectively (Fig. 1-1).

In urban areas of many sub-Saharan African countries, the majority of the households continue to use biofuels at least for certain functions such as food cooking (Karekezi and Majoro 2002). The heavy reliance on biofuel in Africa is attributed to both the lack of accessible and affordable alternative energy sources as well as poverty (e.g. Leach and Mearns 1988, Benjaminsen 1997, Dovie et al. 2004). For instance, the high costs of electricity and liquid petroleum gas (LPG) become too prohibitive and force many households to burn large amounts of biofuel, which leads to pressure on the environment.

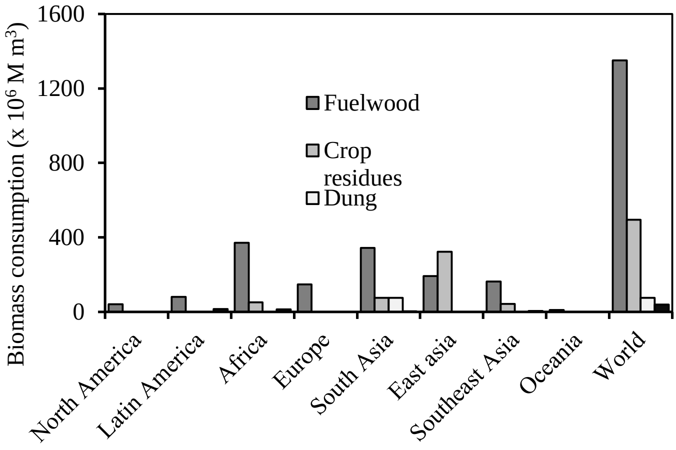

Fig. 1-1 Estimated biomass consumption, by region (Source: Fernandes et al. 2007)

Consumption of fuelwood and charcoal by urban households in sub-Saharan Africa is reported to contribute to deforestation, forest degradation, and land degradation (Hoster and Milukas 1992, Mekonnen and Köhlin 2009). This is partly because these fuels are an important source of cash income for people in both urban and rural areas. The rural consumption of crop residues and dung as alternative to fuelwood implies a reduced re-integration of residues' nutrients into the soils, thus contributing to land degradation and consequent reduction in agricultural productivity (e.g. Stoorvogel et al. 1993, Lal 2005, Fixen 2007).

Forests are the most important sources of woodfuel. The total world forest area is estimated at 3.9 billion ha of which 16 % is found in Africa and about 50% is located in South and Central America and Europe (FAO 2011).

Planted forests account for 7 % of the global forest area or about 264 million ha. The share of trees outside forests smaller than 0.5 ha, and dispersed trees in the landscapes has not been quantified, so they are not included in the Global Forest Resource Assessment by FAO although a considerable share of wood resources is derived from them. Failure to include this resources into forest inventories results in the underestimation of the importance of tree resources outside forests, such as wood production, the conservation of biodiversity and the reduction of the greenhouse gas emission from the atmosphere. For instance, agroforestry in Sub-Saharan Africa is able to keep 8 to 54 Pg C out of the atmosphere through accumulation of carbon in woody biomass and soil, through reduced deforestation of forests, and through production of wood for fuel as a substitute for fossil fuel (Unruh et al. 1993).

Rwanda is one of the countries where the inventory and the assessment of trees outside forests have not been comprehensively carried out despite the relevance of trees on farms for woodfuel. Most of the fuelwood is reported to come from forests, with some from the agroforestry systems. There is evidence that fuelwood collection is done in existing forests plantations by the rural people (ISAR and MINITERE 2008) but the amounts of fuelwood collected is not recorded anywhere.

Removal of fuelwood from Rwandan forests is considered as an illegal activity, forbidden by forest laws and regulations. From the late 1970’s, many forestry programmes and projects operate in Rwanda in order to counterbalance the demand and supply gap of wood, mainly fuelwood. The government strategies for addressing fuelwood scarcity include (MININFRA 2004a, MINIFOM 2010) : (1) increasing the supply through investments in woody biomass production in forest plantations and agroforestry systems , (2) reducing the demand by increasing the technical efficiency of utilisation through the introduction of improved stoves, and (3) promoting alternative sources of energy including electricity, biogas, solar energy and peat. However, these efforts and restrictions do not deter households from collecting fuelwood from forests, possibly due to limited fuelwood collection options or weak enforcement of forests regulations, especially on planted forests.

In principle agroforestry systems play a role in the supply of wood and non-wood products. The combination of agricultural crops with trees brings substantial amounts of fuelwood, though widely neglected in many fuelwood studies. For example, in Kenya, as much as 47 % of the fuelwood is produced on agricultural land (Lundgren and van Gelder 1983, Bradley 1988). It was also observed that planted woody biomass accounted for 65 % of the total wood production in the high and medium potential areas of Kenya (Holmgren et al. 1994). There is reason to believe that even in the Rwanda case a large proportion of the fuelwood is taken from croplands rather than from forests, but this needs to be verified.

About 60% of the total land area of Rwanda is cultivated (MINITERE 2004) and forests occupy only about 11 % of the national territory (CGIS-NUR and MINITERE 2008). Agricultural lands therefore represent potential areas for the integrated production of food, livestock and wood products. In order to maximise the benefits from this integrated system, the competition between energy production and agriculture must be minimised in the broad context of agricultural intensification through the use of improved seeds, fertilisers and technological improvements. Successful plans for increasing agricultural production and fuelwood production require information on the current status of agroforestry systems and the extent to which they are capable of meeting farmers' energy needs for cooking.

Currently, smallholder farmers in Rwanda have planted a variety of trees and shrubs for different uses as firewood, building poles, fodder, medicine and other wood products (Den Biggelaar 1996). Agroforestry provide many other benefits including carbon sequestration and biodiversity conservation (Acharya 2006, Garrity and Stapleton 2011). The use of fast growing multipurpose tree species rapidly sequester carbon, prevent soil erosion, help restore degraded lands, serve as a source of energy, and can be the raw material for various marketable products. It is estimated that for smallholder agroforestry systems in the tropics, the potential C sequestration rates range between 1.5 to 3.5 Mg C ha^{-1} $year^{-1}$ and also have an indirect effect on C sequestration by helping decrease pressure to convert natural forests, which are large sinks of terrestrial C (Montagnini and Nair 2004).

While there are documented social, economic, and environmental benefits of agroforestry, it is important to understand the challenges for fuelwood and agricultural production in leading to poverty alleviation for smallholder farmers in Rwanda. Programs that promote the alleviation of poverty through scaling out the impact of new technologies constitute a major component of rural development efforts (Lipper and Cavatassi 2004). Despite the positive effects of these programmes, the adoption of new technologies, such as agroforestry, remains low. Many socio-economic studies have determined the motivations of farmer choice to plant trees on farms (e.g.

Place and Dewees 1999, Salam et al. 2000, Mahapatra and Mitchell 2001) and have stressed the factors that enhance the adoption of agroforestry technologies (e.g. Scherr 1995, Franzel 1999, Franzel et al. 2001). However, these factors are region-specific, since they apply to particular socio-economic and environmental conditions in a particular region. To this end, the development of agroforestry needs to be responsive to the socio-economic conditions of the agricultural households and to the characteristics of the physical environment.

1.2 Rwanda profile, socio-economic indicators and land use systems

The Republic of Rwanda, in East and Central Africa, in one of the smallest countries in the world, covering an area of 26 338 km^2 of which 1670 km^2 is occupied by water. It borders Burundi in the South, Uganda in the North, Tanzania in the East and the Democratic Republic of Congo in the West. On administrative basis, Rwanda comprises four administrative provinces and the city of Kigali, further subdivided into 30 districts, and then into 416 sectors, and again into 2148 cells. Figure 1-2 shows the geographical location of Rwanda, its administrative Provinces and districts.

Rwanda is ranked the 77th country in the world by its population size, estimated at 10.7 million in July 2011 (NISR 2012a), corresponding to 0.15 % of the world population. The average population density is 384 people km^{-2}, which is one of the highest in the world. The population density per area of arable land is even higher, over 500 people km^{-2} (UNDP and UNEP 2006).

Despite its small size, Rwanda is endowed with a variety of topography, soils, biodiversity and ecological regions. Rwanda is a hilly country with altitudes less than 1500 m in the eastern plateau but rising to between 1500 and 2000 m in the central plateau area and higher in the West and North.

Fig. 1-2 Location, administrative provinces, and districts of Rwanda

The following physico-geographic regions are distinguished, moving from West to East (Sirven et al. 1974): (1) the Congo-Nile Crest, nowhere less than 2000 m in altitude, with peaks rising to between 2400 in the south and 3000 m in the north; it culminates on the north western border in Mt. Karisimbi (4507 m) in the Virunga group of high volcanoes; (2) the Central Plateau, within the altitudinal range of 1500 m and 2000 m, characterises the centre of the country where occurs a mosaic of hills with rounded tops, separated by large swamps; (3) the Eastern Plateau, fairly flat and homogenous, abounding in lakes and swamps, with elevations varying from 1000 to 1500 m; it extends from Kigali to the border with the Republic of Tanzania.

Rwanda has a tropical climate with an average annual temperature of 18^0C and average rainfall of 1250 mm. There are two dry seasons, a short dry season from January to February and a long dry season from June to September, as well as two wet seasons, one from October to December and the other from March to May. Rainfall is heaviest in the west and decreases in the central uplands and to the north and east. Average annual precipitation in the capital Kigali is 1000 mm and average temperature ranges from 19^0C in January to 21^0C in July.

Agriculture is the major sector of growth of the Rwandan economy. It contributes about 36 % to GDP and 48 % to the country's total export earnings (World Bank 2011). Agricultural commodities, mainly tea and coffee, generate 70 to 90 % of total export revenues (Diao et al. 2009). The GDP per capita was estimated at US$ 1300 in 2011 (CIA 2012). A large percentage of the population depends on agriculture for its sustenance. Agriculture is the main source of income for 87 % of the population (MINAGRI 2006) and is done on 1.7 million ha or 75 % or of the total land area estimated at 2.3 million ha. The agriculture production system is based on small farms whose production is consumed by the owners at more than 80 % (Twagiramungu 2006). The average farm size by agriculture household is 0.76 ha at national level (NISR 2010), with the Eastern Province having comparatively large agricultural lands per household (Fig. 1-3). The cropping system consists of an association of crops mainly in the central plateau, and monocultures in the high altitudes regions. Six crops namely maize, cassava, beans, white potatoes, sweet potatoes and banana are cultivated by over 50% of the agricultural households in Rwanda and constitute the common staple food of the Rwandan population.

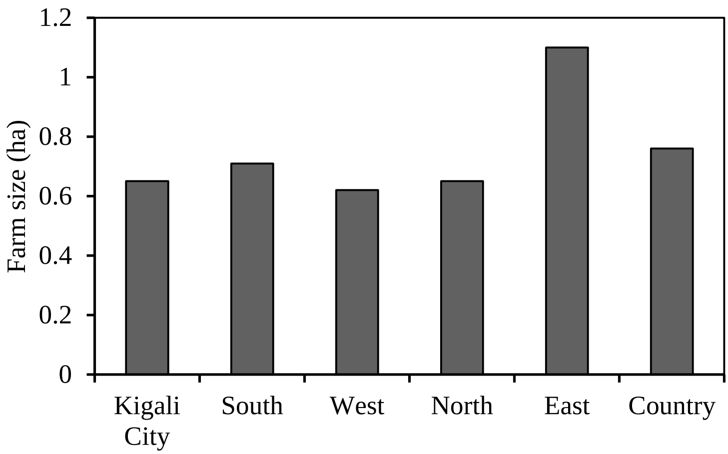

Fig. 1-3 Average farm size by agricultural household in the four provinces of Rwanda and Kigali City (Source: NISR 2010)

In 2007, Rwanda launched the Crop Intensification Programme that aims at increasing agricultural productivity in high potential food crops and ensuring food security and self-sufficiency (Kathiresan 2011). This programme focuses on six priority crops namely maize, wheat, rice, white potatoes, beans and cassava and is implemented in conjunction with the land consolidation programme which aims at joining farms in order to cultivate the best performing crop in specific areas.

Figure 1-4 shows the land use classification in Rwanda in 2007. Almost 75 % of rural land in Rwanda is used for growing crops and for livestock husbandry, while another 20 % is forested. The category "other land" refers to all the land that is neither agricultural nor forested, including built-up and related land and bare land.

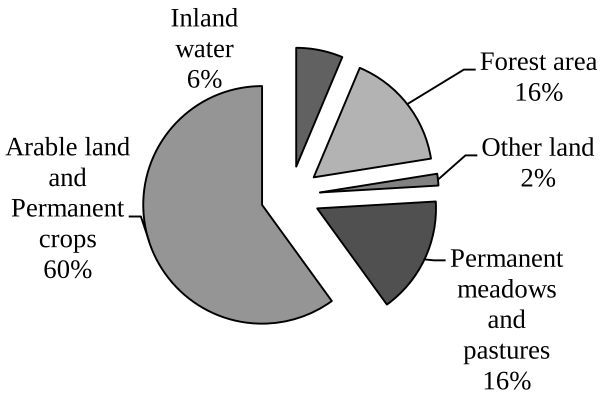

Fig. 1-4 Land use pattern in Rwanda (Source: FAO 2012)

Inland water consists predominantly of lakes, the biggest of which is Lake Kivu shared with DRC Congo, with some 102 800 ha of the lake being on the Rwandan side of the border. Arable land is temporary occupied by agricultural crops, temporary pastures, land used for markets and kitchen gardens, and land under temporary fallows. Arable land, however, does not include all the potentially cultivable land. It includes areas where, for example, coffee and tea are cultivated, but excludes those with trees grown for wood products such as timber and fuelwood. Permanent meadows and pasture describe land used permanently for grazing animals. Forest area is that covered with natural forests, forest plantations and woodlots.

The area under agricultural production has been increasing overtime at the expense of pastures, natural formations and fallows (Fig.1-5). For example, the cultivated land increased from 782 500 in 1982 to 899 133 ha in 2002, corresponding to 64 and 74 % of the national land area respectively (Mpyisi et al. 2003).The change in land use pattern implies variation in the proportion of the area under different land use categories.

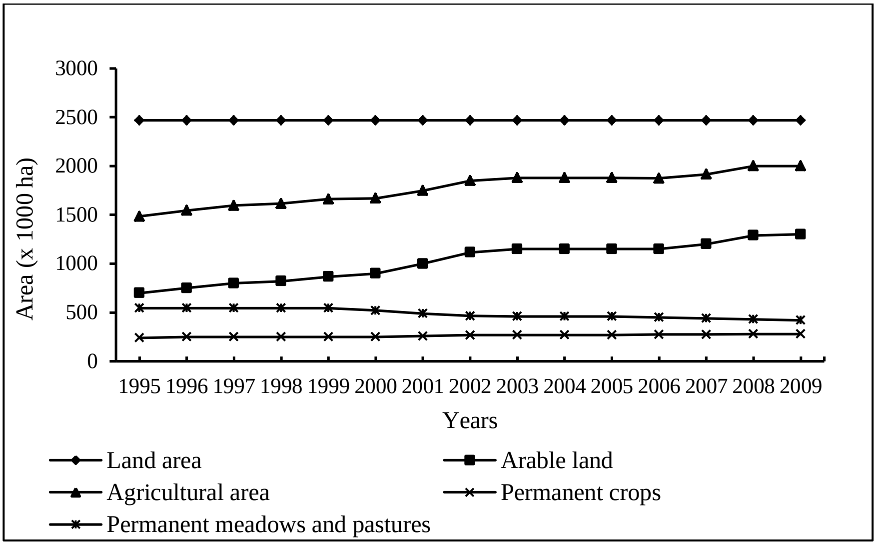

Fig. 1-5 Development of land use categories between 1995 and 2009 (source: FAO 2012)

According to Corbin (1990), the options for extending the cultivated area by clearing new land were almost exhausted between 1980 and1989. Further extension has been achieved by reducing the fallow period, by occupying marginal lands and by clearing forests. With rapidly increasing population, less agricultural land is available on per household basis.

In Rwanda, the environment suffers from various forms of land degradation, soil erosion, deforestation, loss of biodiversity and pollution

(REMA 2009a). Deforestation occurs as a result of agricultural expansion, livestock farming, unsustainable fuelwood extraction, encroachment into forest lands, settlements, forest fires and overgrazing, all of which subject the land to degradation, erosion and landslides (REMA 2009a). Natural forest areas declined by 65% during the period from 1960 to 2007 (MINIFOM 2010).

1.3 History of reforestation and tree planting in Rwanda

Reforestation and tree planting in Rwanda started during the Belgian rule in the 1930s. The earliest stages of tree planting were characterised by planting of fast growing exotic tree species (e.g. *Eucalyptus spp., Grevillea robusta, Cupressus lusitanica*) in communal and private woodlots and along farm contours in order to address deforestation, provide fuelwood and timber, and reduce soil erosion (Languy1954, Derenne1989). The purpose of the Belgian colonial government was to establish 1 ha of woodlots for every 100 persons (Biroli 1980), with a focus on replanting of areas already cleared by cultivators and livestock farmers. During that time, Rwandan farmers were already managing some indigenous tree species (e.g. *Markhamia lutea, Ficus thoningii*, *Euphorbia tirucalli)* on their farms. These trees were deliberately retained on farms during forest clearance for food production and formed the basis of early agroforestry systems in Rwanda. Remnant indigenous trees are still found in agroforestry systems throughout the country, and are often valued for their value including economic and cultural benefits. The early systems integrating trees and crop production begun to increase during the 1970's, when agroforestry was promoted by agroforestry projects as a method to control erosion, maintain soil fertility, produce wood for various uses and increase yield of crops and livestock.

Along with traditional practice of agroforestry, major reforestation activities by the Belgian rule were carried out between 1920 to 1948 (Amsallem et al. 2002)). In the 1960's, after independence, proper afforestation and reforestation plans were drawn up which resulted in the establishment of forest plantations in the Congo Nile Crete region (Weber 1989). Thanks to financial support by many organisations (e.g. World Bank, the European Union, Swiss Development Agency), reforestation and tree planting activities expanded to other areas of the country. Since then, the plantation area increased considerably. At the same time, agroforestry evolved as a scientific discipline, through research and development activities in the 1970's. Agroforestry systems have been developed and promoted, along with systems established for environmental protection including soil protection structures, stabilisation of bench terraces and roadside buffers. These systems were promoted by various donor funded agroforestry projects. Examples of these projects include: the Projet Agropastoral de Nyabisindu, that operated in Nyabisindu in the central plateau of Rwanda, the Gituza and Muhura/Ngarama projects in Byumba funded by CARE International, the Bugesera-Gisaka- Migongo project in Kigali/Kibungo, the Projet Pilote Forestier in Kibuye funded by Swiss INTERCOOPERATION, the Projet d'Intensification Agricole in Gikongoro funded by UNDP/FAO, the Projet d'Intensification Agricole in Gikongoro, and various USAID Farming System Research and Natural Resource Management projects in Ruhengeri funded by USAID. These projects were successful in developing agroforestry technologies but also criticised for their low impact due to low adoption of technologies by farmers (N'Diaye, 1988). Among many factors, the low success rate of these projects was attributed to the failure to promote agroforestry technologies that were most useful and profitable to farmers for their specific conditions (Rocheleau et al. 1989, Kerkhof 1990). For example, most projects emphasized new technologies (e.g. alley cropping, improved fallows) and neglected any locally-developed systems (e.g. home gardens) based on experiences of the farmers.

In Rwanda, the establishment of private forests has been, and still remains, depending on free distribution of tree seedlings from community nurseries and project nurseries. Whereas an important part of the forest and tree resources was destroyed during the period of 1990-1994, reforestation and tree planting activities have taken up again after 1994. Donor and government projects have increasingly planted trees on public land and have supported farm forestry. The national forest policy recognises the importance and potential strategies to promote reforestation and farm forestry in Rwanda. These strategies complement the goals of Rwanda’s vision 2020 and the Economic Development and Poverty Reduction Strategy (EDPRS), which aims at increasing household income and conserving the environment.

1.4 Status of Rwandan forests

Forests in Rwanda provide a wide a range of products to the population and contribute to the national economy. Between 2008 and 2010, the forest sector contributed between US$ 123 and 132 million to the national economy. Forests provide also a wide range of services, which include protection of soil from erosion, landslides, floods, maintenance of soil fertility, and fixing carbon from the atmosphere as biomass and soil organic carbon. Forests are both a resource and habitat for a rich biodiversity in the country. They shelter 2150 known plant species, 151 mammal species including the rare mountain gorilla (*Gorilla gorilla berengei*) and 670 bird species (REMA 2009b). The forests of Rwanda are composed of natural forests, woodlands, savannahs and forest plantations, and underwent heavy deforestation between 1960 and 1999 (Percival and Homer-Dixon 1995, Gasana 1997, MINITERE 2003). The total area forested in Rwanda was 30% of total land area in the 1930's (Masozera and Alavalapati 2004), 25.7% in 1960 and was reduced to 10 % in 2007 (CGIS-NUR and MINITERE 2008). The major groups of forests in Rwanda are further classified into different types based on their cover, development stages, management, and species composition. The area occupied by humid natural forests is the largest, followed by Eucalyptus plantations (Fig. 1-6), corresponding to about 33 and 26 % of the national forest area, respectively. The other predominant forest types are young plantations and coppices, and degraded natural forests, occupying each 16% of the forest area of the country.

Forest cover varies among the four Provinces of Rwanda and Kigali City; high forest cover is found in the West and Northern Provinces, intermediate in the Southern Province and low in Eastern Province. The district wise status of forest cover in Rwanda is shown in Figure 1-7. The savannah forest containing the entire area of Akagera National Park and small remnants of gallery forests are found in the eastern Province. The natural forests of Nyungwe National Park, the Volcanoes National Parks and the savannah forests in Akagera National Park conserve a rich diversity of flora, fauna and habits, which make them attractive for the tourism industry in the country.

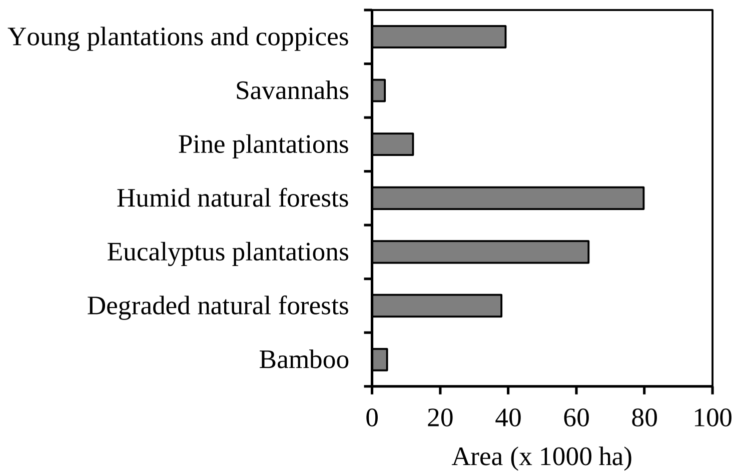

Fig. 1-6 Area (in thousands ha) of different forest types in Rwanda (source: CGIS-NUR and MINITERE 2008)

In total, Rwanda has 525 500 ha of forest of which 224 000 ha are natural forests and 301 500 ha represent forest plantations (Nduwamungu 2011). Of the total area of planted forests, woodlots and trees outside forests are estimated to cover 162 800 ha corresponding to 31 % of the national forest area. Accurate and reliable data on Rwandan forest cover is not available and inconsistent figures are reported by several authors (e.g. CGIS-NUR and MINITERE 2008; GTZ and MARGE 2009a; Drigo and Nzabanita 2010).

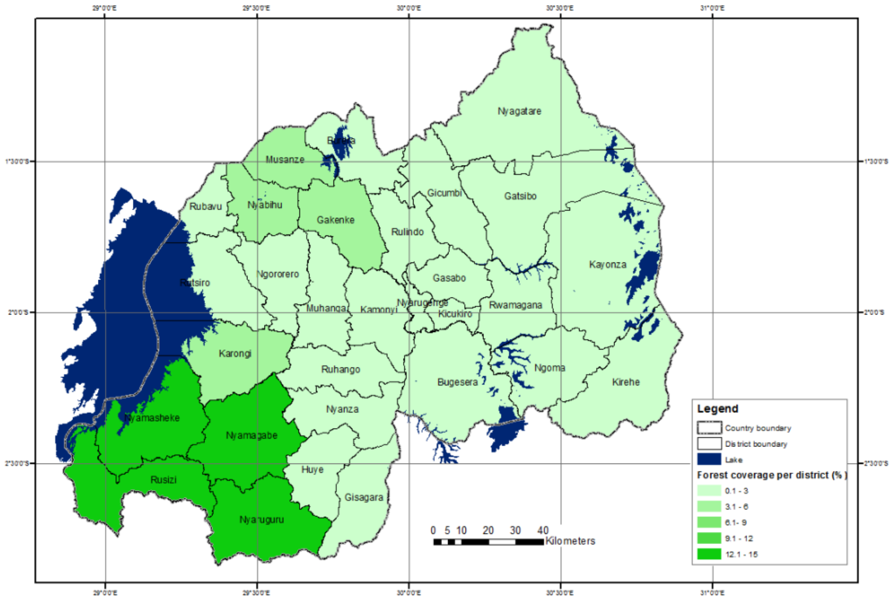

Fig. 1-7 Forest cover classes across the administrative districts of Rwanda (Source: CGIS-NUR and MINITERE 2008)

Using a 25 % forest cover definition and applying forest inventories and remote sensing techniques, Saatchi et al. (2011) estimated that the total Rwandan forest carbon stock in above and below ground biomass is 24 M t C (million tons carbon), corresponding to the average carbon density of 75 t ha^{-1} for a forest area of 330,000 ha. This value of carbon storage is probably an underestimate for the total forest area in the country because carbon accumulation in forests and woodlots below 25% tree cover as well as in trees and shrubs in the various agroforestry systems is not accounted for.

In Rwanda, the natural forests and savannahs are gazetted as protected areas where wood harvesting is excluded by laws. In contrast, Rwandan forest plantations are established to produce timber and fuelwood. Fuelwood plantations occupy 75 % of the total planted forests and 25 % consist of timber plantations (Nduwamungu 2011). These data, however, do not reflect a realistic trend of wood consumption in Rwanda. Since the production of timber goes along with the production of fuelwood, it is difficult to make a clear distinction between timber and fuelwood plantations under current management objectives. For instance, fuelwood plantations consist mainly of eucalyptus managed as simple coppices and coppices with standards, reflecting the possibility to produce building poles and timber also. In addition, the exploitation of timber plantations (consisted mainly of *Pinus* and *Cupressus spp.*) produce timber and large amounts of fuelwood in the non-merchantable section of the trees and branches. Hence, the supply of wood from forest plantations is expected to be higher than estimates based on types of plantations, which would result in lower wood shortages, particularly fuelwood. These shortfalls in the classification of forest plantations in Rwanda are exacerbated by the lack of regular surveys and database on production and consumption in order to establish different product categories from forests.

There is no reliable statistics concerning wood removal from forest plantations. The recorded wood removal from forest plantations and woodlots was 4.7 million m^3 in 2010 of which wood fuel (fuelwood and charcoal) accounted for 4.1 million m^3 or 87 % of the total wood removal (Nduwamungu 2011). In order to fill the gap in wood demand, the country imports wood from neighbouring countries such as DRC, Uganda, Burundi and Kenya. In 2010, Rwanda imported about 1.7 million m^3 of industrial roundwood and 12 million m^3 of sawn timber (FAO 2012). Though consumption and sources of wood supply have not been studied reliably at the national level, it has been estimated that 40 and 90 % of the total volume of industrial and woodfuel come from forests (Nduwamungu 2011). Sourcing fuelwood from forests has been criticised for degrading them, hence the Rwanda government has reacted by regulating access and use of forests. In densely populated countries with limited forest resources, fuelwood collection sources by rural households have not been well established in the literature, and are, to our knowledge, non-existent in Rwanda. Careful examination of fuelwood sources could lead to a different set of conclusions and recommendations than what might result from the assumption that households depend only on fuelwood collected from public forests.

1.5 Status of Agroforestry

In Rwanda, agroforestry, the integration of trees in agricultural landscapes, offers options for increasing agricultural productivity by nutrient recycling, reducing erosion, improving soil fertility and producing wood and non-wood products. In the country, agroforestry has been in practice for hundreds of years. One important characteristic of the traditional agroforestry is the retention and management of indigenous tree species on farmlands (Habiyambere 1999). At present, the Rwandan agroforestry systems are dominated by a wide range of exotic tree and shrub species that are suitable for different farming systems in the country. About 150 tree and shrub species are planted in different arrangements and locations on farms, and produce a variety of wood products, increase agricultural productivity and protect the environment. Of the total number of tree species inventoried on agricultural land, 60 trees species are used to supply fuelwood (Den

Biggelaar 1996). The World Agroforestry Centre (ICRAF) in collaboration with Rwanda Agricultural Research Institute (ISAR), and various agroforestry projects in Rwanda have developed several technologies that now benefit thousands of farmers in different regions of the country. Some of the agroforestry technologies developed and disseminated in rural areas by agroforestry projects and research institutions include (ISAR and ICRAF 2001):

(i) Planting of agroforestry species alone or combined with herbaceous species in order to stabilise bench terraces, reduce soil erosion on slopping lands and generate other benefits such as green manure, stakes for climbing crops, fodder and fuelwood;

(ii) Improvement of soil fertility through N-fixing trees and biomass transfer, and with a mix of green manure and inorganic fertilisers;

(iii) Multipurpose wood production including firewood, timber and stakes to support high value crops including beans, peas and tomatoes;

(iv) Fodder production in order to feed dairy animals in zero grazing systems;

(v) Soil conservation by planting contour hedgerows particularly on slopping lands;

(vi) Fruit production through the integration of exotic and indigenous fruit species in the farming systems, particularly on the home compounds;

(vii) Planting of woodlots for the production of fuelwood and protection of watersheds.

Agroforestry in Rwanda is dominated by individually owned trees planted as small blocks (woodlots), lines (farm boundary and contour lines) and scattered trees on farmlands. Agroforestry practices are used to produce harvestable wood and non-wood products including fuelwood and fruit, and services such as erosion control and improvement of soil fertility. Considering the small national forest area, the potential for agroforestry to augment the wood supply is important, and has the added advantage of supporting agricultural intensification. The land ownership status, however, limits the type of agroforestry adopted by Rwandan farmers, with large farm owners having the possibility to grow woodlots. Agroforestry is promoted among smallholder farmers by government projects, externally funded projects and NGOs. The Rwanda vision 2020 targets to expand agroforestry practices over 80% of agricultural land (MINICOFIN 2000). This goal is in line with the national forest policy which aims to promote farm forestry, and the strategic plan for the environment and natural resources sector that targets sustainable management of Rwanda's natural resources and environment in order to meet the EDPRS (Economic Development and Poverty Reduction Strategy), the MDG (Millennium Development Goals) targets, Rwanda Vision 2020 aspirations and international commitments.

Agroforestry systems and trees outside forests in Rwanda are important sources of woody biomass; they contain about 14 million oven dry tons of woody biomass (Drigo and Nzabanita 2011). However, the cover of trees and woodlots on farmlands is not known precisely. The Rwanda

Ministry of Forestry and Mines estimates roughly that small woodlots (< 0.5 ha), trees in agroforestry and other trees outside forests represent an area of 222 520 ha equivalent[1] to normal forests (MINIFOM 2010). This figure must be taken with care since no comprehensive inventory of trees outside forests has been carried out so far. A recent report by Drigo and Nzabanita (2011) indicates that trees outside forests including trees and small woodlots (< 0.5 ha) cover about 7 % of total national land area. Woodlot owner households target fuelwood production and to some extent building poles (Den Biggelaar 1996) for domestic and commercial purposes. There are no reliable statistics on tree cover in agricultural lands.

Considering the small Rwandan forest cover and land shortage for extensive forest plantations, the opportunity to plant trees occurs mainly on agricultural land. Owing to their multifunctional roles, trees and woodlots on farms are now considered in the preparation of the Global Forest Assessment 2015 (FAO 2010b). To encourage sustainable management of forests world-wide, Rwanda ratified a number of international agreements and commitments (e.g. the Forest Principles of Agenda 21, the Convention on Biological Diversity, the Framework Convention on Climate Change, and Convention to Combat Desertification) that emphasize that an appropriate database is a prerequisite for sound management of the world's natural resources. The idea of sustainable management of natural resources extends beyond forests to apply to trees outside forests as well (Kleinn 2000). The general objective is to enable the provision of information on the status of

[1] The Rwanda Ministry of Forestry and Mines (MINIFOM) estimates that 1600 trees counted on the agricultural land or in other places such as towns and pastures represent 1 ha of a normal forest plantation

trees outside forests and evolution in time and quality in order to take informed decisions related to the optimization of tree resources for sustainable development and food security (FAO 2010b). Since no accurate assessment of tree resources in agricultural landscapes in Rwanda has been carried out, policies aimed at agricultural intensification, farm forestry, environmental protection and energy require information on the distribution of trees and woodlots in agricultural landscapes, their sizes, volume and biomass for effective planning and management.

1.6 Scope and objectives of the thesis

In Rwanda, there is an imbalance between the demand and supply of fuelwood. Growing trees and woodlots on agricultural lands is a common practice throughout the country. However, the actual magnitude of the role of these fuelwood production systems has not been quantified so far. As a result, information of their size, importance, and extent of use by rural households have not been determined. The present thesis aims at quantifying the role of trees and woodlots on farms in fuelwood supply by: (i) identifying the factors that motivate farmers to grow trees and woodlots on their farms, (ii) evaluating the socio-economic factors that influence farmers' choice of fuelwood sources, and (iii) estimating the aboveground woody biomass at farm and landscape level in Rwanda.

This thesis therefore aims to contribute to the theoretical and empirical literature in at least three ways. First, it expands on the household choice model by explaining the factors that contribute to the planting and maintenance of trees and woodlots on farms. In addition, it establishes regional and cross-regional analysis of the main motivators of growing trees and woodlots on farms given a set of different biophysical and socio-economic conditions. Secondly, it presents comparative results among regions on the factors that explain how socioeconomic and location variables affect the household choice of a particular fuelwood source over alternatives. In general, the results provide insights for better targeted policy options. Thirdly, the study estimates and compares the amount of woody biomass present in different agricultural landscapes and analyses the data in relation to the amounts of biomass reported for forest plantations. In particular, estimates of biomass for fuelwood are provided and analysed for their potential in reducing the gap between the supply and demand of fuelwood. To achieve the main aims of this thesis, the study focused on the following research questions:

1) What is the present status of fuelwood demand and supply in Rwanda?
2) What are the socio-economic factors and attitudes that influence the choice of fuelwood sources by smallholder farmers in the low, medium and high altitude regions of Rwanda?
3) What are the motivations and main purposes that drive smallholder farmers to plant trees and woodlots on their farms?
4) What is the current status of woody biomass on farms and its potential to provide fuelwood?

This thesis, therefore, describes what has been documented about fuelwood supply in Rwanda, and interprets this information vis-à-vis trees and woodlots on farms under boundary conditions of household characteristics. It aims to provide information for policy making about farm forestry, especially for meeting the fuelwood demands from smallholder farmers. The analyses of trees and woodlots on farms enable the development of policy recommendations for the development of agroforestry, by focusing on farmers' determinants and purposes of having trees and woodlots on their farms. The thesis focusses on which households have trees and woodlots on farms, and under which conditions. A better understanding of the determinants of household choice of these two agroforestry practices (woodlots vs. trees on farms) and fuelwood source is analysed using a conceptual framework and using empirical models to assess motivations for tree and woodlot farming. Studies in other developing countries which have accounted for household wealth, income and location indicated that households depend differently on forests and agroforestry for fuelwood supply (e.g. Baland et al. 2010, Ashton et al. 2011, Jumbe and Angelsen 2001). The thesis aims to clarify these dependencies through the combined use of comprehensive farm and household level studies coupled with farm woody biomass assessment, to analyse the relevance of agroforestry in meeting the fuelwood demands in subsistence farming households.

1.7 Thesis Outline

The thesis consists of seven chapters. Following the general introduction:

Chapter 2 consists of a review of fuelwood demand and supply in Rwanda and assesses the potential of forests and agroforestry systems to provide fuelwood. It analyses the sources of fuelwood and indicates the importance of trees and woodlots on farms on fuelwood supply. Furthermore, it reviews the effect of fuelwood consumption on land use and its link with deforestation in Rwanda.

Chapter 3 provides a theoretical framework emphasizing the importance of household characteristics and location as determinants of the choice of fuelwood sources. It discusses household demographic and socioeconomic factors that determine the choice of fuelwood from farms, forests and markets.

Chapter 4 provides an understanding of the decision making process of the farmers who plant scattered trees on their farms in the low, medium and high altitude regions of Rwanda. It presents the reasons why and when farmers are planting trees on farmlands and determines the most important aspects that households consider when deciding to plant a variety of different trees species in agricultural lands.

Chapter 5 discusses the factors that motivate smallholder farmers to grow woodlots, as a special form of agroforestry that compete for space with agriculture crops. This chapter, therefore, evaluates the socioeconomic factors that influence agricultural households to adopt farm woodlots in the farming systems of the low, medium and high altitude regions.

Chapter 6 compares the current status of scattered trees and woodlots on farms in terms of their characteristics, total standing woody biomass and biomass for fuelwood at farm and landscape levels among three altitude regions of Rwanda. In addition, the potential for farm woody biomass to reduce the gap between fuelwood supply and demand is discussed.

Chapter 7 consists of a general discussion and synthesis of the main results and gives policy recommendations for the development of agroforestry for fuelwood supply in Rwanda. It also contains an analysis of the potential fuelwood production on agricultural land given a set of different assumptions. Finally, it highlights the relevance of agroforestry for sustainable fuelwood supply and aspects that require further investigation in order to improve understanding of the fuelwood supply and demand balance approaches and to support implementation of policies targeting agriculture, forestry, energy and environment in the country.

Chapter 2 Fuelwood demand and supply in Rwanda and the role of agroforestry

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Abstract

Fuelwood in Rwanda is assumed to come from forests and woodlands, thus contributing to large-scale deforestation. Available studies on fuelwood demand and supply support this assumption and indicate a continuously rising demand of fuelwood, notably from forest plantations. These assertions are insufficiently substantiated as existing forest stock may not be depleted by rapid increase in demand for food and energy resources resulting from population growth, but rather from the need for agricultural land. Evidence suggests that the demands for fuelwood, in addition to other sources of energy, are supplied from agroforestry systems which have not been quantified so far. This review analyses sources and use of fuelwood in Rwanda, indicating the importance of on-farms trees and woodlots in fuelwood supply. It is concluded that the effect of fuelwood consumption on land use is difficult to disentangle as many other factors including land clearing for agriculture, livestock farming, human settlements, illegal cutting of valuable timber species, the demand for charcoal in towns and past conflicts, contributed significantly to the high rate of deforestation in the country. If fuelwood demand is to be met on a sustainable basis, more fuelwood has to be produced on agricultural lands and in forest plantations through species site matching and proper management.

Keywords: Agroforestry; Deforestation; Fuelwood demand; Fuelwood Supply; Forest plantations; Rwanda

2.1 Introduction

Rwanda is a small (26,338 km^2), landlocked country in central Africa, situated at 1,500 km from the Indian ocean and at 2,000 km from the Atlantic ocean. Its population was estimated to be 10.7 million in January 2010 (CIA 2010), and mainly depends on natural resources for its livelihood. It is primarily dependent on agriculture, which is the way of life for about 90% of the population, most of them subsistence farmers. The total area of the arable land is estimated to be about 52% of the country's area (MINITERE 2004a). The remaining area is occupied by water, perennial crops and forests, nature reserves and settlements.

In Rwanda as in many developing countries, fuelwood is a major concern in any discussion on energy resources. This is shown by the fact that biomass (wood and crop residues) is the principal source of energy meeting 94% of national needs (MINITERE 2004b). In fact, 85% of the Rwandan population use firewood and 0.6% use charcoal to meet their energy demands (MINECOFIN 2003). Other sources of energy such as hydropower, solar energy, biogas, peat, and methane gas are available but are not used widely. For instance, in 2004, only 6% of the Rwandan population was reported to have access to electricity (MININFRA 2004a). The country imports all petroleum products, which makes them expensive and less accessible to a large proportion of the population.

In the Rwandan context, wood takes an important share in energy supply. It is being used in both urban and rural households for cooking and lighting. It also provides energy to a wide range of small scale industries and public institutions. Fuelwood supplies have always been considered as coming from forest plantations despite obvious availability of trees and shrubs in agricultural fields.

The need for food and wood as source of energy places a heavy burden on natural forests, and because of conservation interests, these forests have been designated as forest reserves with restricted community access and restricted use. Since 1960s, the need for fuelwood, together with the need to protect the high mountainous areas of Rwanda from erosion, called for the establishment of forest plantations. Also, agroforestry practices were promoted to intensify agricultural production and to provide wood and non-wood products at household level. As a result of conservation measures for natural forests, reforestation and on-farm tree planting activities, the annual deforestation rate declined from 2.9% between 1960 and 1970 (FAO 2005a) to 1.8% between 1990 and 2010. This indicates that, although deforestation was on-going, conservation measures and reforestation efforts counterbalanced this to some extent. Additional sources of wood, including fuelwood trees, were established in agricultural fields as part of agroforestry systems.

Despite all these efforts, an increasing gap between demand and supply of wood has been reported by the Forest Department. While agroforestry is practiced by many rural households, it is unclear how and under what circumstances trees and shrubs are integrated into crop production and to what extent they are useful in increasing agricultural production as well as the supply of wood and non-wood products. Of particular concern is the lack of information on the contribution of the different agroforestry options in addressing the fuelwood scarcity.

Data on fuelwood demand and supply in Rwanda are based on surveys that have been carried out in different parts of the country, in urban and rural areas. Existing data mainly focus on the consumption side, without much emphasis on the supply side or resource base. Therefore, it is unclear to what extent fuelwood consumption causes deforestation, whether there is fuelwood shortage, and what measures have been adopted by rural households to address fuelwood or energy problems. What is common in most projection estimates is the expected and increasing gap between demand and supply of wood products from forests in relation to forest stocks and population projections.

The main objective of this paper is to review the situation of fuelwood in Rwanda and to assess the potential of forests and agroforestry systems combined, to provide fuelwood for the growing population. The review discusses fuelwood consumption and analyses the projected fuelwood demand and supply, linking this to the high deforestation rate reported for the country.

2.2 Fuelwood sources

2.2.1 Natural forests and woodlands

The country's largest natural forests are Nyungwe in the Southern Province, the Volcanoes National Park in the Northern Province, and the forests within the Akagera National Park in the Western Province (Fig. 2-1).

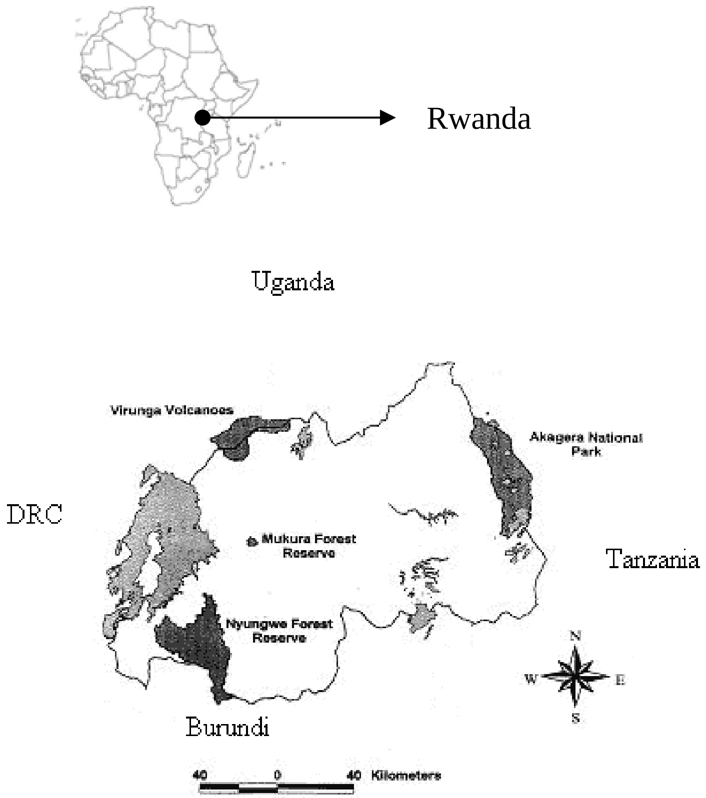

Fig. 2-1 Location of major natural forests in Rwanda

There are also other small natural forests, gallery and savannah woodlands designated as natural reserves, such as the Mukura forest, the forests of Cyamudongo and Busaga, and the savannah of the east (MINITERE 2005). The total area under natural forests in 2002 was estimated to be 233,900 ha (Table 2-1).

It should be noted that before the colonial era, Rwanda may have had much less trees than at present in certain locations. Journals from the early days of the colonial time show landscapes with much less trees than today. A good illustration is the comparison of the present view from the Kandt Museum of Natural History at Kigali, and the picture taken almost 100 years ago from the same spot, showing Mount Kigali and its neighbourhood virtually without trees. Toward the end of the 1920s, planted forests were estimated at 380 ha (Biroli 1982).

Table 2-1 Area of natural and protected forests in 2002 (MINITERE 2004c)

Forests	Area (ha)
1. Nyungwe + Cyamudongo	101,500
2. Gishwati	600
3. Mukura	800
4. Birunga (Volcanoes)	16,000
5. Akagera	90,000
6. Gallery	25,000
Total	233,900

The use of natural forests for wood and non-wood products has undergone various changes in recent history. During the pre-colonial period before 1924, these forests were managed under a wide range of state and communal tenure arrangements. These arrangements led to depletion of the resources through agriculture and grazing. Forest clearing for crop production and pastures was done without control as forests were considered common property.

During the colonial period between 1924 and 1934, the Belgian Colonial Authority restricted the use of natural forests by adopting forest legislation that prohibited forest clearing for agriculture, but recognized community rights to cut and collect firewood and commercial exploitation of valuable timber. Although these forests were declared official reserves by the Belgian Colonial Authority, enforcement of the regulations was frequently absent or irregular. As a result, the population continued to encroach on natural forests in search for land, wood and non-wood products.

During the post-independence period after 1962, the use of forests was regulated by a new forest law. As an example, access to resources in Nyungwe forest in the southwest of the country was limited to a multiple-use zone where controlled harvesting of products was allowed, and in the buffer zone plantations around it (Weber 1989). Nevertheless, local people have continued to collect resources from forests, resulting in conflicts between the management of the forest and the local communities.

Under the current forest law, natural forests in Rwanda have special conservation status. Removal of wood products, including fuelwood gathering, is prohibited. Despite this, many studies have indicated that these forests remain an important source of fuelwood and other products for people living around them (Hoster and Milukas 1992; Monela et al. 1999; Warner 2000; Campbell et al. 2002; Cavendish 2002; Masozera and Alavalapati 2004; Bird and Dickson 2005).

Local consumption by forest fringe communities usually has been in the form of collection of deadwood and branches. Significant amount of fuelwood for local consumption as well as for charcoal production for sale in town were obtained along with massive and extensive clearance of forests. The management of buffer zones, for example around Nyungwe Forest, is an attempt at creating a source of wood and non-wood products from forest plantations while protecting the reserve itself from illegal use.

2.2.2 Forest plantations

The earliest reforestation efforts, dating from 1920 to 1948, had the dual function of protecting mountaintop areas from erosion, and supplying fuelwood (Amsallem et al. 2002). The objective was to afforest one ha of woodland for 100 persons (Biroli 1980). After Independence in 1967, some 20,000 ha of communal land were afforested. Of this plantation area, the first forestry project in the country, Kibuye Pilot Forestry Project, established 5,500 ha of planted forests. Intensive reforestation efforts were carried out between 1975 and 1989, with planted areas rising from 27,160 ha in 1975 to 247,500 ha in 1989. Plantation area expanded up to 1994, when all economic and development activities stopped following war and the Tutsi genocide.

In addition to the establishment of plantations, fast growing tree species were disseminated in rural areas in order to meet the increasing demand for fuelwood and construction materials by the rapidly growing population. Eucalyptus species received much attention due to their fast growth, coppicing ability, caloric value and adaptability to a wide range of soils and climate. In 1990, Eucalyptus species occupied 65% of the total plantation area (Table 2-2). Some 10 eucalyptus species are found in rural landscape, the most common being *Eucalyptus camaldulensis* Dehnh, *E. globulus* Labill., *E. grandis* W. Hill ex Maiden, *E. saligna* Sm. and *E. tereticornis* Sm.

Table 2-2 Distribution of forest plantations by tree species and ownership in 1990 (Mihigo 1999).

	Ownership							
	State[2]		Institutional[3]		Private[4]		Total	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Eucalyptus spp.	30,600	50	69,370	70	61,040	70	161,010	65
Pinus patula	18,360	30	9,910	10	4,360	5	32,30	13
Cupressus lusitanica	4,900	8	7,930	8	8,720	10	21,550	9
Acacia menaloxylon	4,280	7	6,940	7	-	-	11,220	5
Callitris spp.	1,830	3	2,970	3	-	-	4,800	2
Grevillea robusta	-	-	-	-	4,360	5	4,360	2
Casuarina spp.	1,230	2	1,980	2	-	-	3,210	1
Others	-	-	-	-	8,720	10	8,720	3
Total	61,200	100	99,100	100	87,200	100	247,500	100

Next to *Eucalyptus spp*., *Pinus spp*. have also been widely planted. Other tree species in planted forests include *Acacia melanoxylon* R. Br. Ex Aiton, *Callitris robusta* F. Muell, *C. calcarata* (A. Cunn.) R. Br., *Grevillea robusta* A. Cunn., *Casuarina equisitifolia* L. and *C. cunninghamiana* Miq. A few local tree species such as *Polyscias fulva* (Hiern) Harms, *Podocarpus*

[2] State forests include all forests plantations established by government projects, donor-funded projects and all plantations established on government land during the tree planting days and communal work

[3] Institutional forests are those owned by such institutions as churches, educational institutions, and local districts

[4] Private plantations include individual woodlots and plantations by individuals, private enterprises such as tea factories.

falcatus (Thunb.) R. Br. Ex Mirb., *P. latifolius* (Thunb.) R.Br. ex Mirb., *Maesopsis eminii* Engl. and *Albizzia spp*. were planted, particularly in buffer zones around indigenous forest reserves (Habiyambere 1999).

Figure 2-2 gives the changes in area of forest plantations. Between 1970 and 1990, the plantation area quickly expanded from 27,160 ha to 247,500 ha. This was a result of tree planting campaigns and actions by large development projects providing financial and technical support to forest sector development. Between 1990 and 1994, all this stopped because of war and genocide. During this period, the forest area declined by 15,000 ha, mainly due to agricultural expansion, establishment of new settlements and illegal tree harvesting. An additional 25,000 ha of forest plantations were damaged (Habiyambere 1999). In 1995, reforestation activities started again, including rehabilitation of damaged plantations.

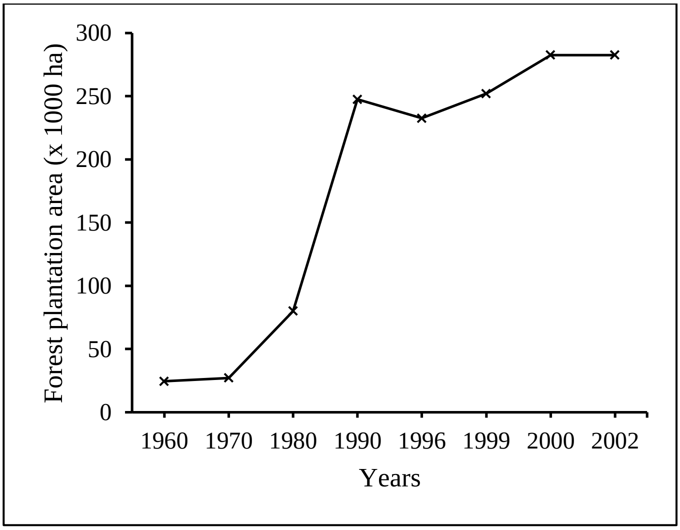

Fig. 2-2 Evolution of forest plantation area between 1960 and 2002 (MINITERE 2005)

A large reforestation effort increased forest cover by an average of 8% per year between 2000 and 2005 (FAO 2005a). Recent forest mapping of forest plantation area C0.5 ha by the Centre for Geographic Information Systems and Remote Sensing of the National University of Rwanda reported a forest plantation area of about 114,000 ha in 2007 and an average reforestation rate of 2,600 ha between 1988 and 2007 (CGIS-NUR and MINITERE 2008). Since the mapping included only forest plantation areas ≥0.5 ha, the total area as reported is an underestimate because it does not account for trees and woodlots on farms despite the fact that these tree resources constitute a major source of fuelwood and income to rural people.

Eucalyptus spp. are most commonly used for plantation forests and on-farm woodlots. Next to multiple uses and advantages, eucalyptus woodlots have come under increasing criticism from politicians and environmentalists because of its alleged negative environmental impact on soil nutrients and hydrology, to the extent that it is suggested that they should be eliminated from marshlands and bottomlands, and prohibited in reforestation in the country (Gahigana 2006).

However, some authors (e.g. Nshubemuki 1988; Munyarugerero 1988; Davidson 1995; White 1995; El-Amin et al. 2001) indicated that the adverse effect of eucalyptus plantations on soils and hydrology is not universal but depends on species, site characteristics and management practices. The problem is related to water use and nutrient uptake by eucalyptus. Where water is scarce, water use by eucalypt plantations may continue longer than in the case of other species, but this might be reduced by planting fewer trees per unit area or by thinning. Depending on management objectives, careful selection of species, planting sites and management practices are required in order to maintain productivity and minimise the negative effects of eucalyptus plantations and woodlots on soil nutrients and water.

In Rwanda, eucalyptus plantations cover about 63,561 ha or 26% of the total forest area in 2007 (CGIS-NUR and MINITERE 2008). These figures do not include coppices and young eucalyptus stands because the mapping has taken into account only stands with height equal or greater than 7 m and tree cover of at least 20%. As result, total area and standing volume is likely to be somewhat underestimated.

The productivity of existing plantations is generally reported to be rather low, and varies with planting location and tree species. Table 2-3 shows the mean annual increments of main plantation tree species recorded in Rwanda.

Table 2-3 Productivity of main plantation tree species in Rwanda (MINIRENA/ISAR 2008)

Tree species	Productivity (m^3 ha^{-1} $year^{-1}$)
Acacia melanoxylon	15.0
Callitris robusta	5.8
Cupressus lusitanica	6.8
Eucalyptus species	6.9
Grevillea robusta	10.0
Pinus spp.	13.1

The productivity rate is as low as 6–10 m^3 ha_{-1} $year^{-1}$ in some cases. The low yields of most forest plantations are mainly due to low site quality, inadequate selection of species and provenances, and inappropriate management techniques during planting, thinning, and harvesting.

Using 10 m^3 ha^{-1} $year^{-1}$ as the average productivity rate, the 240,708 ha of forest plantations may yield 2.4 million m^3 of wood per year. Based on FAO (2005) estimates that 72% of total wood removal from forests in Rwanda consists of fuelwood, the volume of wood (to be converted into biomass) that could be harvested on sustainable basis to supply fuelwood would be about 1.7 million m^3 for a Rwandan population of 10.7 million (January 2010). Hence the theoretical sustainable supply of wood for energy would be 0.16 m^3 $person^{-1}year^{-1}$, which is less than a quarter of the consumption of 0.91 m^3 $person^{-1}year^{-1}$ found by the national wood consumption survey in 1982.

The annual production of existing forest plantations is therefore considered to be insufficient to meet the current fuelwood demand for the population, and the discrepancy will increase with increasing population. Even with additional plantations on estimated area of approximately 81,000 ha (CGIS-NUR and MINITERE 2008), higher biomass production in forest plantations cannot be achieved without silvicultural treatments and selection of species that perform well on land usually of marginal quality.

2.2.3 Agroforestry systems

Under agroforestry, trees and shrubs are grown in agricultural fields in association with crops, either as single trees, linear formations or woodlots. These trees produce goods such as fuelwood, stakes for climbing beans, fodder, building poles, timber, and fruit and medicines, and provide service functions such as soil conservation and soil fertility replenishment. Den Biggelaar and Gold (1996) reported that both indigenous and exotic tree species were appreciated by farmers and used in agroforestry systems. This indicated that these tree species were considered by farmers as being less competitive to crops and have minimal negative effects on soils (i.e. less allelopathic effects and efficient use of water and nutrients). So far, 152 tree species have been recorded, of which 60 species are used as fuelwood (Den Biggelaar 1996).

Despite limited farm sizes in Rwanda, farmers incorporate trees and shrubs within small farms by choosing appropriate locations for planting multipurpose tree species. Survey data reported by Samyn (1993) showed that the average wood production in the farming systems was approximately 1.5 m^3 ha^{-1} $year^{-1}$. As a result, smallholder farmers in general will not be able to produce all the fuelwood and other wood products they need for domestic use on their own farmland.

Theoretically, a national average of 0.6 ha of family farm may satisfy the energy needs for cooking for a family of six members. On such small farms, it is possible to incorporate trees by using agroforestry practices such as boundary planting, alley cropping and short term improved fallows with fast growing and less competitive tree species. The planting of selected tree species in spatial and temporal combination with agricultural crops can be practised to fulfil service and productive functions of which fuelwood supply is one.

The use of fuelwood from agricultural fields frees rural households from gathering fuelwood from forests and wooded lands. The production and consumption of fuelwood from agroforestry systems thus can release the burden of long time collection of wood for energy by children and women in rural areas, albeit at the cost of increased competition with food crops.

Agroforestry shrubs that are established on farms combine fuelwood production with soil erosion control, stakes for climbing beans, green manure and fodder for livestock (Roose et al. 1993).The desirable characteristics of tree and shrub species that fit the requirements for fuelwood species include nitrogen fixing ability, rapid growth, coppicing ability and ability to grow in degraded and deficient soils (Nair 1987; Mead 2005). In order to increase food production as the main objective, agroforestry species that ensure increased efficiency of fertilizer use (Breman and Kessler 1995) should be considered as an important criteria for choosing tree species that will enhance food production and fuelwood supply. These tree species, also referred to fertilizer trees, go beyond the production of food. They also conserve the natural resource base and protect the environment. Such fertilizer trees including *Calliandra calothyrsus*, *Gliricidia sepium*, *Leucaena diversifolia*, *Senna spp.*, *Sesbania sesban* and *Tephrosia vogelii* have been identified as outstanding fuelwood species. Regular harvesting of these trees for fuelwood may result in a substantial removal of nutrients, depending on management.

Significant nutrient removals can result from harvesting branches for firewood because of the higher nutrient content in branch wood and bark. These materials should be left on the field and incorporated into the soils in combination with mineral fertilizers in order to increase crop yields. In Tanzania, fertilizer trees were able to provide up to 10 t of wood biomass per hectare, thereby sequestering 2.5-3.6 t of carbon per hectare per year (Nyadzi 2004).

Many surveys in Rwanda (e.g. AFRENA 1988; Den Biggelaar 1996; Mukuralinda et al. 1999) reported the utilization of less suitable fuelwood species for energy supply such as *Vernonia amygdalina* Del., *Euphorbia tirucalli* and *Ficus thonningii*. The use of these tree species indicates farmers' strategies to address fuelwood problems. Table 2-4 shows a short list of promising fuelwood species in the highlands, midlands and lowlands of Rwanda. Data on coppicing ability, yield and wood specific gravity are given for some species to give an indication of the potential value of the species as fuelwood. Current and potential agroforestry practices that could provide fuelwood while ensuring agricultural intensification are presented and discussed below.

Scattered trees on-farms

The use of scattered trees and shrubs is a traditional practice in the various land use systems in the country. The intensification of agricultural production results from the ability of the system to improve soil fertility, and to provide shade and mulch to associated crops. In this system, trees are managed to produce timber, firewood, fodder, poles, fruit, and bean stakes.

Table 2-4 Firewood species for the high, medium and low elevation zones of Rwanda

Species	Coppicing ability	Yield ($m^3 ha^{-1} year^{-1}$)	Specific gravity
(a) High elevation zones			
Acacia mearnsii	Yes	10 - 25	0.50 - 0.70
Alnus nepalensis	Yes	10 - 15	0.32 - 0.37
Alnus acuminata	Yes	10 - 15	0.50 - 0.60
Mimosa scabrella	Yes		
Chamaecytisus palmensis	Yes	15 - 20	
Melia azedarach	Yes		0.66
Sesbania sesban	Yes	2 tons stems $ha^{-1} year^{-1}$	
(b) Medium elevation zones			
Grevillea robusta	Poor but pollards		0.57
Calliandra calothyrsus	Yes	5 - 15	
Leucaena diversifolia	Yes	15 - 40	0.45 - 0.55
Eucalyptus globulus	Yes	10 - 60	0.80 - 1.00
Jacaranda mimosifolia	Yes	20	0.45 - 0.72
(c) Low elevation zones			
Gliricidia sepium	Yes		
Senna spp.	Yes	15	0.6 - 0.8
Azadirachta indica	Yes	13 - 17	0.68
Casuarina cunninghamiana	Not readily		
Casuarina equisitifolia	Not readily	15	
Eucalyptus camaldulensis	Yes	17 - 25	0.60
Eucalyptus citriodora	Yes	15	0.75 - 1.00
Eucalyptus tereticornis	Yes	20 - 25	≥ 0.75

In banana and coffee plantations, overstory trees with light shade are preferred by farmers in order to reduce competition for growing space and light with crops (Djimde et al. 1988).

Indigenous tree species including *Markhamia spp*., *Acacia spp*., *Ficus spp*., *Polyscias fulva* and *Erythrina abyssinica* are commonly found in land use systems as scattered or isolated trees. Among exotic tree species, *Grevillea robusta* A. Cunn. ex R. Br. is widespread and is often intercropped with banana and coffee in order to provide firewood, stakes for climbing beans and mulch. Experiences within the Projet Agropastoral de Nyabisindu on the central plateau of Rwanda indicated that with 350 trees of Grevillea per hectare, the annual yield after 9 years was 14.6 m^3 ha^{-1} $year^{-1}$ of wood and 3.07 t $ha^{-1}year^{-1}$ of fresh leaves (Kerkhof 1990). Branches lopped from grevillea are commonly used as fuelwood or as stakes for climbing beans.

In the highlands of Rwanda where annual rainfall is between 1,300 and 1,800 mm, scattered eucalyptus trees or trees planted at wide spacing are found growing together with food crops in agricultural fields (Nduwamungu et al. 2007). However, in all land use systems, fruit tree species including *Persea americana*, *Mangifera indica*, *Carica papaya* and *Citrus spp.* are also found, mostly as isolated trees near the home compound.

Woodlots

The most common tree species used in on-farm woodlots are Eucalyptus spp. (mostly *E. camaldulensis* and *E. tereticornis*) followed by *Grevillea robusta* (Balasubramanian and Sekayange 1992). Small eucalyptus woodlots are found in all farming systems of Rwanda. Farmers who own woodlots target fuelwood production, followed by building poles (Den Biggelaar 1996). NISR (2010) reported that 8.5% of agricultural households own on-farm woodlots only and 34.4 % of the households had both scattered trees and woodlots on their farms. Hence, many households in Rwanda (43 %) own woodlots of different sizes. A recent study regarding woodlots from 0.06 to 5.20 ha concluded that very small woodlots are not profitable and that the maximum benefit can be obtained for a woodlot of 0.5 ha (GTZ and MARGE 2008). Since the average farm size in Rwanda is about 0.75 ha, only those few farmers who own larger land areas may benefit from woodlots.

Exotic potential fuelwood shrubs for growing in on-farm woodlots include *Calliandra callothyrsus*, *Senna spectabilis*, *S. siamea* (Lam.) H.S. Irwin & Barneby, *Gliricidia sepium* (Jacq.) Kunt ex Walp, *Mimosa scabrella* Benth., *Sesbania sesban* (L.) Merrill. and *Leucaena spp.* These species are fast growing and respond positively to frequent cutting. However, their yields are location-specific and vary under different agroecological zones and silvicultural treatments. Results from fuelwood production trials in the Kakamega district of Kenya, similar to many environments in Rwanda, showed total aboveground biomass yields of 34 and 62 t ha^{-1} year^{-1} fresh weight at 10,000 and 40,000 stems ha^{-1} in *Calliandra calothyrsus*, 46 and 81 t ha^{-1} year^{-1} in *Sesbania sesban*, 34 and 35 t ha^{-1} year^{-1} in *Mimosa scabrella* at similar stocking densities (Kerkhof 1990). These figures indicate that fuelwood production potential in woodlots using fast growing and coppicing tree species can be very high.

Tree legumes planted along contour lines and erosion control ditches

Depending on biophysical conditions of the site, farmers may use legume tree species such as *Calliandra calothyrsus*, *L. diversifolia*, *Senna spectabilis* and *Alnus spp.* to reduce runoff and control soil erosion. Periodic cutting of these shrubs provide fodder for animals, fuelwood for cooking, stakes for climbing beans, and green manure for soil amelioration. Overstorey tree species such as *Grevillea robusta* and *Cedrela serrata* may also be integrated into hedgerows of shrubs (Balasubramanian and Sekayange 1986). At maturity, overstorey trees provide timber and fuelwood.

Alley cropping with tree legumes

Alley cropping is one of the agroforestry systems in which food crops are grown in alleys formed by the hedgerows of shrubs that are periodically pruned during cropping to prevent shading, to reduce intercrop competition for moisture and nutrients, and to provide green manure for the associated food crops. On sloping farmlands, alley cropping may lead to terrace formation, minimising water runoff and soil erosion (Kabaluapa et al. 2008). Additionally, the woody portion of pruned stems provides fuelwood and stakes for climbing beans. Leaves may also be used as protein-rich fodder for livestock.

The suitability of alley cropping system for the highland and the semi-arid regions of Rwanda was investigated by various researchers (e.g. Yamoah et al. 1989; Yamoah and Burleigh 1990; Balasubramanian and Sekayange 1992) by use of tree legumes such as *L. diversifolia*, *Calliandra callothyrsus*, *Senna spectabilis* and *Sesbana sesban*. As found by

Balasubramanian and Sekayange (1992), the mulch from green lopping improved soil fertility, with little or no reduction in crop yields. Additionally, Experiments with *Calliandra calothyrsus*, *Senna spectabilis* and *Leucaena leucocephala* (Lam.) de Wit in the semi-arid zone of Bugesera, Rwanda, led to the production of fuelwood of 3.7–5.0 t ha^{-1} $year^{-1}$ (Balasubramanian and Sekayange 1992). *Gliricidia sepium* (Jacq.) Walp. is also a promising fuelwood species. Under favourable environmental conditions (annual rainfall of 900-1,500 mm, elevations of 0-1,200 m, deep and well drained fertile soils), this species is capable of producing 3.6-7.1 t ha^{-1} $year^{-1}$ dry weight of fuelwood (FAO 1993). Evidently, such productivity will have consequences for crop yield, as competition will increase and crop yield will decrease with increasing resource capture by the trees. In the case of alley cropping, competition between trees and crops cannot be avoided, and the farmer will have to consider the trade-off between production of agricultural crops and the growth of trees.

The coppicing ability of many multipurpose shrubs makes them produce substantial amounts of stem biomass that can be used as fuelwood. For leucaena and sesbania, the number of coppice shoots per stump increases with stump height (Misra et al. 1995). Dry matter production in hedgerows of *L. leucocephala* and *Calliandra calothyrsus* are higher for calliandra (124-196 kg/100 m hedge) than leucaena (66-102 kg/100 m hedge/year) when cut at different cutting heights (Newmann and Pietrowicz 1986). Converted to a per hectare basis, these yields in hedgerows correspond to theoretical annual dry matter production of approximately 4-6 t ha^{-1} for *L. leucocephala* and 10-16 t ha^{-1} for *Calliandra callothyrsus*.

Generally, the highest productions are due to high coppicing ability and fast growth rates that allow successive harvests, sometimes three times, within a year. This is the case for some agroforestry species (e.g. *Mimosa scabrella*, *Jacaranda mimosifolia* D. Don, and *Alnus acuminata* Kunt) that have been identified for their adaptability and growth in various parts of the country by agroforestry research from 1980s.

Compared to tree blocks, alley cropping produce progressively more mulch and hence yield significantly higher nutrient masses. In Benin, the cut dry matter produced from five cuttings of *Gliricidia sepium* and *Flemingia macrophilla* per cropping season ranged from 855 to 1,651 kg ha^{-1} year^{-1} for alley hedges and from 777 to 869 kg ha^{-1} year^{-1} for tree block (Böhringer and Leihner 1997). Topographic conditions and land scarcity in Rwanda make alley cropping a promising agroforestry system that can contribute to erosion control, soil fertility replenishment and provision of fuelwood for cooking in rural households.

Boundary planting

Boundary planting involves the planting of trees along the perimeters of farmers' properties for land delimitation, timber, fuelwood, soil conservation and wind protection. This system may also provide secondary benefits such as fodder, mulch and stakes for climbing beans. Less shading tree species that not compete with crops are used. By managing this system, farmers are able to continue cropping trees right up to the edge of the homestead. Most farmers in Rwanda are found to use *Grevillea robusta*, *Cupressus lusitanica*, *Euphorbia tirucalli*, *Erythrina abyssinica*, and *Dracaena afromontana* to demarcate farm and plot boundaries. The first two tree species are large size trees commonly used in plot demarcation, boundary marking, stabilization of roads and as windbreaks. In addition to fuelwood, they are also used for other products including construction poles and timber.

Live fences

Live fences with indigenous shrub species such Euphorbia spp. and some exotic tree species such *Calliandra calothyrsus*, *L. diversifolia*, and *Senna spp.* are also established into hedges around farms and homestead in order to provide fodder for farm animals, mulch and to protect planted crops from livestock damages. Besides their main function live fences can provide fuelwood, act as wind breaks or control erosion, depending on the species used.

Improved fallows

Many researchers in agroforestry (e.g. Buresh and Cooper 1999; Nakakaawa et al. 2004; Kwesiga and Coe 1994) have found that fallow technologies with multipurpose shrubs increase yields of subsequent crops and that large amount of harvested woody biomass can be used as fuelwood. Owing to the severe land shortage, fallowing is impractical for the majority of agricultural households in Rwanda. However, agroforestry research and development in Rwanda and in other countries in Africa found that improved fallows, that involve the rotation of planted N-fixing trees with crops, can produce substantial amount of fuelwood next to improving soil fertility and soil structure (Kwesiga and Coe 1994; Sanchez et al. 1996; Mafongoya and Dzowela 1999; Banzi et al. 2004; Pye-Smith 2008).

Studies on fuelwood consumption in Zambia confirmed that 11% of firewood consumed by rural households comes from improved fallow fields (Govere 2002). In Eastern Zambia, *Sesbania sesban* improved fallows produced 15 and 21 t ha^{-1} of fuelwood after 2 and 3-year fallows, respectively (Kwesiga et al. 1999) while in western Kenya, 15 and 21 Mg ha^{-1} of fuelwood were harvested from sesbania fallows after two and three years, respectively (Kwesiga and Coe 1994). In the same region, on small plots of 0.01-0.08 ha planted to improved fallows, Jama et al. (2008) concluded that the actual fuelwood harvested from the plot would last a typical household between 11.8 and 124 days depending on legume tree species and fallow duration. Further, they argued that this would increase to 268.5 and 1173.7 days if farmers were to increase the area planted to 0.25 ha.

The foregoing supports the view that improved fallows may provide ample quantities of fuelwood. More importantly, the use of these fertilizer trees increases the yields of subsequent crops. A recent meta-analysis from 94 studies published in Sub-Saharan Africa concluded that fertilizer tree systems could double and even triple the yields of maize (Sileshi et al. 2008). In Kenya, 53 and 42% increase in maize yields were recorded for *L. leucocephala* and Gliricidia sepium, respectively (Akinnifesi et al. 2006). In Zambia, sesbania fallows were reported to have increased maize yields by 500% (Chirwa et al. 2003) while in Tanzania, the improved fallows with tephrosia and sesbania increased maize yields to 40 and 68%, in that order (Gama et al. 2004).

The benefits of fallows depend upon biomass accumulation; longer fallow periods generally result in greater increases in crop yield and residual effect (Kwesiga et al. 1999). However, land scarcity and high population density in Rwanda make extended fallow periods impractical to smallholder farmers. The latter practice continuous cultivation to produce food crops for their families. Improved fallow can be practiced in the Eastern Province where the average area by agricultural household is 1.1 ha (larger than the national average of 0.76 ha).

Alternatively, relay fallow cropping with N2 fixing trees is a form of improved fallow technology in farming systems where landholdings are small. The system allows concomitant cultivation of trees and crops (ex. Maize), with fixation of N (sesbania, tephrosia, gliricidia). Relay fallow cropping with sesbania or tephrosia was found efficient in southern Malawi where the average landholding was 0.4 ha and the population density 300-500 persons km^{-2} (Akinnifesi et al. 2009).

2.3 Fuelwood consumption

Various reports have presented data describing the fuelwood consumption and supply in the country. Unfortunately, the majority of existing figures are historical or estimations used to justify the assumed impact of fuelwood consumption on forest stock and the balance between the demand and supply of wood products including fuelwood. Considerable amount of data on wood consumption have been generated in the past and speculations about fuelwood demand and supply balances have been based on these data. Different government institutions generated data on wood consumption at different periods of time (e.g. MINAGRI 1983; MINITRAPE 1992; MINECOFIN 2003). A study conducted in 1993 by Hategeka (1997a) focussed on fuelwood and residue use in the long rainy season and long dry season in four different parts of the rural areas of the country and in 48 institutions in Capital Kigali, and concluded that fuelwood contributes more than 80% of all energy used in the country.

Per capita fuelwood consumption has been given into different units, in kg or in m^3 of wood or vegetable materials, or in the percentage of the population using a given source of energy. In most cases, data on fuelwood consumption was derived by multiplying estimated per capita consumption with population figures. A more recent survey conducted in 1993 estimated the average daily consumption of fuelwood in households at 1.33 kg of air dried wood per person per day (Hategeka 1997a). This amounts to 486 kg of dried wood per person per year, equivalent to 0.67 m^3 per capita per year[5].

Between 1981 and 1982, an average per capita firewood consumption of 0.83 m^3 $year^{-1}$ was reported by MINAGRI (1983). Using the long term monitoring methods of measuring biomass consumption, Karenzi (1994) estimated the daily consumption of fuelwood in rural Rwanda to be 0.91 kg per capita, corresponding to 327 kg $year^{-1}$. Using an average fuelwood density of 725 kg m^{-3}, per capita fuelwood consumption is about 0.5 m^3 $year^{-1}$.

Differences in fuelwood consumption data arise from different sampling designs and different methodologies that have been used at different periods and localities. Sample sizes varied from less than 100 households to approximately 1,000 households in selected administrative

[5] Author's estimate based on a fuelwood density of 725 kg m^{-3} (FAO 2004)

units distributed over the country. Obviously, the question arises on how to select a representative household in fuelwood consumption study in a country with different agroecological zones and socio-economic characteristics of resident populations.

Although data on fuelwood consumption are available, no information is provided on the total demand in order to establish the balance between demand and consumption. Since many surveys on fuelwood consumption indicated the use of crop residues as supplementary fuels used when fuelwood is scarce, it is assumed that the demand of fuelwood is larger than consumption.

Fuelwood is not only used by households, but also by some industries and miscellaneous institutions. The amount of fuelwood used varies with the type of enterprise, the institution and production process undertaken, the scale of operation, and the efficiency of equipment used (Kgathi and Mlotshwa 1994). In most cases, basic information on the consumption figures of fuelwood by institutions and industries is as unreliable as that on household use. A few available studies suggest that institutions and industries use large amounts of fuelwood. For example, Hategeka (1997a) reported that substantial amounts of fuelwood are used by bakeries (1.71 m^3 day^{-1}), brickworks (0.96 m^3 day^{-1}), schools (0.91 m^3 day^{-1}) and restaurants (0.50 m^3 day^{-1}). This historical data has been collected in a specific study site, Capital Kigali, leading to erroneous figures when extrapolated to the national level.

On the extent to which fuelwood is used in government institutions and small scales enterprises, data are scarce and less reliable. Information is generally lacking regarding the amount of fuelwood used to produce a given amount of products. As a result, quantitative comparisons of fuelwood use cannot be accurately made. In general, as more than 90% of Rwandans depend on fuelwood for cooking meals, most of the demand comes from households, the rest being shared between industries and institutions.

Many authors (e.g. Cline-Cole et al. 1990; Lefevre et al. 1997; Turker and Kaygusuz 2001; Pandey 2002; Bandyipadhyay and Shyamsundar 2002) have identified factors that influence fuelwood consumption. The location of households relative to forest resources, and to urban and rural settings, is one of these factors. Fuelwood consumption studies carried out in Rwanda have not made a clear distinction in per capita fuelwood consumption between rural and urban areas. Only MINECOFIN (2003) made the distribution of households by main source of energy for cooking and lighting by urban and rural residence. Table 2-5 shows the percentage of the population using different sources of energy for cooking and lighting in both areas in 2002.

From table 2-5, it is clear that wood, as firewood and charcoal, supplies energy for cooking to 92.2% of the population in rural areas and to 93.5% of the population in urban areas. The slight difference in the proportion of people using fuelwood between urban and rural areas could be explained by access and more intense use of vegetable materials for energy needs in rural areas. The consumption of vegetable materials is higher in rural areas (7.1% of rural dwellers) than in urban areas (3.4% of urban dwellers). At national level, these materials are used by 6.5% of the population.

Table 2-5 Energy consumption of resident population in Rwanda in 2002 (MINECOFIN 2003)

Energy type	Energy use (%)					
	Cooking			Lighting		
	Urban	Rural	National	Urban	Rural	National
Electricity	0.7	0.0	0.1	25.9	0.6	4.6
Private hydro-electric source				0.1	0.0	0.1
Solar, plates/Electric generator				0.2	0.1	0.1
Gas	0.2	0.0	0.1			
Kerosene/bush lamp	0.2	0.1	0.1	26.1	8.9	11.6
Lampion/wicker				41.7	68.7	64.4
Candle				1.8	0.2	0.5
Firewood/wood	52.2	91.0	84.9	2.4	18.3	15.8
Charcoal	41.3	1.2	7.5			
Vegetal materials	3.4	7.1	6.5			
Other	1.3	0.1	0.3	0.7	2.4	2.2
Not specified	0.7	0.4	0.5	1.1	0.8	0.8
Total	100.0	100.0	100.0	100.0	100.0	100.0

Other sources of energy such as electricity, petroleum products, peat and methane gas are little used compared to fuelwood (Fig. 2-3). While biomass contributed 93% of total energy consumption in 2005, electricity supplied only 0.9% and fossil fuels accounted for 6.1% (MINEFI-DGTPE 2005). Petroleum products are used mainly in transport sector, in industry and in lighting at household level. Electricity is rarely used for cooking but finds application in industries, in private and public institutions. In some households, particularly in urban areas, electricity is mainly used for lighting, and for refrigeration.

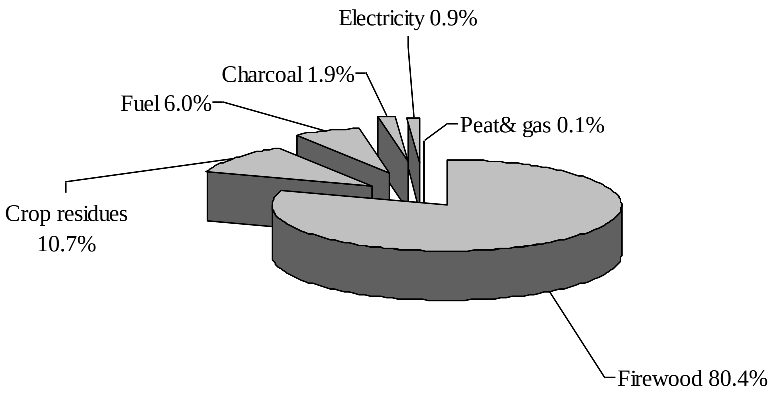

Fig. 2-3 Contribution of energy sources to total energy consumption in Rwanda in 2005 (MINEFI – DGTPE 2005)

Though the country has considerable potential of energy sources other than biomass, these have been exploited on much smaller scales. For example the annual hydroelectric power production from four national power stations was 45 MW in 2003 while the potential is estimated at approximately 90 MW (MININFRA 2004b). Reserves of methane gas deposits ranging from 55 to 70 billion m^3 in Lake Kivu are estimated to potentially produce between 200 MW and 700 MW as recoverable energy potential.

Peat reserves amount to 155 million tonnes of which one third is an exploitable raw material (MINEFI-DGTPE 2005), albeit not in a sustainable way. The solar energy is little used but has considerable potential as the recorded insulation is nearly 5.2 kWh m^{-2} day^{-1} (MININFRA 2004b). These energetic sources, once fully exploited, present advantages of being easily accessible and available in ample quantities that can be used to substitute fuelwood for use in households, industries and miscellaneous institutions.

In households, cheap and accessible sources of energy are used. The use of fuelwood is predominant in rural areas as well as in urban areas. A study by Leach and Mearns (1988) suggests that even in cities where fuelwood is more expensive than the modern alternatives, people prefer fuelwood because: (i) the supply is more secure, (ii) the fuelwood is available in small, affordable quantities in local markets, and (iii) fuelwood requires no expensive initial investment in cooking stoves. Therefore, to understand urban fuelwood problems, it is essential to understand the structure of urban fuel markets.

Urban dwellers in the capital Kigali have few affordable alternatives to firewood and charcoal for cooking, as all petroleum products and electrical tariffs are comparatively expensive (GTZ and MARGE 2008). In addition, few urban households, estimated at 26% of urban dwellers have access to electricity while on national level, electrical connections is estimated to cover only 8% of the country's area (MININFRA 2004b). In addition to other reasons, this leads to increasing cost of fuelwood and charcoal in the capital Kigali. For instance a bag of charcoal of approximately 45 kg is sold at a retail price of approximately US$ 12 at the time of this review (2009).

2.4 Fuelwood demand and supply balances

The balance between fuelwood demand and supply in Rwanda has always been estimated based on population data, per capita fuelwood consumption and forest stock, neglecting trees on farms. In 1981, the fuelwood gap calculated as the difference between sustained harvests from forests and the amount of fuelwood consumed was estimated at 2.8 million m^3. This gap was 3.0 million m^3 in 1990, and 4.5 million m^3 in 1997 (MINITERE 2002). In 2004, the overall wood deficit, including fuelwood, was reported to be 6.7 million m^3 (MINITERE 2004c). These data indicate that fuelwood demand has been higher than supplies as estimated from forest stock only, without accounting for the amounts of wood that can be collected from agricultural lands. Using the average of 1.5 m^3 ha^{-1} $year^{-1}$, wood from 1.4 million ha of agricultural lands would be about 2.1 million m^3 $year^{-1}$. As a result, supplies from agricultural lands substantially reduce the projected fuelwood gap. In Fig. 2-4, the observed pattern indicates that fuelwood demand has been increasing over the years, while total production of forests has been declining.

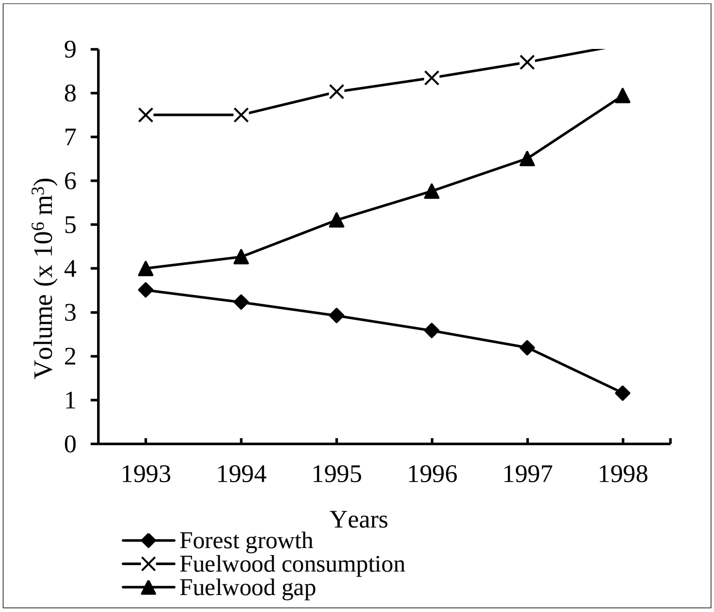

Fig. 2-4 Fuelwood demand and supply forecast for Rwanda, 1993-1998 (Murererehe 2000)

The consumption of all wood products was projected to follow the same trend as fuelwood consumption. Figure 2-5 gives a comparison between potential wood removals, wood needs and gaps, from 1960 to 2002. It shows that population growth increases utilization of wood from forests. Already in 1970, when population size was about 2.7 million, wood forest resources alone were not enough to meet the demand for wood products, including fuelwood. In the following 10-year period, the population increased significantly to reach almost 4.8 million in 1980. Wood deficit became progressively worse after 1990.

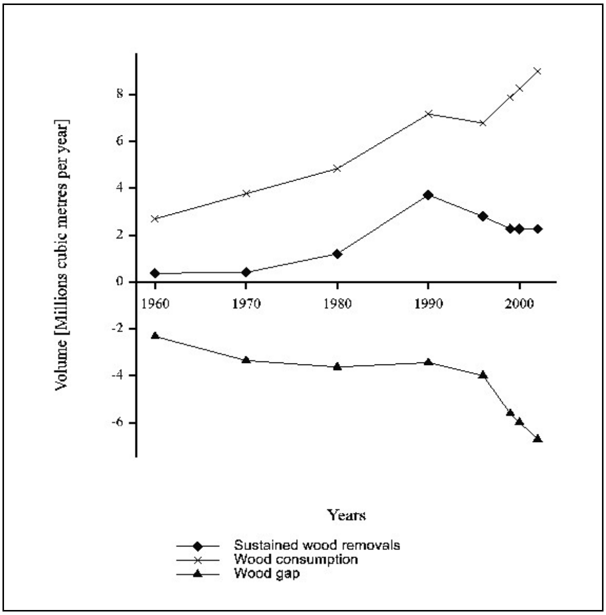

Fig. 2-5 Needs and sustained yield of wood in Rwanda (MINITERE 2004c)

The volume of wood consumed annually carries some level of bias in the estimation because per capita wood consumption was calculated based on the size of the population assuming that all people consumed equally the same amount of wood and depended only on forests to meet their energy requirements for cooking. Consequently available data on fuelwood demand and supply balances should be interpreted bearing in mind that trees in agricultural fields and other alternative sources of energy for cooking have not been considered in the estimation of fuelwood gaps.

2.5 Impact of fuelwood consumption on land use

In Many Sub-Saharan Africa, rural fuelwood use is often cited as a factor in large-scale deforestation without sufficient evidence (Mercer and Soussan 1992). A study carried out in the Southern African Development Coordination Conference (SADCC) region concluded that rural subsistence households do not cause deforestation (Misana 1988). In Mali, Benjaminsen (1997) found that locally induced deforestation caused by fuelwood use did not represent an immediate problem in rural areas. In Kenya, Mahiri and Howorth (2001) concluded that deforestation and subsequent degradation had little to do with fuelwood consumption as much was extracted from outside the forests. In their review on fuelwood consumption in developing countries, Arnold et al. (2003) concluded that fuelwood supplies come from non-forest resources, hence fuelwood collection by rural dwellers has much less impact as might be concluded from forest supply of fuelwood only.

In Rwanda, between 1960 and 2002, the forest area declined dramatically from 634,000 ha to 221,200 ha, corresponding to a reduction in cover of about 65% in the last four decades (MINITERE 2005). Table 2-6 shows the change in forest cover for the main protected forest areas in Rwanda between 1960 and 1999.

Table 2-6 Protected forests' cover change in Rwanda between 1960 and 1999 (MINITERE 2005)

Protected forest	Forest cover (ha)						Cover change (%)
	1960	1970	1980	1990	1996	1999	
Nyungwe	114,025	108,800	97,000	97,000	94,500	89,150	21.8
Gishwati	28,000	28,000	23,000	8,800	3,800	-	-
Mukura	3,000	3,000	2,000	2,000	1,600	1,600	46.7
Birunga	34,000	16,000	15,000	14,000	12,760	12,760	62.5
Akagera	267,000	267,000	267,000	241,000	220,000	90,000	66.3
Other[a]	150,000	150,000	90,000	50,000	20,000	-	86.7
Total	596,025	572,800	494,000	412,800	352,660	193,510	

[a] Gallery forests and savannah woodlands

The cause of the deforestation in Rwanda between 1960 and 1999 is associated mainly with the need to open up and exploit land area for food production, thereby removing the wood production system. The expansion of agriculture land is generally considered to be the main cause of deforestation in tropical Africa (e.g. Boahene 1998; Adedire 2002; Zhang et al. 2002; Pote et al. 2006). Through this practice, substantial quantities of wood resources are collected for household energy source or either burn on field or left in the agricultural fields. Various reports (e.g. Percival and Homer-Dixon 1995; Gasana 1997; MINITERE 2003) presented additional significant causes of deforestation in order of importance as livestock farming, logging for valuable tree species, collection of wood products including firewood and charcoal production, bush fires, mining, and conflicts and war.

The impact of wood consumption including fuelwood on deforestation has been analysed in relation to total annual wood consumption and annual allowable cut. As a result, some authors (e.g. Gasana 1991a; Gasana 1994) estimated that deforestation occurs when the rate of wood harvest is greater than the growth of new stock. From the definition view point, deforestation encompasses the removal of forests leading to change from land use for forest to other land uses, or reduction of forest crown cover to less than 10 per cent. Fuelwood gathering in existing forests by rural households is a common practice that normally does not change forest cover. In contrast, commercial exploitation of forests for firewood and charcoal leads to deforestation as it has been the case in the savannah woodlands in the eastern region of Rwanda (Hoster and Milukas 1992).

High deforestation rate was registered after the outbreak of the civil war in 1990 and the genocide that has followed in 1994. During these periods, people were obliged to leave their area and settle elsewhere. Forests were identified as the campsites of these displaced people and hence large forests areas were cleared for shelter, with subsequent collection of fuelwood. The main driving force however, was the need for agricultural land rather than the need for fuelwood.

Immediately after the genocide of 1994, there was spontaneous occupation of the natural ecosystems by Rwandan returnees, aggravating the deforestation. This emergency situation has induced the declassification of the 2/3 of the eastern savannah falling within the Akagera National Park and almost virtual disappearance of Gishwati Forest in the North of the country (MINITERE 2003). In fact, these two ecosystems which are naturally fragile were forced to accommodate considerable numbers of people and cattle, greatly exceeding their carrying capacity. Therefore, the need for land for agriculture and settlement has most forced people to clear forests.

2.6 Conclusion

In Rwanda, forest plantations and agroforestry systems are the main sources of fuelwood. Imprecise estimates of the quantities of fuelwood collected from forest plantations are available. However, supplies from agricultural fields have not been quantified while they have a high potential to provide fuelwood on sustainable basis. The current country statistics have not included on-farm tree resources into the energy supplies, making the forecast of fuelwood demand and supply balances doubtful, and leading to overestimation of the gap between wood supply and consumption.

Since it is evident that a large part of the demand for fuelwood already comes from agroforestry systems and that agroforestry practices are promoted to ensure agricultural intensification, it should be analysed how much wood can be grown on farmlands, and how much competition this will give to crop yields. The assumption that all fuelwood used by the population comes from forests and thereby resulting in the depletion of forest stock is biased because as the problem of scarcity of fuelwood becomes more severe, the households are forced into a number of coping strategies, which include for instance the consumption of crop residues, the intensive use of tree species on farms and intensive planting of trees.

Given the small size and low productivity of forest plantations, the major source of fuelwood is agroforestry. As a viable option for land management, on-farm trees and woodlots can contribute significantly to fuelwood production in rural areas while improving the overall land productivity. This strategy, however, is only possible on farms with an area equal to or larger than 0.76 ha, because of the basic need for land for crop production. In order to address deforestation, more wood products should be produced on agricultural lands through well managed agroforestry practices and in forest plantations on selected sites. For this, the choice of tree species is crucial, as well as consideration of multipurpose tree species having fuelwood attributes, high biomass production rates and increased positive effects on crop yields.

Chapter 3 Choice of fuelwood sources in rural Rwanda: conceptual framework and empirical estimations

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Submitted

Abstract

Households in Rural Rwanda rely heavily on fuelwood for their energy needs for cooking meals. However, conditions that determine household choice of fuelwood sources are unknown. In this paper, we analysed the determinants of household choice for fuelwood from farms, forests, and markets. We used a conceptual framework that links demographic, economic and location factors to the likelihood of choosing a specific fuelwood source. A multinomial logistic model applied to household-level data collected across three altitude regions indicated that gender of household head , household size, farm size, household location, source of income, and monthly income had significant effects on the choice between fuelwood sources. The model predicted that many households obtained fuelwood from farms and forests, and from markets only in some cases. The choice of farms was influenced by farm size and farm income. The choice to collect fuelwood from forests was enhanced by household location in low and medium altitude regions, smaller farm size, lower monthly income, and having a female householder. The choice for markets was positively affected by larger household size, off-farm income and smaller farm size. These results implied that land and income poor households tend to collect fuelwood from forests, and that well-off households rely on market purchase of fuelwood. The analysis highlighted the need to promote agroforestry and forestry in conjunction with policies supporting diversification of income in rural areas, developing fuelwood markets and addressing energy related issues in view of agroecological factors, as well as socioeconomic conditions of the farmers.

Keywords: Fuelwood source; Household choice; Rural households; Rwanda

3.1 Introduction

In rural communities of developing countries, many households use traditional fuels for cooking, and kerosene for lighting (Cecelski et al. 1979; Heltberg et al. 2000).These sources of energy are inefficient, expensive and hazardous to health. Traditional fuels are far less efficient that modern ones, for example candles produce only 1%, and kerosene wick lamps only 2% of the luminosity of electricity per kilowatt hour of energy used. Generally kerosene is considered to be 3 to 5 times more efficient than wood and Liquid Petroleum Gas (LPG) 5 to 10 times more efficient for cooking (Barnes and Floor 1996). It was found that poor people spend a greater proportion of their income on energy than the wealthy. Better-off households spend between 3-7% of their income on energy services but the poor spend 15-28% (Eberhard and van Horen 1995). In addition, the combustion of biomass fuels results in high levels of acute respiratory infections and eye problems caused by smoke inhalation by women and children while cooking over inefficient stoves (Energia News 2001).

Despite all these problems, biomass fuels (firewood, charcoal, cow dung, crop residues, grasses) remain the dominant form of energy used for cooking. It was estimated that 96 % of the Rwandan population use fuelwood (NISR 2006). In the urban areas, the households that have electricity in their houses still depend on charcoal and firewood for cooking. Energy remains very expensive, accounting for 14% of all non-food expenditure of households (NISR 2006). The high cost of electricity and LPG results in rural households to use biomass in order to meet cooking and lighting needs. The widespread use of biomass for energy results from the lack of alternatives and financial resources that can enable households to move from traditional fuel to ‘modern” fuels (Karekezi et al. 2004).

In Rwanda, the alternative sources of energy are not used widely and many rural households continue to depend on collected fuelwood (GTZ and MARGE 2008). Although fuelwood collection from forests is banned, it is apparent that restrictions do not prevent rural households to collect fuelwood from forests. Illegal harvesting of trees (including charcoal making) in 80 % of existing forests have been recorded (ISAR and MINITERE 2008). This suggests that fuelwood scarcity force many households to break the rules and regulations on forest use regardless of the strong enforcement of the regulations by the decentralized services of the forest department at all levels of the administrative organisation.

Studies of household fuelwood use in Rwanda have not put forward its sources and amounts being collected from each source. Without supporting evidence, many reports (e.g. Percival and Homer-Dixon 1995; GTZ and MARGE 2008; NISR 2010) concluded that forest resources are very important for agricultural households and those with no or not enough farm fuelwood get supplies from public and private forests illegally, purchase fuelwood or burn crop residues collected from their own farms. Literature on the extent to which households in rural areas cope with fuelwood crisis is extensive (e.g. Brouwer et al. 1989; Brouwer et al. 1997; Dovie et al. 2004). For the rural households, the level of poverty can’t allow the population to move up the energy ladder, the cost of commercial energy sources being prohibitive (SEA 2006; MININFRA 2009). As far as Rwanda is concerned, conditions that determine the choice of fuelwood collection sources are not well understood.

In many developing countries, models have been developed to link household level fuelwood demand to household characteristics and energy substitutions (Masera et al. 2000; An et al. 2005; Ouedraogo 2006; Gupta and Köhlin 2006), and there has been none at all in Rwanda where the population derive livelihoods from subsistence agriculture and depend on biomass to produce energy for cooking meals. When and where affordable alternatives sources of energy for cooking are not widely available, it is possible to estimate the probability of a household using fuelwood to identify its source, and to determine conditions that make a household choose that particular source. Since there are different types of fuelwood collection sources, the multinomial logistic regression model is capable of establishing a relationship between the choice of fuelwood sources and the household socio-economic characteristics.

In this paper, we framed some hypothesis and constructed models that link the household characteristics to the choice of fuelwood collection sources. The main question was "what household demographic, economic and location variables determine the household choice of a particular fuelwood source over alternative sources of fuelwood? We believe that the model methodology provides a better understanding of the choice of fuelwood sources and indications for implementing forestry and energy policies aimed at enhancing sustainable supply of energy for cooking and addressing resource degradation.

3.2 Methodology

3.2.1 Conceptual framework of the choice of fuelwood sources by rural households

The purpose of this conceptual framework is to explain the determinants of the choice of fuelwood sources by rural households in rural Rwanda, that is, the choice of collection and consumption of fuelwood from forests, farms and markets. Natural forests and other indigenous forests are not structural sources of fuelwood because their conservation status as forest reserves or parks excludes wood exploitation, including wood for energy.

Within a region, households have different socioeconomic status and therefore do not have the same choice of fuelwood sources. It is anticipated that the household socio-economic characteristics and agroecological locations are associated with the choice of fuelwood sources. This relationship can be explored by logistic regression methods. Fig. 3-1 consists of a framework for fuelwood choices available to rural people and conditions that determine collection and consumption. The main components of this framework are described below.

Decision parameters

In the framework above, the decision parameters constitute a set of different household characteristics and location variables that need to be analysed in order to identify the combination of best predictors of the household choice of fuelwood sources. The household characteristics, including income, household size and farm size are assumed to be among the determinants of household choice of fuelwood source. Besides these, there are also agroecological factors including agro-bioclimatic factors and availability of forest resources that drive households to choose a particular fuelwood source. The decision on the choice of a fuelwood source is therefore represented by a model that includes the characteristics of the households and their environment because the households of the rural areas are heterogeneous and forests are unevenly distributed across the different regions of Rwanda (MINIFOM 2010). Hence, the household choice of fuelwood sources depends largely on socio-economic conditions and the status of forest resources in the neighbourhood of households.

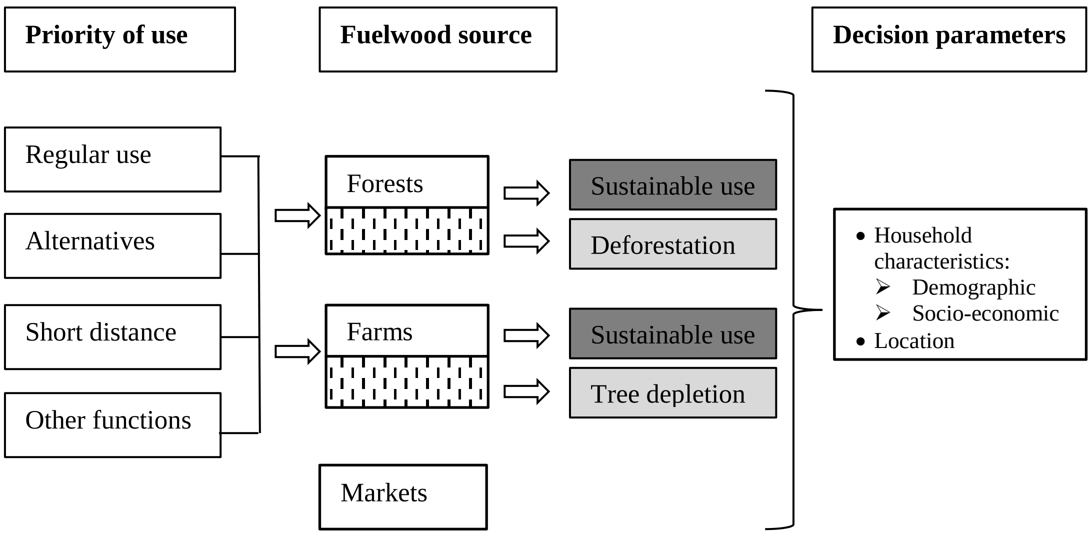

Fig. 3-1 Conceptual framework of main components affecting the choice of fuelwood sources by rural households in Rwanda

Household fuelwood consumption depends on available amount of local resources, which are closely connected with the rural economy and living standard (Xiaohua and Zhenming, 1996). Well-off rural households may tend to have better access to fuelwood from own farms or purchased fuelwood, being less reliant on forests. Since affordable alternatives to fuelwood are not available, the energy ladder model (Hosier and Dowd 1987; Leach 1987; Koumoin 1998; Masera et al. 2000; Chambwera 2004) may not apply to the rural situation. In this model, income is the major ingredient that induces a change in fuel use, resulting from a shift from cheaper technologies (e.g. cow dung or crop wastes) to more modern technologies (Electricity, gas). Wealth parameters including income, farm size and livestock ownership can influence the rural household decision to collect fuelwood from his farm or to purchase fuelwood. Many studies (e.g. Gupta and Köhlin, 2006; Abebaw 2007; Gupta et al. 2009; Arabatzis and Malesios 2011) investigated the association between various socio-economic variables and fuelwood consumption. They found that income, farm size and number of members in households predicted the consumption of fuelwood. Fuelwood consumption is also linked to demographics, cash income and land based livelihoods (Dovie et al. 2004). The poorer the rural households are according to their economic status and resources endowments, the greater is the dependence on forests for fuelwood collection.

Since the majority of rural households are income poor and survive on subsistence farming, a representative household collects either all, a part or none of its fuelwood requirements subject to boundary conditions of its size, income, income sources, farm size and other resources. In addition, the availability and location of forests influence the probability for the households to collect fuelwood from forests. On-scale basis, the potential supply and demand of fuelwood varies with location of the household relative to the forest area (Top et al. 2004; Köhlin and Parks 2001).

The association between the choice of a fuelwood source and various household characteristics and location variables can be determined by a model predicting the probability that a household belongs to a particular category of fuelwood source. Given the different fuelwood sources available in rural areas, the predicted probabilities can be used to compare the relative choice of fuelwood sources by rural households. Thus, these probabilities can be used to predict when the choice of a source may or may not occur, relative to alternative sources of fuelwood.

Fuelwood sources

Generally, rural Rwandan households have different fuelwood sources. Farms, forests and markets are the major sources of fuelwood and other wood products. Some rural households collect and use fuelwood from more than one source. These households are considered here as collectors of fuelwood from multiple sources. By its forest policy, Rwanda aims at making forestry one of the bedrocks of the economy and of the national ecological balance. In order to achieve these aims, the country carries out massive reforestation activities and education about forest management. The government policy also supports the development of forests on private lands and promotes agroforestry. As a result of these efforts, the forest area increased by about 2.5 % between 2000 and 2010 (FAO 2010c). However, existing literature indicates that forests are threatened by the population dependence on fuelwood and charcoal for energy (Musahara 2006; CGIS-NUR and

MINITERE 2008; REMA 2009). For the Rwandan forests and agroforestry systems to provide a variety of ecological, social and economic benefits, it is necessary to examine and understand the factors that drive rural households to collect fuelwood from a given source, and, especially, determine how free are the households to choose between different types of fuelwood sources.

Under conditions of low income and small farm size, many households are reliant on fuelwood from forests. Dependence on forests for meeting the household needs is expected to continue and might even increase if substitute sources of energy for cooking are not widespread. There are, however, trade-offs between collection from forests and farms, which are consistent with the rural poverty and subsistence farming on small farms. The growing shortage of fuelwood and restriction of access to fuelwood from forests drive many households to increase tree planting on their farms, thus enhancing competition between food crop and tree crop production. Under conditions of high income and large farm sizes, the households are able to produce the fuelwood they need on their farms or can purchase fuelwood. However, this type of fuelwood source is not accessed by many households partly because they are income poor. If the farmers are unable to meet their fuelwood requirements from trees and woodlots on farms, they usually collect fuelwood from forests, purchase fuelwood if they have money to do it, or choose to collect fuelwood from multiple sources to secure sufficient energy for cooking.

Basically, the choice of a fuelwood source is determined by four conditions. Firstly, if fuelwood is plentiful on farms, households will depend on trees and woodlots on farms (i.e. agroforestry) for the supply of energy for cooking. In this way, the household farm will collect fuelwood on sustainable basis. If there are plenty of fuelwood on farms, the probability associated with the choice of farm to supply fuelwood is high. In this case, the household members won't walk long distance in order to collect fuelwood from forests and won't purchase fuelwood.

Secondly, if there is medium abundance of fuelwood in farmlands, rural households bridge the gap in fuelwood requirements by choosing other sources of energy such as markets if they have money to buy fuelwood, or collect supplementary supplies from forests. In this case, the probability of choosing farm fuelwood decreases since the abundance of fuelwood decreases. This situation may follow the case of high abundance of fuelwood on farms, after many years of continuous exploitation without replanting. If the amount of farm fuelwood is small, rural households will probably deplete trees on farms and will switch to sources of fuelwood outside their farms. The cumulative effect of farm fuelwood consumption decreases the total availability of fuelwood. The chance of choosing to collect fuelwood from farms decreases since the stock of on-farm trees and woodlots decreases also. Some households can compensate fuelwood shortage by burning increasing amounts of crop residues, cow dung and grasses. This consumption behaviour leads to environmental consequences including reduced soil fertility, erosion, and even localized desertification (Lindstrom 1986; Karlen et al. 1994; Andrews 2006). For increased crop yields, the collection of crop residues entails the household to increase fertilizer inputs to make up for nutrients removed in the plant materials.

Thirdly, there might be some cases of unavailability of wood resources on farms. This implies that there are no fuelwood trees available on farms or if they do, they are very few to meet the household demand for fuelwood. In this case, the collection of fuelwood from farms is not the first option to rural households. Households' coping strategies to fuelwood scarcity are also known (Mlambo and Huizing 2004; Madubansi and Shachleton 2007; Cooke et al. 2008; Palmer and MacGregor 2009; Akther et al. 2010; Bandyopadhyay et al. 2011). These strategies range from low cost to high cost options including increased time and labour inputs in fuelwood collection, reducing the energy consumption, increased use of purchased fuelwood and use of non-traditional fuels. Fuelwood purchase is an option to wealthy households. The poor households will address fuelwood scarcity through collecting fuelwood from forests. Since living trees are not felled for fuelwood, fuelwood collection by rural households does not induce deforestation (Morton 2002). The collection of fuelwood in form of dead wood is however a threat to forest biodiversity (Christensen et al. 2009).

If the fuelwood shortage is excessively high, the rural households will exert pressure on trees and woodlots present on agricultural land, leading to depletion of woody biomass on farms and land degradation. In the most extreme situation, any tree present on farms is removed, including the use of unsuitable fuelwood species on-farms such as *Vernonia amygdalina* and *Euphorbia tirrucalli* and *Ficus thonningii* (den Biggelaar 1996). Hence, the probability that rural households choose farms as a source of fuelwood is nil or little.

Fourthly, the demand for energy for cooking meals can exceed supplies from farms and forests. Supplementary supplies are obtained from markets and multiple sources. Purchased fuelwood is expensive; higher welfare households will purchase fuelwood and rural poor households will increase biomass collection from different sources. A switch between fuelwood sources may reflect a change in the household socio-economic status or the household adaptation to fuelwood scarcity.

Priority use of different types of fuelwood

Many factors determine the production of fuelwood and its consumption. Since fuelwood is usually produced by households for their own consumption, a model of household production is appropriate for household choices regarding its collection and consumption. The priority use of fuelwood from each of the three fuelwood sources presented above depends not only on household characteristics, but also on resource accessibility, the availability of alternatives and the size of the fuelwood source. An empirical focus is on the distance travelled to collect fuelwood. The distance determines the time allocated to collection and labour input (Bandyopadhyay et al. 2011) and the extent of forest degradation (Kuri 2007). Farm forestry may be an option for short distance collection of fuelwood while releasing the pressure on forests. In case of fuelwood scarcities, substitutes in the consumption of rural source of fuel are important. Local resources comprise other biomass fuels such as grasses, crop residues and cow dung. These are less suitable fuel sources usually used by few households, thus are not included in this framework.

The above discussion implies that if fuelwood is abundant on farms, households do not encroach on existing forests. During the time of reduced availability, household members would walk outside their farms to collect fuelwood or to purchase it from markets. Should the households adopt the first strategy, forests in their regions can be overexploited, leading to forest degradation, biodiversity loss and other environmental consequences.

When the probability of collecting fuelwood from farms is high, fuelwood can face an increasing harvesting pressure, leading to a decline in the availability of this resource. In response to this, wealthier households intensify tree planting on farms or purchase fuelwood. In contrast, poor households collect fuelwood from forests or use unsuitable sources of energy for cooking. In rural situation, the theoretical projection of the choice of fuelwood sources may results in different substitution effects among the fuelwood types.

3.2.2 Theoretical model and empirical methods

The specification of the household fuelwood choice can be derived from a random utility model (e.g., Ben-Akiva and Lehrman 1985; Train, 1998; Louviere et al. 2000). Let us consider a household i from a sample of *N* households who have to choose a fuelwood source from a feasible set defined by $j=1, 2, 3$ alternatives, corresponding to farms, forests and markets. We assume that each household attaches a utility value U_{ij} to each source depending on his preferences and household-specific characteristics X_i. For the ith household faced with J choices, utility of choice J can be written as:

$$U_{ij} = X_{ij}\beta_j + \varepsilon_{ij} \tag{1}$$

where U_{ij} represents the utility, X_{ij} is a vector of explanatory variables relating to the choice of fuelwood sources, $\mathcal{E}_{ij}$ relates to other unobserved factors that affect utility, and β_j is a vector of unknown parameters, coinciding with the variables that are deemed to influence utility of choice j. In this model, a household chooses the fuelwood source that maximizes his utility. Let C_{ij} denotes a discrete choice variable taking the value of 1 if a household gets its fuelwood exclusively from a source j and 0 otherwise. For example, a household will collect all its fuelwood from the first alternative (in this case, farms) only if the following inequality holds:

$$C_{i1} = 1 \text{ if } U_{i1} > U_{ij}, j = 2, 3 \quad \text{(2a)}$$

$$C_{i1} = 0 \text{ otherwise}$$

and the corresponding probability that a household i collects its fuelwood from farms can be expressed as:

$$P_{i1} = \Pr(U_{i1} > U_{i2} \text{ and } U_{i1} > U_{i3}) \quad \text{(2b)}$$

Therefore the probability that j is chosen is the probability that the random utility of choice j exceeds the random utility associated with any other choice h different from j. The analytical model followed here is the multinomial logit regression framework.

$$U_{ij} > U_{ih}, j \neq h \quad \text{(3)}$$

Equation (3) can be further be re-arranged , as shown by McFadden (1974):

$$\Pr(X_{ij}\beta_j + \varepsilon_{ij} \geq X_{ih}\beta_h + \varepsilon_{ih})$$

or (4)

$$\Pr(\varepsilon_{ih} - \varepsilon_{ij} \leq X_{ij}\beta_{jh} - X_{ih}\beta_h)$$

Equation 4 suggests that the choice probability is a cumulative distribution, which is the probability that the difference in the random component of the utility from two alternatives is below the difference in their deterministic components (Train 2003).

Multinomial logit models have been used by many authors (eg. Dubin and McFadden 1984; Hosier and Dowd 1987; Heltberg 2005; Couture et al. 2009) as a tool in empirical modelling. This model is used to predict the probabilities of the different possible outcomes of a categorically distributed dependent variable, given a set of independent variables which may be real-valued, binary-valued or categorical-valued. In this study the logistic formulation led to the estimation of the probability of making the choice of a particular fuelwood source given the demographic and the socio-economic characteristics of the households. Let there be dependent variable categories 1, 2, ..., J with 1 being the reference category. One regression is run for each category 2, 3, ..., J to predict the probability of Y_i (the dependent variable for any observation i) being in that category. Then the probability of Y_i being in category 1 is given by the adding-up constraint that the sum of the probabilities of Y_i being in the various categories equals one. The regressions are, for k = 2, 3, ..., J:

$$Pr(Y_i = k) = \frac{exp(X_i\beta_k)}{1+\sum_{i=2}^{J} exp(X_i\beta_j)} \tag{5}$$

and to ensure satisfaction of the adding-up constraint ,

$$Pr(Y_i = 0) = \frac{1}{1+\sum_{i=2}^{J} exp(X_i\beta_j)} \tag{6}$$

where Y_i is the observed outcome for the i^{th} observation on the dependent variable, X_i is a vector of the i^{th} observations of all the explanatory variables, and β_j is a vector of all the regression coefficients in the j^{th} regression.

The equation form of the model that gives the probability of the households' choice of a particular fuelwood source $P(Y_i = 1)$, can be represented as:

$$\ln\left(\frac{P_i}{P_1}\right) = X\beta \quad \text{for i = 2, 3, ..., J} \tag{7}$$

$\ln\left(\frac{P_i}{P_1}\right)$ gives the log odds-ratio for each combination of levels of the explanatory variables X. A variety of explanatory factors are investigated to determine their possible influence on the individual household choice of a fuelwood collection source. These factors are presented in Table 1. Maximum likelihood method is used to estimate the regression coefficients. The estimated coefficients give the impact of the predictor variable on the probability of choosing the category of fuelwood source in relation to a specified reference category. In logistic models, the coefficients give the change in the log-odds of choosing a fuelwood source for unit change in the predictor variables. These coefficients were calculated using STATA 11.0.

The empirical model above was used to test different hypotheses referring to household choice of fuelwood sources. The selection of the explanatory variables was guided by previous empirical studies on energy choices, economic theory and field observations in the study area. Many studies (e.g. Leach 1992, Masera et al. 2000, Gupta and Köhlin 2006) emphasize that there is an energy transition process whereby different combinations of fuels are used at different stages of economic developments following the energy ladder concept. However, this does not apply to Rwanda where most households are constrained by their physical and economic environment which renders them dependent upon fuelwood. The continuing heavy reliance on fuelwood is attributed to many factors including the lack of adequate modern energy supply and poverty. These factors in Rwandan economy force both rural and urban households to use fuelwood obtained from forests, farms and markets. The widespread use of fuelwood arises from a combination of household characteristics and location. In this study, we hypothesize that socio-economic characteristics and location of households explain the household choice to use purchased fuelwood or to collect it from farms or forests.

The use of fuelwood from the three main sources in Rwanda invokes cash and opportunity costs. Fuelwood collected from farms and forests carry the opportunity cost of using labour and land to supply energy for cooking food. The time and budget constraints implicitly capture this opportunity cost. When the households use purchased fuelwood, their choice for fuelwood market is determined by the market price. For non-market participants, the choice for farm and forest fuelwood is determined by fuelwood availability and the opportunity cost of collection labour. Empirical evidence based on the household economic framework suggests that the reason for widespread collection of fuelwood in rural areas is the very low opportunity cost of collection labour time (e.g. Dewees 1989, Bluffstone 1995, Baland et al. 2010). Hence, high labour cost limits fuelwood supply from farms and forests.

The combination of locally available fuelwood, and low opportunity costs of collection labour time can affect the choice for fuelwood markets by poor households. Fuelwood becomes expensive where forest and agroforestry resources are scarce or where increasing opportunity costs of collection labour make self-collection unattractive. Once commercialized fuelwood is accessible and affordable, fewer households choose to collect fuelwood from farms and forests. Households with better socioeconomic status are thus able to pay for market fuelwood rather than collecting fuelwood from farms or forests. The choice for fuelwood markets stems from time and energy savings in fuelwood collection. This is likely to benefit women and children who are most involved in fuelwood collection in many developing countries.

3.2.3 Data

The data in our study were derived from a socio-economic survey of households carried out in 2007/2008 in the low, medium and high altitude regions of Rwanda. Each of the three regions comprises three to five agroecological regions of which each presents a homogenous group of households in terms of land uses and socio-economic conditions. The study used 40 households selected randomly in the lowest administrative unit known as “Cell” to represent a particular agroecological region. This sampling strategy aimed at maximising neighbourhood level variations by sampling households from a setting with much local variation (Smith 1989).

In total, 480 households were interviewed using a structured uniform questionnaire. This questionnaire was in three sections. The first section collected information on the demographic and socio-economic conditions of the sample households. The second was on land use, with detailed information on planted trees and woodlots on-farms and their main characteristics of uses. The third section was on fuelwood consumption and fuelwood sources and the amounts of fuelwood used for cooking meals.

The key outcome variable of interest was the main source of fuelwood used in cooking meals. This was constructed from the question: "Where do you usually get the fuelwood you use for cooking meals?" Very often respondents mentioned more than one source of fuelwood. Questions related to how and where household obtained fuelwood or charcoal they used for cooking meals, and how much money the household spent on purchased fuelwood, enabled to validate or to determine the main fuelwood source in case of ambiguity.

Because Rwandan economy is based on agriculture and rural households depend on subsistence farming, we included a measure of the choice of fuelwood source focusing on farm sizes. In rural economy, land size can be considered as a source of livelihood and income because it gives the opportunity to grow both food crops, cash crops and other perennial crops including trees. The household surveyed was to report the size of farm. This data was assigned to farm size categories (below 0.6 ha; from 0.6 to 1.0 ha; and over 1 ha) for 444 households who owned lands. It was noted that 36 households (i.e. 7.5% of the sample households) were landless and depended on borrowed or hired plots for crop farming.

In the survey questionnaire, the interviewer had to record the monthly income brackets in Rwandan francs (1US$ = 604 Rwf, December 2011) to which a household belonged (< 5 000 Rwf; 5 000 – 10 000 Rwf; 10 000 – 15 000 Rwf; 15 000 – 20 000 Rwf; and > 20 000 Rwf). The geographical location of the households was recorded to capture any specific effects of non-observed regional characteristics (e.g. forest cover, topography, soil types, climate, etc.) that may influence the choice of a particular fuelwood source. For example, our expectation was that, in region where forest resources are abundant, resident households are forced to make use of these resources. The location of household was recorded on nominal level that is, each sample household in LAR was attributed 1, household in MAR 2, and household in HAR 3. For the analysis, however, a set of dummy variables was created for convenience.

Household size and gender of the heads of households have been found to influence the choice of fuelwood sources in many studies (e.g. Liu et al. 2005; Macht et al. 2007; Sapkota and Odén 2008). In this study, the gender of the head of the household was used to construct a dichotomous measure of whether a household was headed by a female, coded 0, or by a male, coded 1. The size of the households was measured by the number of members in the households by classifying households into five categories of 1 - 3 persons; 4 - 6; and > 6 persons.

The main source of income was a dummy variable that indicated whether a household generated income from agriculture activities or not. For this variable, the respondent was asked “What is the main source of income in the household?” This variable was coded 1 if the respondents answered any activity outside agriculture (off-farm income) and 0 if the respondent answered agriculture (farm income). As an indicator of wealth, a dummy variable, accounting for whether the household owned livestock, was included also. The effect of ownership of livestock enabled to examine whether livestock owner and non-owner households depended differently on farms, forests and markets for fuelwood supply. The size of the sample households across the different levels of the outcome and the predictor variables are presented in Table 3-1.

Among predictor variables, household size, monthly income, and farm size are continuous variables. Other predictor variables of household choice of fuelwood source namely location of the household, main source of income, gender of the head of the household, and ownership of livestock, are framed as binary variables.

3.2.4 Descriptive assessment of the sample households

The main interest in the analysis was to determine important variables that determine the choice of a fuelwood source. In the study area, there was three sources where fuelwood could be collected by rural households. Table 3-2 gives a list of main explanatory variables for which household data were elicited and their summary statistics across the three fuelwood sources.

The statistics of the variables are based on numerical values assigned to them, hence are difficult to interpret. Therefore, we present the percentage of households for different levels of predictors variables by main types of fuelwood sources.

Table 3-1. Characteristics of the variables included in the model, N = 480

Variable	Variable acronyms	Frequency
a. Outcome variable:		
Fuelwood sources	SFWD	
Farms		234
Forests		140
Markets		106
b. Predictor variables		
Location of the household		
LAR	REG1	200
MAR	REG2	160
HAR	REG3	120
Number of the household members	HSIZE	
1 - 3		100
4 - 6		229
> 6		151
Main source of income	SINCO	
Farm		384
Off-farm		96
Monthly income (in Rwandan Francs)	INCOM	
< 5 000		203
5000 - 10 000		143
10 000 - 15 000		44
15 000 - 20 000		21
> 20 000		69
Gender of head of the household	GEND	
Female		137
Male		343
Farm size (in ha)	FSIZE	
0		36
< 0.6		214
0.6 - 1.0		145
> 1.0		85
Ownership of livestock	LSTOC	
No		182
Yes		298

* 1 US$ = 604 Rwandan Francs, October 2011)

Many (49 %) households collected fuelwood from farms; 29 % of the sample households obtained fuelwood from forests and 22 % of the households purchased fuelwood (Fig. 3-2). These percentages indicate that much pressure is put on farms since fuelwood from forests and market purchase carry some costs which many rural households can't afford.

Table 3-2 Definition and summary statistics of predictor variables by fuelwood sources

Variables	Farms (N = 234)		Forests, N = 140		Markets, N = 106		Max	Min
	Mean	SD	Mean	SD	Mean	SD		
Gender of head of household (1 if male, 0 if female)	0.74	0.44	0.63	0.48	0.76	0.43	1	0
Household size	2.03	0.70	2.09	0.71	2.29	0.72	3	1
Source of income (1 if off-farm, 0 if farm)	0.16	0.37	0.16	0.37	0.33	0.47	1	0
Monthly income	2.32	1.46	1.85	1.22	2.35	1.41	5	1
Farm size	1.72	0.84	1.39	0.85	1.53	0.89	3	0
Ownership of livestock (own = 1)	0.65	0.48	0.56	0.50	0.64	0.48	1	0
Location of the household								
LAR = 1, 0 otherwise	0.42	0.50	0.44	0.50	0.37	0.48	1	0
MAR = 1, 0 otherwise	0.28	0.45	0.48	0.50	0.26	0.44	1	0
HAR = 1, 0 otherwise	0.30	0.46	0.08	0.27	0.37	0.48	1	0

In general, all the fuelwood sources were used by the rural households regardless of their socio-economic status and locations (Fig. 3-3). There were, however, different patterns in the proportions of households for the use of fuelwood from farms, forests and markets when the data was split among a range of the household characteristics. Large proportions of the total number of lowland (50 %) and highland households (58 %) collected fuelwood from farms, while a large part of midland households (42 %) gathered fuelwood from forests (Fig. 3-3A). More male than female heads of households collected fuelwood from farms or purchased fuelwood, implying that male headed households were less reliant on forests to obtain fuelwood for cooking food (Fig. 3-3B).

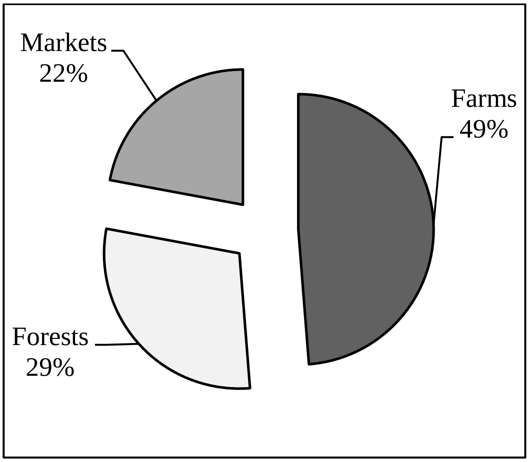

Fig. 3-2 Percentage of households by types of fuelwood collection sources

Figure 3-3C indicates that an increase in the size of the household was associated with a decrease in the percentages of households collecting fuelwood from farms and forests. In contrast, as the farm size increased, the proportions of households that purchased fuelwood from markets, increased (Fig. 3-3C). Similarly, as farm size increased, the proportions of households collecting fuelwood from farms increased also (Fig. 3-3D).

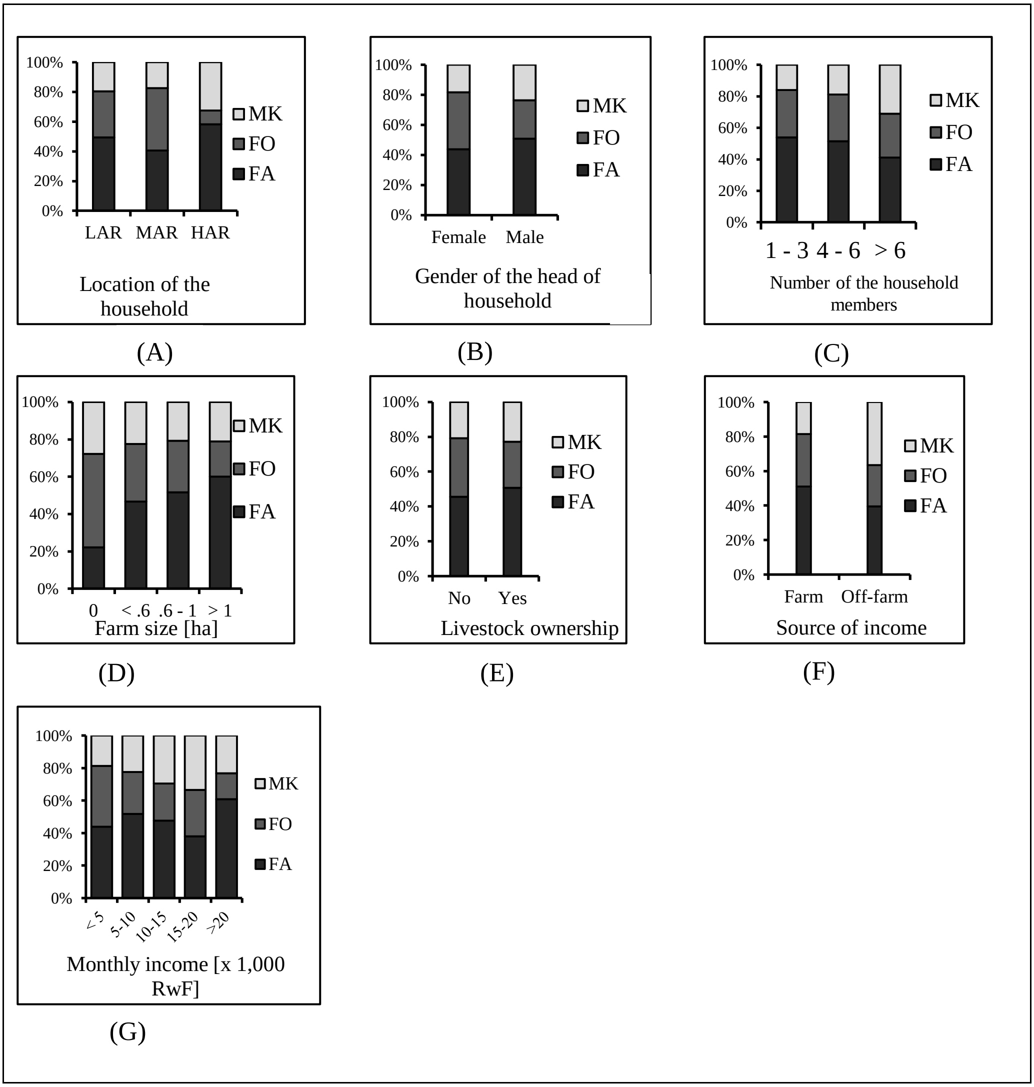

Fig. 3-3 Percentage distribution of households according to four fuelwood sources and location of the household (A), gender of heads of households (B), household size (C), farm size (D), the livestock ownership (E), source of income (F), and monthly income (G). Fuelwood sources are FA = farms, FO = forests and MK = markets. The stacked columns compare the proportions of households among the fuelwood sources and across the different levels of the household characteristics.

The proportions of livestock and non- livestock farmers did not differ much for the choice of markets (Fig. 3-3E). In contrast, more non-livestock farmers than livestock farmers collect fuelwood from forests. The distribution of rural households by their main source income indicated that more farm income households collected fuelwood from farms and forests more than their off-farm counterparts, except for market purchase of fuelwood. Since market options are present across the variables examined, market for fuelwood is functional in the study area and all income categories of households participate in this market (Fig. 3F). There was no distinct pattern between monthly income and the proportions of households obtaining fuelwood from farms and forests.(Fig. 3-3G). There is, however, a distinct pattern with market at least for the first four categories of monthly income: a move from lower to higher monthly income categories implied an increase in the proportions of households using fuelwood from markets (Fig. 3-3G). The test of the relationship between pairs of predictor variables showed no substantial correlations between them (Table 3-3). This indicated that there was little multicollinearity in the data. Although the correlations between these variables were statistically significant, the coefficients were small, suggesting that these variables were measuring different things (there was little collinearity). Of all the predictors, source of income, household size and farm size correlated significantly with the outcome, fuelwood source ($p < 0.01$), indicating that these two variables were associated with fuelwood sources used by rural households.

Table 3-3. Correlation matrix between pairs of variables

	GEND	HSIZE	SINCO	INCOM	FSIZ	LSTOC	REG1	REG2	REG3	SFWD
GEND	1									
HSIZE	-0.04	1								
SINCO	0.13**	-0.01	1							
INCOM	0.02	0.00	0.08	1						
FSIZ	0.01	-0.06	0.15**	0.16**	1					
LSTOCK	0.02	-0.02	0.12**	0.22***	0.32***	1				
REG1	0.03	0.04	-0.02	0.11*	0.19***	-0.01	1			
REG2	0.02	-0.08	0.03	-0.20***	-0.24***	-0.09*	-0.60***	1		
REG3	-0.05	0.04	-0.01	0.10*	0.05	0.11*	-0.49***	-0.41***	1	
SFWD	-0.02	0.13**	0.14**	-0.04	-0.13**	-0.03	-0.03	0.05	-0.02	1

* p < 0.05; ** p < 0.01; *** p <0.001

3.3 Results

3.3.1 Empirical results

A complete logistic regression model including the intercept and odds ratios is the recommended reporting format of logistic regression results (Peng and So 2002, Field 2009). The results of the multinomial logistic regression estimation are presented in Table 3-4 following this recommendation. The chi-square statistic reliably distinguished between fuelwood source categories given different sets of households characteristics (χ^2= 92.8, p < .000 with df = 16). The estimation results showed that the choice of a fuelwood source by a household was affected by demographic, socio-economic and location variables (Table 3-4).

The following observations were made from Table 3-4. The reference category is collection of fuelwood from farms. The estimated parameters therefore give the impact of the explanatory variable on the probability of choosing the category of choice in relation to the reference category. The choice of fuelwood from forests over farms was affected by location of the households in LAR and MAR, gender of head of the household, monthly income, and farm size. The choice between markets and farms was affected by household size, source of income and farm size.

The empirical results presented in Table 3-4 enables us to understand the effects of predictor variables on household choices among the three fuelwood sources. The geographical location of the household appeared to be one of the most decisive variables in the choice of fuelwood sources. Relative to HAR, the coefficient for the location dummies of household location in LAR and MAR are positive and significant for the choice of collecting fuelwood from forests, while they are negative and insignificant for the choice of fuelwood purchase from markets. These results imply that households in LAR and MAR depend relatively more on forests. In contrast, HAR households tend to collect fuelwood from farms and buy fuelwood from markets in few instances

Table 3-4. Multinomial logistic regression estimates of the effects of household characteristics on the choice of a particular fuelwood source relative to other fuelwood sources[a]

Variable	Forests		Markets	
	Coefficient	S.E	Coefficient	S.E
Gender of head of household (1 if male, 0 if female)	-0.686**	0.247	0.045	0.287
Household size	0.100	0.161	0.513**	0.174
Source of income (1 if off-farm, 0 if farm)	0.180	0.311	1.106***	0.289
Monthly income	-0.202*	0.091	0.011	0.087
Farm size	-0.401**	0.148	-0.359*	0.157
Ownership of livestock (own = 1)	0.102	0.252	0.006	0.272
Location of the household				
LAR (1 if LAR, 0 otherwise)	1.513***	0.373	-0.331	0.288
MAR (1 if MAR, 0 otherwise)	1.784***	0.381	-0.378	0.324
Constant	-0.655	0.580	-1.418*	0.593

Note: Numbers in parentheses are standard errors

[a] Model $\chi^2 = 76.16$***, Pseudo $R^2 = 0.08$

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

We included household demographic characteristics, notably gender of the head of the household, and household size to derive differences in fuelwood sources among households. These two variables affected the choice of fuelwood source differently. Gender of the head of the household significantly reduced the probability of collecting fuelwood from forests. Though not significant, gender of the head of the household appeared to increase the probability of purchasing fuelwood. These results mean that, relative to female, households headed by men appear less inclined to collect fuelwood from forests: households headed by men choose to use fuelwood collected from farms, or to purchase fuelwood.

Household size did not significantly affect the choice of fuelwood collection from forests. Though not significant, the positive sign of the coefficient of this variable for the probability of choosing forests over farms indicated that large households tend to collect fuelwood from forests. However, he effect of household size on the probability of choosing fuelwood purchase from markets was significant and positive, indicating that an increase in household size was associated with an increase of the probability of fuelwood purchase from markets. Thus, larger households, therefore, are likely to buy fuelwood from markets as the most convenient sources fuelwood.

The effect of source of income was invariably positive for the choice of forests and markets as source of fuelwood, pointing that off-farm income increase the propensity to choose fuelwood from these two sources. Off-farm income was negative but statistically insignificant for the probability of collecting fuelwood from forests, hence forests appears not to be a structural source of the fuelwood for off-farm income households. Instead, the estimated result showed that off-farm income had a strong and positive influence on the choice of markets. Hence, households that derive income from off-farm enterprises were less likely to collect fuelwood from farms but strongly preferred to buy fuelwood from markets.

Contrary to expectation, monthly income was insignificant for the choice of market as a source of fuelwood. On the other hand, a move from a lower to a higher income category of household decreased significantly the likelihood of choosing forests as source of fuelwood. Hence, when monthly income rises, the only influence is to decrease the probability of a household choosing to collect fuelwood from forestlands, suggesting that households in higher income category are more likely to obtain fuelwood from farms.

Farm size significantly influenced household choice of fuelwood from forests and markets and the signs of the coefficients of this variable was consistently negative. Increasing farm size reduced the propensity that households choose collecting fuelwood from forests and purchasing fuelwood from markets. The inverse relationship between farm size and the household choice of forests suggests that larger households are less likely to collect fuelwood from forests. Similarly, larger farm owners are less likely to purchase fuelwood. Thus, the only option left to larger farm owner households is to depend on farm fuelwood. The effect of livestock ownership on choice of fuelwood source is positive, but is statistically not significant. This means that livestock farmers tend to have more dependency on fuelwood from forests and markets, but the impact of this variable on the probability of household choice of these two sources is not statistically different from zero.

3.3.2 Classification of households by main fuelwood categories

In Table 3-5, three fuelwood categories are listed, together with the correct and incorrect classifications of the households as predicted by the model. From the row totals, 234 households fall into the category of farms, 140 households into the category of forests, and 106 household into the category of markets. These results match those presented earlier in Table 3.1. The predicted frequencies of households under each fuelwood category should be read column-wise with the cells on and off the diagonal representing correct and incorrect predictions, respectively.

Table 3-5. Correct and incorrect classifications of the households according to three types of fuelwood.

	Predicted			Total
Observed	Farms	Forests	Markets	
Farms	189 (80.8%)	37 (15.8 %)	8 (3.4%)	234 (100%)
Forests	82 (58.6%)	50 (35.7%)	8 (5.7%)	140 (100%)
Markets	69 (65.1%)	23 (21.7%)	14 (13.2%)	106 (100%)
Classification accuracy				253 (52.7%)

Note: Figures in shaded cells are correct classifications. Percentage of correctly classified households to the total number of households included in the analysis are given in parentheses.

Of the 234 households that were originally predicted to collect fuelwood from farms, 189 households (i.e. 80.8 %) were predicted correctly, and 45 households (i.e. 19.2 %) were predicted incorrectly (37 households (i.e. 15.8 %) were predicted to collect fuelwood from forests and 8 households (i.e. 3.4 %) were predicted to purchase fuelwood from markets)). Similarly, of the 140 households that were predicted to collect fuelwood from forests, 50 households were correctly predicted, and 90 households were incorrectly predicted (82 households were predicted collect fuelwood from farms and 8 households were predicted purchase fuelwood from markets). For the choice of market purchase of fuelwood, 14 households and 92 households were correctly and incorrectly predicted, respectively. The incorrect predictions represent the cross-effects of the factors influencing the choice of fuelwood categories. Many households were inclined to collect fuelwood from farms. On the other hand, many households were predicted to use both farms and forests, and farms and markets simultaneously. There is, therefore, a strong substitution of fuelwood sources particularly between farms and other fuelwood sources.

The model predicted higher percentage of households choosing farms as source of fuelwood when all significant predictor variables were included in the model (Table 3.6). The model overall accuracy was 53 % and the error rate was 47 %. The error rate is high since the model resulted into many misclassified households. Looking at individual fuelwood source categories, the model correctly predicted 75 % of households as the main users of fuelwood from farms, 20 % of households as users of fuelwood from forests, and 5 % of households as users of market fuelwood (Table 3-6).

Table 3-6. Classification of households by the model predicted categories of fuelwood sources

Fuelwood sources	Baseline		Model predictions	
	n	%	N	%
Farms	234	48.8	186	74.7
Forests	140	29.2	56	19.8
Markets	106	22.1	20	5.5
Total	480	100	262	100

The fuelwood choice model excelled at identifying farms as the main source of fuelwood, but compared to baseline model, model performance was low in classifying the households into the categories of markets and forests. Figure 3-4 indicates the predicted probabilities for household choice to collect fuelwood from farms, forests and markets given a set of boundary household characteristics included in the fuelwood choice model.

The model predicted the highest probability for household choice to collect fuelwood from farms, followed by the choice to collect fuelwood from forests and least for the choice of market purchase of fuelwood. These results corroborate the model classification results presented in Tables 3-5 and 3-6 since many households are correctly classified as users of farm fuelwood.

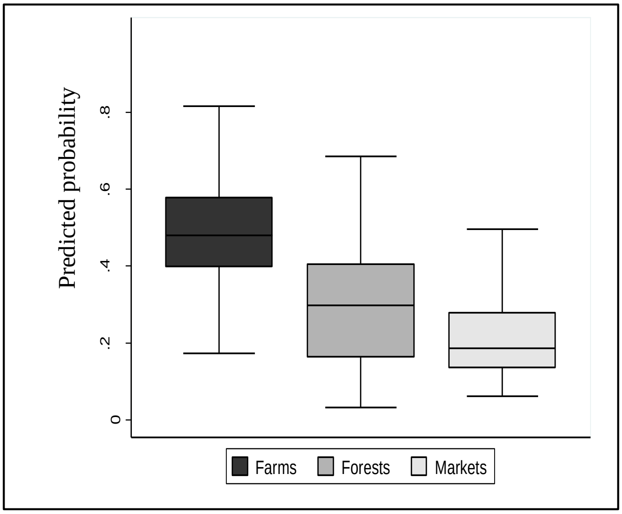

Fig. 3-4 Predicted probabilities for household choice of fuelwood from farms, forests and markets in rural Rwanda

3.4 Discussion

From the evidence presented, farm size has much influence on the choice of farms as main fuelwood sources. Larger farm owners tend to rely on fuelwood from farms, while smaller farm owners choose forests as their preferred fuelwood source. If farm size is a measure of the household wealth as reported in many studies (e.g. Edmonds 2002; Blank et al. 2004; Jongur 2011), poverty affects the choice of fuelwood source. Land-poor households cannot afford the planting of trees on their farms, hence they exert pressure on surrounding forests. The impact of fuelwood gathering on forest degradation, deforestation and biodiversity loss will therefore especially be caused by land-poor households. It is likely that the practice of farm forestry, especially among larger farms owners, can partly meet the fuelwood demands of the rural households, thereby reducing pressure on forests.

Large farm owners choose to use fuelwood from farms over forests. This result complies with the findings of many other studies focusing on the relationship between farm size and the choice of fuelwood sources (e.g. Heltberg et al. 2000; Van't Veld et al. 2006; Cooke et al. 2008; Damte and Koch 2011). Large farm owners have the ability to produce fuelwood for themselves. Many farm and household surveys found that the households benefit fuelwood from farms mainly as secondary products (e.g. den Biggelaar 1996; Peeters et al. 2003; Gopal and Dixit 2010). Larger farm categories accommodate woodlots and large number of multipurpose trees. Since many rural households in Rwanda are facing land scarcity, a secure fuelwood production can only be achieved by a few households and even fewer are able to meet their fuelwood needs in the long term because of continuing land fragmentation due to the mode of land acquisition by inheritance. Another wealth indicator used in the analysis is ownership of livestock. Using this indicator, however, we find that ownership of livestock was irrelevant for household choice of fuelwood source.

In general, household size increases the probability to buy fuelwood from markets. Larger households choose to buy fuelwood from markets. A similar result was found by Baland et al. (2010) in their study on the linkages between alternative measures of poverty and collection of forest firewood by rural households. In poor countries with large family sizes, it is paradoxical that many households could buy fuelwood from markets, incurring costs on purchased fuelwood, in comparison with free collection from agricultural lands and forestlands. There is a possibility that large household demand for fuelwood leads to reduced availability of fuelwood in farms and forests.

Thus, fuelwood scarcity and the lack of affordable alternatives prompt these households to resort to purchased fuelwood as the last option.

A location dummy variable was included in the analysis to capture differences in household choice of fuelwood sources from three altitude regions. Compared to households in HAR, households in LAR and MAR depend more on fuelwood collected from forests. The location of household, therefore, underlines the importance of the spatial context of the choice of fuelwood sources as it has been found in other studies (e.g. Vikram 2006; Rao and Reddy 2007). From field observation and forest inventory reports, HAR is known to have a large forest cover and most households own farm woodlots. The finding of this study, therefore, imply that households in HAR depend on trees and woodlots on farms for domestic fuelwood consumption. In contrast, LAR and MAR have comparatively smaller forest resources and households depend on them for meeting their fuelwood demands. Differences in bio-physical conditions and historical aspects of forestry and farm forestry development in these regions could be an important determinant of differences in fuelwood consumption choices, fuelwood availability and access in these regions.

The choice of fuelwood from forests in LAR and MAR may results in forest degradation. The collection of dead trees and dry branches leads to degradation of wildlife habitat, disruption of ecosystem processes and erosion (Driscoll et al. 2000). These ecological effects of firewood collection from forests could be reduced by introducing polices that foster the promotion of farm forestry in the context of the stated goals of the Rwandan forest policy. In parallel with this goal, public decision makers may implement policies affecting markets and marketing channels of wood products, including for instance subsidies on fuelwood prices as it is done for instance for fertilisers.

Our results suggested that gender dimension was an important factor when making the choice between farms and forests. The effect of the gender of the household head provides confirmation that female- headed households are more dependent on forests than male-headed households. This category of households could be affected by the time required and the travel distance to gather fuelwood from forests as found in other studies (e.g. MacDonald et al. 2001; Bandyopadhyay et al. 2011). The results of the study imply that female-headed households do not take the decision to establish their own sources of fuelwood. Shackleton et al. (2008) observed that female-headed households own fewer trees on their farms than do male-headed households. The choice of collecting fuelwood from farms by male-head of households leads to a positive attitude towards agroforestry practices and management of forests.

The main source of income is also an important determinant of household choice of fuelwood source. Off-farm income increased the likelihood of a household choosing markets as a source of fuelwood. This meets expectation that off-farm income translates into a better purchasing power - as increased income enables households to purchase fuelwood. Off-farm income enables the rural households to buy fuelwood from markets. Farm income alone does not enable households to be less reliant on collected fuelwood. This reliance is likely to decrease with increased household involvement in off-farm income generating activities. If income sources are diversified in rural areas and fuelwood market organized, most households can use purchased fuelwood. From the evidence presented, lower income households collected fuelwood from forests. This result corroborates many studies focusing on energy choices and fuelwood consumption (eg. Chambwera and Folmer 2007; Couture et al. 2009). The households in the higher income categories, however, choose to buy to collect fuelwood from their farms. Increased income, therefore, stimulates the choice of alternatives to forest fuelwood.

3.5 Conclusion

In rural Rwanda, there are different types of fuelwood sources. In this study, we looked into the determinants of household choice of fuelwood from farms, forests and markets. The constructed model indicates that the households with different demographic, economic and location attributes make different choices of fuelwood sources. The model predicted that many households prefer fuelwood from farms, forests and markets in some cases. The model framework taking into account the different household characteristics is applicable also for other countries where rural populations practice subsistence farming on small farms and depend on singly on fuelwood as source of energy for cooking. Current government efforts to reduce poverty and to promote alternative sources of energy in rural areas can affect the outcome of this framework through inclusion of energy efficient options and a wide array of welfare factors of the rural households.

In general, the main determinants that distinguish the choice of fuelwood sources were location of the household, gender of head of households, household size, farm size, source of income and monthly income. Although fuelwood collection from forests is prohibited, there is evidence that the households still gather fuelwood from them, though the size of the forest resource could be small . The policy objective of promoting forestry may consider the importance of household location in fuelwood collection choice. This policy can be implemented in conjunction with public policies supporting the creation of jobs in rural areas and improvement of markets, especially for fuelwood.

Organising and developing the fuelwood market may be a way out of deforestation and depletion of trees in agroforestry. This would have some beneficial effects on forests and farms, on the costs of fuelwood and would provide an additional source of income for farmers. For instance, the government may even start buying fuelwood from farms and sell it at reduced price to low income households. In this way, the production of fuelwood on farm is stimulated, low income households could get their fuelwood at reduced costs and forest degradation and deforestation could be addressed.

The choice of collecting fuelwood from forests could result in unsustainable use of forests and forest degradation. Household collection of fuelwood in forests reflects weak enforcement of rules and regulations. Forest policies should look for prospects that harness forestry and agroforestry systems as renewable sources of fuelwood in rural areas along with energy policies aimed at reducing consumption of fuelwood, promoting alternative energy sources and addressing deforestation. We contend that energy policies can build on the proposition that fuelwood has a high value as a source of energy for cooking and is particularly obtained from farms, forests and markets regardless of time, energy and budget constraints.

Extension services should be aware of the different factors affecting the relative choice of fuelwood sources by the households and the different characteristics and circumstances. Their interventions must target specific regions and different groups in the rural communities. For instance, improved stoves could be promoted in the high altitude region; agroforestry and afforestation programme could target the low and medium altitude regions. In particular, sustainable management of forests and agroforestry systems will be achieved, if female-headed households, small farm owners, and low income households are targeted in terms of access to technical information, income generating activities and access to affordable sources of energy for cooking. The results of the study demonstrated that larger farm owners and larger income households collect fuelwood from their own farms. For this category of farm owners, direct support in meeting fuelwood needs may not be required.

Chapter 4 Household determinants of tree planting on farms in rural Rwanda

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Abstract

In Rwanda, trees on farms are widely recognized for increasing and diversifying farm productivity while releasing pressure on existing forests. However, the motivation of rural households to keep trees on farms is often unclear. This study evaluates rural households demographic and socio-economic characteristics, as well as their attitudes, that influence the presence of trees on farms. Data used in this study were collected from a survey of 480 households across three altitude regions of Rwanda. Binary logistic regression analysis using PASW Statistics was applied to determine relevant predictor variables for the presence of trees on farms. The results show regional variation in explaining the presence of trees on farms. When data from the three regions were analysed together, significant predictor variables comprise the gender of head of the household, the number of salaried members of the households, the amount of farm fuelwood use, the number of meals per day, the geographical location of the households and the selling of tree products. The presence of different tree species on farms was driven by economic factors, of which availability of food, firewood, and poles, and total income were most common. The results of the study imply that policy measures that target food security and income diversification in rural areas may, at the same time, enhance tree planting. Moreover, it is concluded that rural development and extension in agriculture should be site specific, to account for biophysical conditions and specific rural household motivations to plant trees on farms.

Keywords: Agroforestry; Altitude regions; Logistic regression; Rural households; Trees on farms

4.1 Introduction

In many developing countries, forests are declining in area and the associated biodiversity and regulating functions are lost. To a large extent, this results from population increase, leading to high demand for agricultural land. In Africa, the net annual loss of forests exceeded 4million hectares between 2000 and 2005 (FAO 2007). Cleveland (2008) reported both direct and indirect causes of deforestation. Agricultural expansion by subsistence farmers has been identified as a major factor in many studies on deforestation (e.g. Colchester and Lohmann 1993; Brown and Pearce 1994; Barraclough and Ghimire 1995; Palo and Mery 1996; Sponsel et al. 1996; Dubois 1997). In Rwanda, where 90% of the population depends on agriculture for their livelihoods, the annual deforestation rate between 2000 and 2005 reached an alarming rate of almost 7%, which is very high even compared to the high average annual deforestation rate of 3.9% reported for Africa (FAO 2005b). The main effect of deforestation is environmental degradation associated with such problems as soil erosion, soil fertility decline, climate change, biodiversity depletion and poverty. Environmental degradation is particularly acute when living conditions of poor households relying on natural resources as a basis for farming, building poles and energy production are concerned.

The development of sustainable agricultural technologies has been taken up to address the problems referred to above. Agroforestry using multipurpose trees in different regions of Rwanda have been evaluated before (e.g. Newmann and Pietrowicz 1986; Yamoah et al. 1989; Balasubramanian and Sekayange 1992; Roose et al. 1993; Niang et al. 1995; Burleigh and Yamoah 1997) and have shown to be promising for smallholder farmers.

On farms, different tree species may be present in form of scattered trees, along erosion control ditches, along contours, on farm boundaries, or established as rotational woodlots or blocks (Balasubramanian and Egli 1986; den Biggelaar 1996; den Biggelaar and Gold 1996). Such trees are managed in combination with crops in agroforestry systems and serve a number of ecological and economic functions that are partly similar to those of trees in forests, although different in extent (Kleinn 2000). However, the presence of trees on a limited amount of agricultural land may seriously interfere with crop production due to competition for scarce resources. Despite existence of trees in the agricultural landscape, and the competition interference with the crop, the motivation of farmers to plant trees on relatively small sized farms of less than 1 ha for 80% of farmlands (NISR 2010), is largely unknown.

Farm level studies can provide insights into the socio-economic factors and attitudes leading farmers to plant trees on farms. Issues concerning the adoption of agroforestry practices have been discussed in many studies (e.g. Godoy 1992; Adesina 1994; Alavalapati et al. 1995; Ayuk 1997; Franzel et al. 2001). In the Rwanda context, qualitative surveys identified the reasons why farmers planted trees on farms or adopted agroforestry technologies (e.g. von Behaim and Bezzola 1994; Den Biggelaar 1996; Bigirimana 2002; Uwiragiye 2002; Tuyisenge 2003; NISR 2010). Many of these studies were conducted in different parts of the country using structured interviews or focus- group discussions. Research on adoption of agroforestry generally focused on social, biophysical and wealth parameters, leading to the ranking of constraints and benefits by rural households as well as priority areas for research (e.g. Djimde et al. 1988; Mukuralinda et al. 1999).

The development of agroforestry in Rwanda is among the guiding principles of the forest policy (MINIFOM 2010). The Rwanda government promotes farm forestry in order to curb depletion of forest resources, declining soil fertility and environmental degradation, and to contribute to solving the rural energy crisis, dealing with land scarcity, and preventing soil erosion. Achieving these goals requires attention to farmers' attitudes and decision making about planting of trees. Farmers' choices to grow trees depend on many social, cultural, economic and technical factors, and for interventions aimed at stimulating agroforestry practices to be successful, these factors must be understood. In addition, local situations are important to consider when examining why smallholder farmers grow trees in association with crops.

There is little information available on farmers' decisions about tree planting and maintenance on farms and the perceptions and attitudes which influence their decision-making. To this end, we investigated the reasons why and when farmers are planting and under which conditions they are retaining trees on their farms. Here, trees on farms refer to trees on farmlands other than those found in woodlots. The study focused on the low, medium and high altitude regions of Rwanda in order to account for regional differences in attitudes and motivations towards tree planting . The specific objectives of the study were: (1) to identify factors that lead farmers to keep trees in agricultural lands across the low, medium and high altitude regions of Rwanda, (2) to determine factors that may increase agricultural household motivations for keeping them on farms, and (3) to determine the most important aspects that households consider when deciding to keep different tree species on their farms. We presumed that an understanding of the process by which farmers make tree maintenance decisions may broaden the general farmers' perception, and may lead to an increase in the number of trees grown on farms and the benefits the farmers may take from this. The findings of the research are believed to be useful to policy makers, researchers, development professionals and extension agents in developing and disseminating agroforestry technologies and practices that aim to meet the needs and demands of smallholder farmers.

4.2 Methods

4.2.1 Study sites and selection of sample households

Rwanda comprises three altitude regions characterized by elevations and rainfall (Gotanègre et al. 1974). The low altitude region (LAR) has altitude less than 1,500 m and rainfall less 1,000 mm. The medium altitude region (MAR) has an average altitude of 1,700 m with a maximum of 1,900 m, with rainfall between 1,000 and 1,250 mm. The high altitude region (HAR) covers the areas between 1,900 and 2,500 m, where annual rainfall ranges between 1,250 mm and more than 2,000 mm.

Data for this study were gathered in these three regions, which where subdivided by Delepierre (1982) into 12 agro-ecological zones (Fig 4-1), defined by altitudes, rainfall and soil characteristics (Table 4-1). Since the altitude regions cover large and disconnected areas, considerable heterogeneity exists in farmers' characteristics. The regions were further stratified in agroecological zones. Trees on farms along with agricultural crops are influenced by agro-ecological conditions, and the agroecological zoning invokes similarities with farming systems (Olson 1994).

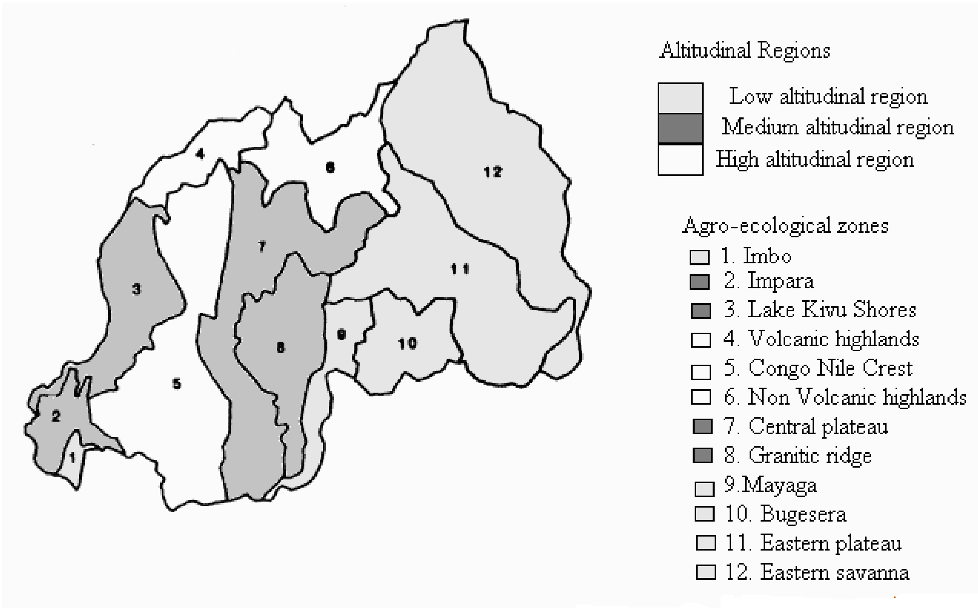

Fig. 4-1 Agro-ecological zones of Rwanda

In order to capture the households' characteristics, a further stratification of the agroecological zones was made based on administrative units[6].The administrative structure of Rwanda is organised into Districts, Sectors and Cells. The first two units were randomly selected from each agroecological zone. A single Cell within an administrative sector was chosen as the sampling unit. Since each cell is sparsely occupied by farming households

[6] The Republic of Rwanda comprises four Provinces and the City of Kigali, divided into 30 Districts, which are subdivided into 416 Sectors, which are further subdivided into 2,148 Cells. The Cell is the smallest politico-administrative unit of the country and hence closest to the people.

that have different socioeconomic status, subgroups could not be formed. Therefore a different sampling scheme was adopted to select a random sample of households for the survey.

Table 4-1 Characteristics of the different agroecological zones and corresponding number of interview households

Agroecological zones by altitudinal regions	Altitude (m)	Rainfall (mm)	Soil groups (FAO 2006)	Number of sample households
Low altitudinal region				200
Bugesera	*1300 - 1500*	*700 - 900*	*Nitosols and ferralsols*	*40*
Eastern Plateau	*1400 - 1800*	*900 - 1000*	*Ferralsols*	*40*
Eastern Savanna	*1250 - 1600*	*800 - 900*	*Nitosols and ferralsols*	*40*
Imbo	*970 - 1400*	*1050 - 1600*	*Vertisols*	*40*
Mayaga	*1350 - 1500*	*1000 - 1200*	*Nitosols*	*40*
Medium altitudinal region				160
Central Plateau	*1500 - 1900*	*ll00 - 1300*	*Humic Nitosols and humic Ferralsols*	*40*
Granitic Ridge	*1400 -1700*	*1050 - 1200*	*Leptosols*	*40*
Impala	*1400 - 1900*	*1300 - 2000*	*Lixisols*	*40*
Lake Kivu Shores	*1460 - 1900*	*1150 - 1300*	*Nitosols*	*40*
High altitudinal region				120
Congo Nile Crest	*1900 - 2500*	*1300 - 2000*	*Humic ferralsols*	*40*
Non-volcanic highlands	*1900 - 2500*	*ll00 - 1300*	*Ferralsols*	*40*
Volcanic Highlands	*1600 - 2500*	*1300 - 1600*	*Andosols*	*40*

Forty households were randomly selected in each cell (Table 1). In this sampling, the number of sample cells equalled the number of agroecological zones, and the total number of households arising from three to five corresponding agroecological zones, was considered to be representative of a particular altitude region. In fact, agricultural and agroforestry practices within each altitude region are relatively uniform in terms of households' needs, interests, opportunities and constraints as was reported in many survey studies (e.g. Djimde et al. 1988; Niang and Styger 1990; Mukuralinda et al. 1999; Zaongo et al. 2003). Therefore, the results of the household survey were combined and extrapolated to apply to each altitude region in order to understand the motivations of households to plant trees on farms over the entire study area.

From this sampling, the number of sample households surveyed was 200, 160 and 120 in the LAR, MAR and HAR respectively. In total, 480 rural households were interviewed. Data collection was done on a per household basis using a structured questionnaire. The household heads or their wives were chosen as respondents based on the presumption that they had satisfactory information regarding their farms. The choice of the wives in the absence of their husbands was supported by the fact that tree species choices, their management and uses appear not differentiated by gender (e.g. Bonnard and Scherr 1994).

Moreover, adoption of agroforestry technologies appears gender neutral (e.g. Gladwin et al. 2002; Phiri et al. 2004). Since agriculture decisions in farming households are often jointly taken, information on management of trees on farms and their benefits are difficult to differentiate between the wives and their husbands. If the head of the household or his wife was not present, the household was rejected for interviewing and the next household was visited.

4.2.2 Survey Instrument

A uniform pre-tested structured questionnaire was used to derive information on demography, livelihood activities, socio-economic status, tree species growing on the farms and their uses, agricultural crop production, and household fuel consumption. The questionnaire also included the sources of the fuelwood collected, the distance travelled to gather fuelwood, and the amount of fuelwood purchased or collected from each source.

Fuelwood and vegetable materials are the main sources of energy for cooking in Rwanda (REMA 2009). Hence, the survey included questions about the use of these materials, their sources, frequency of use per week, and on farmers' strategies when the fuel in use was short in supply. Since it was not possible to know the precise amount of fuelwood collected or purchased by households, interviewees were asked to specify the number of bundles of firewood and bags of charcoal they used per week or per month. Then, where bundles of firewood and bags of charcoal were available, these were weighted using a spring scale. The average weight (in kg) was used to estimate the amount of fuelwood being used in the households for which bundles of firewood were unavailable by the time of the survey and for which the number of bundles or bags of charcoal being used were recorded. The average weight of a bundle of wood splits and of a bag of charcoal was 12.5 and 35 kg respectively.

In rural areas of Rwanda, modern energy sources such as electricity, gas and kerosene are hardly used. Respondents were asked for other sources of energy used in cooking meals when fuelwood was not available. The household interviews also provided information on level of education, source of income, income and expenditure, the number of meals per day, the types of stoves in use, farms sizes, crop types, tree species on farms and their uses, income from the selling of tree products and tree species collected for fuelwood.

4.2.3 Statistical Analysis

Several factors are hypothesized to affect occurrence of trees in the study area based, on published evidence . In order to identify those factors that best explain tree planting and retention in farm fields, binary logistic regression analyses have been applied to the data of 480 households in the low, medium and high altitude region of Rwanda, and across these three regions. This type of regression is generally used when the dependent relates to a categorical dichotomy. In our study, the dependent variable is composed of two categories “presence of trees on farms” and “absence of trees on farms” whereas the independent variables include a mix of categorical and continuous variables. The category of “presence of trees on farms” includes both trees that have been planted many years ago and subsequently retained on farms, and those planted by the head of the household for example after acquisition of the land.

Logistic regression is a preferred statistical technique for analysing models of dichotomous dependent variables (Hosmer and Lemeshow 1989;

Menard 1995). Discriminant analysis can also be used to predict a discrete outcome, but it is used to predict group membership for only two groups. When the independent variables are categorical, a mix of continuous and categorical, logistic regression is preferred because it results into fewer classification errors compared to discriminant analysis (Montgomery et al. 1987; Lei and Koehly 2003; Rausch and Kelly 2009). Moreover, logistic regression has similarity to linear regression and is related through an appropriate link function (Dobson 1990). Just like ordinary regression, logistic regression has also straightforward statistical tests and the ability to incorporate non-linear effects and a wide variety of diagnostics (Hair et al. 1998). Logistic regression tools models have been widely used for statistical analysis of proportions or rates in educational, social and behavioural sciences (e.g. Catts et al. 2001; Flowers and Robinson 2002; Glaser et al. 2002), in biological and medical sciences (e.g. Udris et al. 2001; Phillips et al. 2003; Sahiner et al. 2004) as well as in management sciences (e.g. Jo et al. 1997; Avlonitis et al. 2000). These models have recently been applied to decisions of household energy consumption choice (e.g. Macht et al. 2007; Couture et al. 2009; Ekholm et al. 2010). Damte and Koch (2011) used logistic regression methods for evaluating the choice of fuelwood sources in rural Ethiopia, while Neupane et al. (2002) demonstrated its application for understanding the determinants of the adoption of agroforestry in Nepal. In a binary logistic regression model, the dependent variable is of binary nature and this applies in the case of the presence or absence of trees on farms. This dependent variable is 0 in the case of absence of trees, and 1 if trees are present. Categorical variables were incorporated into the regression models by recording them using an indicator coding (Field 2005). This means that if there were c categories for a variable, then the variable was taken as having c vectors, with the first category denoted (1, 0, …, 0), the next category (0, 1, …, 0), …, and the final category (0, 0, …, 0, 1). Logistic regression procedures have been used for each altitude region and for all regions combined, in order to identify which variables predict whether a farm is likely to have trees or not. In each case, the model assumed that farmers faced socio-demographic and economic factors that influence their choices to keep trees on their farms. Let Y_i represent a dichotomous variable that equals 1 if there are trees present and 0 if no tree was present. Given several predictor variables, the probability of Y_i occurring is given by the following equation (Dobson 1990):

$$P(Y_i) = \frac{1}{1+e^{-(b_0+b_1X_1+b_2X_2+\ldots+b_nX_n+\varepsilon_i)}}$$

in which $P(Y_i)$ is the probability of Y occurring, e is the base of natural logarithms, b_0 is the intercept, b_n is the regression coefficient of the corresponding variable X_n and ε is the residual term.

The equation form of the logistic transformation of the probability of farmer's decision to plant or retain trees, $P(Y_i = 1)$ can be represented as:

$$Log\left[\frac{P\left(Y_i = 1\right)}{1-P_i\left(Y_i = 1\right)}\right] = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \ldots + \beta_n X_n$$

or

$$Log\left[\frac{P\left(Y_i = 1\right)}{1-P_i\left(Y_i = 1\right)}\right] = \beta_0 + \sum_{i=1}^{n} \beta_i X_i$$

where P_i is the probability that trees are present, ($1-P_i$) is the probability that a farm has no trees, ($P_i/(1-P_i)$) denotes the odds of having trees on farms, β_0 is a constant, β_i represent the coefficients associated with the predictor variables denoted X_i. The coefficients represent the effects of the predictor variables on the odds of having trees on farms. The transformation from odds to probability is a monotonic transformation (Sweet and Grace-Martinez 2003, Johnson and Bruce 2008), meaning that the odds increase as the probability increases or vice versa. A positive coefficient of a predictor variable means that an increase in this variable is associated with an increase in the odds of having trees on farms. Inversely, a negative coefficient means that an increase in the predictor variable implies a decrease in the odds of having trees on farms.

The parameters β_i of the variables influencing the presence of trees on farms, were estimated using a maximum likelihood estimator. Forward inclusion was used to select the predictor variables one by one and to include them in the model if they were statistically significant. In this way, the variables were included in the model one by one in an iterative process. At each stage in the process, after a new variable was added, a test was made to check if other variables could be deleted without notably increasing the residual sum of squares. This procedure was completed when the inclusion of additional variables did not make significant improvement to the fit of the model.

To determine the fit of the models, the goodness of fit test, which is the chi-square difference between the baseline model (i.e. with the constant only) and the final model (containing one or more predictor variables), was performed. Model coefficients were tested for their significance for inclusion or elimination by carrying out a Wald test and by determining the Hosmer - Lemeshow statistics (Hosmer and Lemeshow 1989), Cox and Snell R^2 (Cox & Snell 1989) and Nagelkerke R^2 (Nagelkerke 1991). The Hosmer - Lemeshow statistics indicated a good fit if the significance value was greater than 0.05. The two R^2 -statistics are based on the log likelihood of the model compared to the log likelihood of a baseline model.

The model variables were tested for multicollinearity using collinearity statistics viz. tolerance value and Variance Inflation Factor (VIF). A tolerance value less than 0.1 indicated a serious collinearity problem (Menard 1995) and a VIF greater than 10 was also a cause of concern of collinearity (Myers 1990). The Statistical Package program SPSS/PASW Statistics was used for the analysis.

4.2.4 Conceptualization of variables included in the models

In Rwanda, the average area of farmland by household is 0.76 ha, and about 80% of farmlands are less than 1 ha (NISR 2010). Therefore, many farms are small and production of trees, crops and livestock has to take place on a small area. Establishing and maintaining trees as a sole crop requires households to allocate part of their farmlands to trees, which further reduces the size of the farms; because of competition between trees and crops, woodlot owners are not expected to adopt production systems that integrate trees and crops on very small farms, since they can acquire fuelwood from the woodlot.

One of the factors that limit farmers to plant trees, is the size of the farm (Niang and Styger 1990; Mukuralinda et al. 1999). In response to scarcity of wood and non-wood products, farmers may plant trees in their agricultural lands in a way that minimizes competition on crops, and possibly has positive effects on crop productivity as well e.g. through soil improvement. Both small and large farms are expected to have trees, but possibly in different configuration. The small farm size is partly due to family heritage, where land is becoming smaller in successive generations. The common mode of land ownership is by inheritance for about 82% of households (NISR 2010). Typically, older heads of households have large farms as compared to young farmers, and the age of household head is strongly related to farm size. It is likely that older households are able to plant and keep more trees on their farms than younger household heads.

The level of education of the household head has a positive effect on the presence of trees on farms (Haglund et al. 2011; Muhammad et al. 2011). Educated people have more income opportunities and can afford to use more land for growing trees. In addition, educated farmers are considered to be innovative or opinion leaders and willing to take more risk than illiterates. Therefore, education level of household head could be hypothesised to encourage farmer decision to keep trees on farms, and this aspect was included in the equation as an independent variable.

The social context of Rwanda in a post-genocide situation implies that some households are headed by females. A national survey in 2008 found that female heads of households represented 27% of the total agricultural households (NISR 2010). Even under normal circumstances, women were found to contribute 40-80% of agricultural farm labour, even though men were present in the households (Randolph and Sanders 1992). Thus, women are expected to have a decision making role for the family in crop production as well as in on-farm tree planting and retention.

In Rwanda, the common source of income for the majority of rural households is crop and livestock farming. Additional income results from off-farm activities predominantly done by the heads of households. Off-farm employment may generate more income than farm labour; hence the heads of households involved in off-farm employment are less likely to take the decision to keep trees on farms. It is anticipated that the employment of the heads of households in off-farm activities is negatively associated with the presence of trees on farms. In addition, households in which family members are involved in off-farm employment that generates more total income, may be less motivated to use household labour in planting and maintaining trees. Thacher et al. (1997) reported that households allocated family labour to off-farm employment for purposes of increased income.

Higher income households are expected to keep less trees on their farms as compared to lower income households because the former can afford to purchase wood products from local markets. Similarly, expense categories of households are expected to follow the same trend, meaning that farms of low expense category of households may have more trees than those of higher expense category of households . Agroforestry may enhance food production and farmers' economic conditions through positive contribution to household income (Neupane and Thapa 2001). Potential selling of tree products (including fuelwood) may have a positive effect on farmers' decision to keep trees on their farms. From field observation and knowledge of the study area, there are farmers who sell fuelwood and charcoal while they do not produce wood on their farms. This category of farmers get the products from tree planters and serve as intermediate between the producer and the buyer in wood products trade. Therefore, the selling of tree products was included in the analysis in order to determine whether the market for wood products justify the presence of trees on farms.

Farmers make decisions on the presence of trees on farms based on household and farm characteristics (Bannister and Nair 2003). In a household where adult members (aged ≥16 years) are present, it may not be easy for the head of the household to take a decision to adopt a technology or to grow trees due to the greater influence of these members. Adult members in the households (aged ≥16 years) influence this decision partly because they are involved in farming activities. The number of adult household members is expected to be positively associated with the presence of trees on farms. In contrast, the larger the household size, the greater its energy needs for cooking meals, and the more emphasis on secure energy supply. As a result, a link between the production of sufficient food and fuelwood is expected, and this may be achieved by keeping trees on farms.

Some studies have emphasised scarcity of fuelwood as one of the key factors to motivate farmers in planting trees (Dewees 1992; Dixit and Dixit 2010). Other studies reported that fuelwood from agroforestry is a secondary product from multipurpose trees (e.g. den Biggelaar 1996; Jama et al. 2008). As long as fuelwood could be collected from forests without paying for it, farmers had little incentive to keep and plant fuelwood producing trees on their farms. Due to scarcity of fuelwood, rural households increase frequency of collection from nearby forests. However, as fuelwood collection distance increases, the frequency of collection from the same sites declines with households refocusing their attention to nearby sites (Fisher et al. 2005). Thus, estimations of the amount of fuelwood collected per month, the monthly frequency of collection, the amount of fuelwood used per week and the distance travelled to nearest source of fuelwood affect the household choice to keep trees on their farmlands.

With improved economic wellbeing, households become less dependent on forests for their energy supply (Sikei et al. 2008). These households do not collect, but may purchase fuelwood or use other sources of energy such as electricity or gas for cooking. It is assumed that an increased expenditure on firewood is inversely related to the presence of trees on farms, and that a rise in the number of times households purchase fuelwood is also inversely related to the likelihood of the presence of trees on farms. Similarly, if the amount of fuelwood purchased is larger, it is less likely that the households own trees on their farms.

Many studies (Adhikari 1996; Cooke 1998; Fisher 2004) identified an inverse relationship between fuelwood collection frequency and the distance travelled to collection site. Increased distance to fuelwood collection sites requires more energy and become a burden to collecting household members. In response to this problem, households may prefer to manage their own fuelwood source. It is anticipated that an increase in distance to sources of fuelwood increases the probability that households choose to establish, if possible, short distance sources of fuelwood including trees on their own farmland.

In Rwanda, about 99% of the rural population uses firewood and charcoal for cooking meals (NISR 2006). Fuelwood use has remained high even when households are encouraged to use alternative technologies to improve efficiency of cooking, thereby reducing the impact of fuelwood consumption on deforestation. It is hypothesized that the number of meals per day, leading to frequent use of fuelwood for cooking meals, is correlated with the presence of more trees on farms. When improved stoves are used, the need to keep trees is less because improved stoves use wood efficiently and the households can afford to buy small quantities of wood. Therefore, ownership of an improved stove is expected to be negatively associated with the presence of trees on farms.

The amount of forest area per capita in Rwanda is very small (0.03 ha per capita) and the FAO standard of 1 ha per capita to simultaneously meet the ecological balance and wood demands is unattainable (MINIFOM 2010). The remaining forests are unevenly distributed geographically and by ownership (CGIS-NUR and MINITERE 2008; ISAR and MINITERE 2008). As a result, the demand for wood is higher in areas with little forest cover compared to those areas with higher forest cover. A decreasing tree cover may motivate farmers to increase their local source of wood products and therefore the respondents' opinion of the change in tree cover was included in the model in order to test whether the change in availability of forest resources had significant effect on the presence of trees on farms. In general, the geographical location and associated agro-ecological factors are expected to have significant impact, linked to favourable environmental conditions for successful planting of trees. The altitude influences not only the temperature but also the relief characteristics and consequently affects vegetation and farming systems. Hence altitude region may have an effect on the presence of trees on farms.

Finally, rural households in Rwanda are affected by a shortage of fuelwood throughout the country. Fuelwood collection in public forests is illegal, and households are barred from collecting fuelwood from these forests. Thus, it is hypothesized that fuelwood demands drive many households to keep trees on farms. In addition, households that use alternative fuels are expected to have fewer trees on their farms.

4.2.5 Model

Given the hypothesized factors of households' determinants of the choice of keeping trees on farms, models were developed for each altitude region and for the entire study area. Except the variables gender of the head of the households, the selling of tree products on markets and the distance to the source of fuelwood that are binary as well as the variable number of meals per day that is continuous, the remaining variables are dummies transformed from categorical continuous variables. For each altitude region and for the entire study area, the model was as follow:

$$
\begin{aligned}
Log\left[\frac{P\left(Y_i=1\right)}{1-P_i\left(Y_i=1\right)}\right] = {} & \beta_0 + \beta_1 AGE + \beta_2 HSEX + \beta_3 ADUL + \beta_4 CHIL \\
& + \beta_5 HSIZE + \beta_6 MAGRIC + \beta_7 MFEMPLOY \\
& + \beta_8 MIEMPLOY + \beta_9 MBUS + \beta_{10} MTOT \\
& + \beta_{11} HEMPLOY + \beta_{12} EDUC + \beta_{13} SINCOME \\
& + \beta_{14} INCOME + \beta_{15} EXPENSE + \beta_{16} MEAL
\end{aligned}
$$

$$+ \beta_{17}STOVE + \beta_{18}FARM + \beta_{19}WLOT + \beta_{20}RFIRE + \beta_{21}TPROD + \beta_{22}TINCOME + \beta_{23}SFUEL + \beta_{24}FPURCH + \beta_{25}FCOLLECT + \beta_{26}EXPFIRE + \beta_{27}DIST + \beta_{28}FBUNDLE + \beta_{29}ALTENERG + \beta_{30}SEASON + \beta_{31}TCOVER + \beta_{32}STRAT + \beta_{33}REGION$$

where

AGE	Age of the head of the households, from value 1 = 16-20 years to value 10 = > 60 years
HSEX	Gender of the household head, HSEX = 1 if female, and 0 otherwise
ADUL	Number of adult household members, defined as individuals aged 16 years and above, from value 1 = 1-2 persons to value 4 = > 6 persons
CHIL	Number of children in household, defined as individuals aged below 16 years, from value 1 = 0 to value 7= > 10 children
HSIZE	Total number of household members, from value 1 = 1-3 members to value 5= > 12 members
MAGRIC	Number of household members involved in agriculture, from value 1 = none to value 5= > 6 persons
MFEMPLOY	Number of salaried members of the household, from value 1 = none to value 5= > 6 persons
MIEMPLOY	Number of household members involved in informal employment, from value 1 = none to value 5= > 6 persons
MBUS	Number of household members involved in small business, from value 1 = none to value 5= > 6 persons
MTOT	Total number of household members employed, from value 1 = none to value 5= > 6 persons
HEMPLOY	Employment of head of household, HEMPLOY = 1 if employed and 0 otherwise

EDUC	Education level of the head of household, on a scale of 1 = no school to 7 = some university
SINCOME	Main source of income, coded for 7 categories of activities
INCOME	Estimated monthly income during the past 12 months, from value 1 = < 5,000 Rwf to value 10 = > 70,000 Rwf
EXPENSE	Estimated monthly expenses during the past 12 months, from value 1 = < 5,000 Rwf to value 10 = > 70,000 Rwf
MEAL	Number of meals per day, ranges from 1 to 3 times per day
STOVE	Type of stove used for cooking meals, STOVE = 1 if improved, and 0 otherwise
FARM	Farm sizes in ha, with values ranging from 1 = landless to 5 = > 2 ha
WLOT	Ownership of a woodlot, WLOT = 1 if the household owns a woodlot and 0 otherwise
RFIRE	Amount of farm fuelwood use, from 1= very small to 6 = very high
TPROD	Selling of tree products. If the household sells tree products, TPROD = 1 and 0 otherwise
TINCOME	Estimated annual income from selling of tree products during the past three years, from value 1 = no income to value 12 = > 100,000 Rwf
SFUEL	Sources of fuelwood, dummy coded for eight sources of fuelwood
FPURCH	Frequency of purchasing fuelwood per month, on a scale of 1 = no purchase to 7 = > 17 times
FCOLLECT	Frequency of collecting fuelwood per month, on a scale of 1 = no collection to 8 = > 21 times
EXPFIRE	Monthly expenditure on firewood estimated for the past 12 months, from value 1 = no expenses to value 12 = > 10,000 Rwf
DIST	Distance to the source of firewood and charcoal, from value 1 = < 1 km to value 5= > 10 km
FBUNDLE	Number of firewood head load bundles used per week, on a scale of 1 = < 5 bundles to 5 = > 16 bundles
ALTERNERG	Other sources of energy used for cooking, evaluated for five categories
SEASON	Season of the year in which much fuelwood is used, coded for five

	categories
TCOVER	Change in tree cover during the past five years as being less, same or high
STRAT	Coping strategies to lack of fuelwood for cooking, dummy coded for 11 categories
REGION	Geographical location of the households in the LAR, MAR and HAR. REGION = 1 for location in LAR, MAR or HAR, and 0 otherwise

4.3 Results

4.3.1 Characteristics of the variables tested in the models

This section provides background for interpreting the variables that were used to describe farmers' motivation to plant and keep trees on farms. The variables tested in the models were grouped into three categories: (1) demography and socio-economic conditions; (2) land use; (3) fuelwood production and use.

Demography and socio-economic conditions

For the entire study area, 44% of respondents were male and 56% female. The highest proportion of the interviewees (i.e. 15%) were over 60 years old, followed by respondents between 41 and 45 years of age (11%). Each individual household had 4–6 members in about 48% of the cases. Only 3% of household members were not involved in agriculture and more than 85% were not employed nor involved in commercial business. Overall, 1–2 household members were employed in various sectors for the majority (62%) of the cases.

The most important occupations of the household heads were agriculture (77%), formal employment (7%), informal employment (4%), handcraft (2%, and livestock grazing (0.2%). There were 9% of householders who were not engaged in any productive activity because they were old or disabled. The respondents indicated various level of formal education: 27% did not attend formal education, hence they were unable to read and write; 53% were at the primary level education; 16% at secondary education; and 5% at university level. Therefore, for the entire study area, the rate of literacy of the respondents was about 73%.

Agriculture was the most important source of income for 80% of the households. Crop and livestock farming were the primary activity for 94 and 5% of households. They were listed as secondary by 5% (when livestock was the primary activity) and 55% (when crop growing was the primary activity) of the respondents. Most households combined agriculture with other activities such as farming of small and large livestock, poultry, and employment in formal and informal sectors.

Agriculture was the most important source of income for 80% of the households. Of these, 25% diversified their income sources through the selling of tree products. Only 9% of households sold avocado, mango, papaw, guava and citrus fruit. The annual income generated from the selling of tree products was less than 10,000 Rwandan Francs (FRW) or approximately US$ 17 (based on 1 US$ ≅ 590 RWF, July 2010). Frequency analysis indicated that 72% of respondents had an annual income of approximately US$ 200 (or US$ 0.6 per day), with the highest percentage of households in this category being found in MAR (81%), followed by LAR

(70%) and HAR (63%). For the majority of households (83%), the annual expenses were roughly equal to annual income, and savings were seldom made.

Land use

Households with farms less than 0.6 ha made up 44% of the total number of households. Farms of 0.6–1 ha amounted to 30% of the total, farms of 1–2 ha amounted to 14% and households with lands > 2 ha accounted for 4%. In LAR, 39% of the respondents had farms of 0.6–1 ha. Farm holdings of this size were reported by 30 and 19% of respondents in the highlands and midlands, respectively. For the whole study area, more than 70% of respondents reported farm sizes of less than 1 ha and 8% of cultivating farmers didn't own any land but depended on rented or borrowed lands. All households managed their farms predominantly for the production of food crops. Across the three altitudinal regions, respondents grew a range of agricultural crops belonging to different product categories (Table 4-2). There were few cases of regional differences in growing specific crops associated with local climatic and soil conditions.

For the whole study area, 73% of the surveyed households had scattered, boundary or contour planted trees on their farms. The percentage of respondents who established trees in LAR, MAR and HAR were 77, 76 and 63%, respectively. Woodlots were reported to be available on 42% of farms, with the highest proportion of respondents being recorded in the HAR (62%), followed by the MAR (47%) and least in LAR (27%). Of the 42% woodlots owners recorded in the whole study area, 32% also kept scattered trees on their farms (Fig. 4-2). These figures are in agreement with those reported by the National Institute of Statistics of Rwanda in 2008.

Table 4-2 Percentages of households growing food crops in the three altitudinal regions

Crop	Percentage of households			Mean
	LAR	MAR	HAR	
Cereals				
Sorghum	37	21.9	50.8	35.4
Maize	59	26.9	54.2	47.1
Wheat			31.7	7.9
Rice	13	3.8		6.7
Roots and tubers				
Cassava	65.5	55		45.6
Sweet potatoes	32.5	70.6	8.3	39.2
Irish potatoes	9	10	85.8	28.5
Taro	2.5	21.3	1.7	8.5
Pulses				
Bean	90	91.9	66.7	84.4
Peas	0.5	0.6	20	5.4
Oil plants				
Soybean	4.5	20.6		8.8
Groundnut	12.5	3.1		6.3
Vegetables				
Spinach	0.5	8.8	11.7	6
Tomatoes	1.5	5		2.3
Onions	0.5	2.5		1
Carrots		0.2	0.4	0.6
Eggplants	0.5	0.6		0.4
Stimulants				
Coffee	4.5	6		2.1
Tea			6.4	2.1
Fruit				
Banana	24	35.6		21.9
Natural insecticide				
Pyrethrum			0.8	0.2

Fig. 4-2 Distribution of respondents according to the availability of woodlots and trees on farms

Fuelwood production and use

Of the 480 respondents, 220 (46%) collected fuelwood from their own agricultural land. Thus, more than 50% of households obtained their supplies from outside their own farmlands. Within the LAR, MAR, and HAR, respondents who collected fuelwood from trees on farms represented 43, 41 and 58%, respectively.

When respondents were asked ‘‘How do you rate the amount of fuelwood obtained from your own agricultural fields’’, many respondents rated the amount of fuelwood from farms as being small. In the HAR, MAR and LAR, the majority of respondents rated the amount of on-farm fuelwood as high, moderate and small, respectively (Fig. 4-3). All altitude regions combined, about 69% of the respondents collected fuelwood, 14% used purchased fuelwood and 17% utilized both collected and purchased fuelwood.

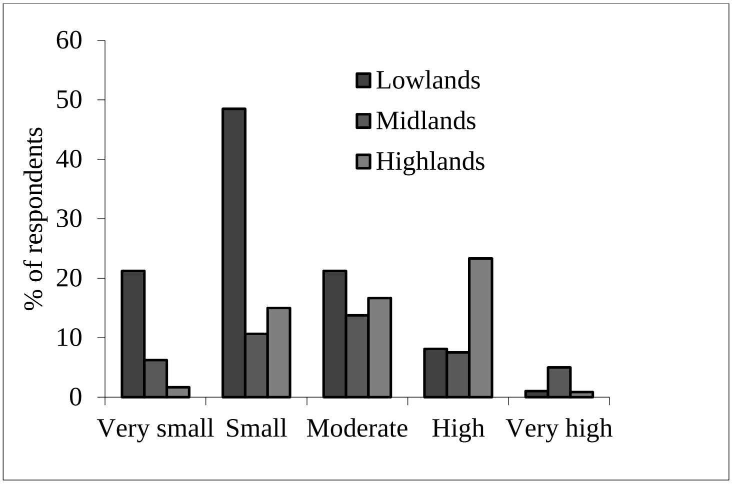

Fig. 4-3 Percentages of respondents rating the amount of fuelwood from farms on a scale of very small to very high in the three altitude regions

In order to get a better insight into the source of fuelwood, respondents were asked to indicate where they usually collect or buy fuelwood. The first three major sources of fuelwood were identified as: (1) farms; (2) forests; and (3) markets (Table 4-3). In general, respondents gathered fuelwood from their farms but diversified sources of fuelwood in order to meet their fuelwood needs by collecting firewood from public and private forests, bushes and by purchasing firewood from markets or from neighbours.

About one quarter of the households collected fuelwood 10-13 times per month, and 33% of households purchased fuelwood less than two times per month; 28% of households purchased fuelwood two to five times in a month. The high monthly frequency of fuelwood collection prompted many households to collect fuelwood at least once every 2 days.

Table 4-3 Percentage distribution of respondents according to fuelwood sources in the low, medium and high attitude regions and in the whole study area

Sources of fuelwood	Percentages of households			All regions
	Lowlands	Midlands	Highlands	
Farms	23.8	31.8	41.2	30.9
Forests[a]	28.1	42.4	3.5	26.0
Farms and markets	5.4	3.0	4.4	4.4
Farms and forests	2.2	3.8	16.7	6.5
Bushes	17.8			7.7
Markets	15.7	7.6	19.3	14.2
Forests and markets	7.0	11.4	14.9	10.4
Total	100	100	100	100

[a] By forests, we mean public forest plantations, natural forests, savanna woodlands, other wooded lands and private woodlots in which households collect firewood as a source of energy for cooking meals

The frequency of collecting fuelwood was not significantly related to the distance travelled to the source of this material. With long distance to fuelwood sources, the number of household collectors tended to decrease. Table 4-4 presents the percentage distribution of respondents according to monthly frequency of fuelwood collection and the distance to nearest sources of fuelwood. Only for distances less than 1 km, the number of household collectors is higher compared to longer distances.

Expenditures on firewood and charcoal were made by only a few households in the study area. Thus, approximately 67% of households did not purchase any firewood and 97% did not purchase charcoal, indicating that

Table 4-4 Percentage distribution of sample households according to monthly fuelwood collection frequency and distance to nearest source of fuelwood

Monthly frequency of fuelwood collection	Distance to the nearest source of fuelwood		
	< 1km, n =285	1 - 5 km, n=109	5.1 - 10 km, n = 10
< 2 times	49 (17.2 %)	9 (8.3 %)	0
2 - 5 times	41(14.4 %)	8 (7.3 %)	0
6 - 9 times	40 (14.0 %)	15 (13.8 %)	1(10 %)
10 - 13 times	31(10.9 %)	17 (15.6 %)	0
14 - 17 times	20 (7.0 %)	6 (5.5 %)	1 (10 %)
18 - 21 times	68 (23.9 %)	32 (29.4 %)	0
> 21 times	36 (12.6 %)	22 (20.2 %)	8 (80 %)

rural households predominantly resort on collected fuelwood. The percentage of households that purchased firewood (33%) was higher compared to that using purchased charcoal (3%). The average monthly expenditure on firewood ranged between US$ 2 and US$ 9 per month while expenditure on charcoal was between US$ 5 and US$ 8.5 per month.

Out of the 480 rural households surveyed, 93% of the respondents relied on firewood for cooking meals, 1% used crop residues and 0.4% used charcoal only. Both firewood and charcoal were used by 6% of the total number of sample households. Wood burning stoves were used by 76% of respondents and only 20% used traditional stoves, implying that firewood was used efficiently by many households. The majority (i.e. 79%) of respondents reported that meals were taken twice a day (lunch and dinner).

Fuelwood consumption in households appeared to be the same across the LAR, MAR and HAR. Ninety six per cent of households consumed approximately 100 kg of firewood per week, corresponding to a daily fuelwood consumption of 2.3 kg per capita[7]. In the MAR, many households consume more than 100 kg compared to the remaining two altitude regions. More fuelwood than normal was used during the long wet season as reported by 61, 86 and 71% of respondents in LAR, MAR and HAR, respectively. In a few occasions, households consumed less than 20 kg of charcoal per week, or approximately 3 kg per day.

When firewood was short in supply, many respondents (about 90%) had no alternatives, but a few indicated that they supplemented fuelwood with crop residues (7%), grasses (1%), a mix of grasses and crop residues (1%), and cow-dung (0.4%) particularly in the LAR where livestock farming is common and cow-dung is readily available. Table 4-5 indicates coping strategies when the energy sources for cooking meals were unavailable. These strategies varied widely among households across the altitude regions. However, a reduction of the number of meals per day, followed by ‘‘no cooking’’ appeared to be the common strategies to many rural households.

To the question on changes in tree cover during the past 10 years, there was no much difference in the proportions of households that reported an increase in tree cover (44%) and a decline in tree cover (46%) for the whole study area. On regional basis, there were notable differences in the proportions of respondents (Fig. 4-4).

[7] Authors’ estimation based on 7 days per week and average household size of 6 members

Table 4-5 Percentage distribution of households according to coping strategies to unavailability fuelwood in the low, medium and high altitude regions of Rwanda

	Percentages of households			
	Lowlands	Midlands	Highlands	All
Coping strategies	n = 103	n = 79	n = 71	n = 253
No cooking/no meals	24.3	25.3	1.4	18.2
Borrowing firewood from neighbours	2.9	2.5	0.0	2.0
Collection of sources of fuel everywhere	1.9	30.4	8.5	12.6
Cooking less firewood demanding food	25.2	1.3	14.1	14.6
Less firewood demanding and reduced frequency of cooking	1.9	0.0	2.8	1.6
Collecting firewood from existing constructions	0.0	0.0	2.8	0.8
Permanent use of another fuel	0.0	2.5	7.0	2.8
Purchase of fuelwood (firewood, charcoal)	0.0	1.3	1.4	0.8
Reducing the frequency of cooking meals	1.0	11.4	11.3	7.1
Reducing the number of meals per day	36.9	17.7	23.9	27.3
Stop less important activities using the fuel in shortage	0.0	0.0	8.5	2.4
Use of energy saving stoves	0.0	0.0	1.4	0.4
Temporal use of another fuel	2.9	7.6	15.5	7.9
Temporal use of another fuel & reduced frequency of cooking	2.9	0.0	1.4	1.6
Total	100	100	100	100

Many farmers that keep trees on their farms (48%) reported that there was less trees today and 47 % of farmers who did not own trees on farms thought that there were more trees during the present time. Different opinions on the changes of tree cover may originate from different knowledge of tree cover and different perception of the availability of forest resources in the neighbourhood of the households.

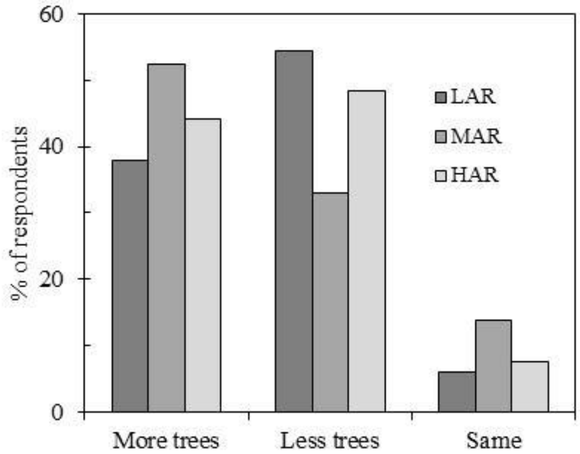

Fig. 4-4 Rate of forest cover change during the last 10 years by the respondents in the low, medium and high altitude regions of Rwanda

4.3.2 Farmers' motivations for keeping trees on farms

Of the 350 households who owned trees on farms, 1-4 tree species were growing on their farms and generally used for more than one purpose. This number of species is lower compared to the farm species diversity recorded in other studies because in our study, tree species in and around the home compounds were not recorded. In fact, the study focused only on tree species on farms that are on more productive areas of wood products and services while increasing crop yields. In general, households were motivated to plant trees on farms for economic benefits which can be grouped into 11 product categories. The proportions of households utilising different tree species for different products categories were small, indicating large variations in species preferences and management objectives (Table 4-6).

Fruit tree species including *Persea americana* (avocado), *Citrus spp.*, *Carica papaya* (papaw), *Mangifera indica* (mango) and *Psidium guava* (guava) were found to be among the most planted tree species on farms. These were used mainly as sources of food and income from the selling of fruit. The study found that the majority (56%) of households planted *Grevillea robusta* mainly to produce timber (22%), firewood (17%) and both timber and firewood (7%). Because the trees are not felled before they attain a size that can produce timber, firewood from *G. robusta* is collected mostly during pruning and pollarding used by farmers to manage competition for light with crops. The remainder of firewood is obtained from branches and non-merchantable stems after final felling. Although Grevillea trees were present on farms, they were seldom used for firewood. People were primarily motivated to plant them for timber and management of the trees in agroforestry systems provide firewood only as additional benefit. Other tree species planted on farms that targeted timber production included *Ficus spp.*, *Markhamia spp*., *Erythrina abyssinica*, *Cedrela serrata*, *Cupressus lusitanica*. The first three species are indigenous and commonly maintained on farms as a source of timber for making woody products.

Table 4-6 Percentage distribution of households according to trees species on farms and their uses

	Tree product categories[a]											
Tree species	Fi	Ti	Po	Ti&Fi	Fi&Po	Ti&Po	Fo	Ic	Fo&Ic	Fd	Other[b]	Total
Persea americana		0.3					40.0	3.7	24.0		0.6	68.6
Grevillea robusta	16.9	21.7	2.9	7.1	2.3	0.9					4.3	56.0
Ficus sp.	6.0	5.4		0.3						2.3	6.9	20.9
Eucalyptus sp.	6.9	1.7	5.7	2.9	1.4	0.3					0.3	19.1
Carica papaya							14.9	0.3	2.6			17.7
Markhamia sp.	3.4	8.0	0.9	1.4	0.3	0.6					0.3	14.9
Vernonia amygdalina	14.6										0.3	14.9
Mangifera indica							10.3	2.0	2.6			14.9
Euphorbia tirucalli	11.7				0.3						1.4	13.4
Psidium guayava							8.0	0.6	2.0			10.6
Senna spectabilis	9.1		0.6		0.6						0.3	10.6
Cedrela serrata	1.1	7.4	0.9	0.3	0.3	0.3						10.3
Citrus lemon							5.4	0.3	3.1			8.9
Calliandra calothyrsus	8.0									0.6		8.6
Cupressus lusitanica	0.3	6.6	0.3	0.6								7.7
Ricinus communis	2.0										4.0	6.0
Erythrina abyssinica	0.9	2.6									2.3	5.7
Leucaena sp.	5.1									0.3		5.4
Jacaranda mimosaefolia	1.1	1.7	0.9	0.6							0.3	4.6

Fi : Firewood; *Ti*: Timber; *Po*: Poles; *Ti&Fi*; Timber and firewood; *Fi&Po*: Firewood and poles; *Ti&Po*: Timber and poles; *Fo*: Food; *Ic*: Income; *Fo&Ic*: Food and income; *Fd*: Fodder

[a] Percentage of households are only presented for tree species recorded on ≥ 5% of farms in the whole study area.

[b] Other tree product categories include staking materials for climbing beans or heavy banana bunches, trees for boundary marking, cultural value, erosion control, soil improvement, fence, medicine, ornament or a combination of these benefits with major benefits (e.g. firewood, timber, poles, fodder, etc.)

Next to grevillea trees, the most cited sources of firewood comprised mainly shrub species including *Vernonia amygdalina*, *Euphorbia tirrucalli*, *Senna spectabilis*, and *Calliandra calothyrsus*. Eucalyptus trees were preferred for fuelwood use by many rural households (19%) in the study area. The economic reasons for owning *Eucalyptus spp.* included firewood (7%) and building poles (6%). Other reasons for planting eucalyptus on farms included the production of timber, a combination of timber and firewood as well as a mix of both firewood and building poles. Though eucalyptus were appreciated for multiple values, they were not present on many farms, probably because rural households were aware of the competition effects of eucalyptus on agricultural crops. Beside commonly planted tree species, many other multipurpose tree species were reported by very small proportions of households.

4.3.3 Factors affecting household choice to keep trees on farms in the low, medium and high altitude regions

Table 4-7 presents the results of correlation analysis among the factors affecting the presence of trees on farms in the low altitude region. The results showed a significant positive correlation ($p < 0.05$) between number of adults in the household and monthly expenditure ($p < 0.001$).

Table 4-7 Correlations among characteristics of the households in the low altitude region of Rwanda.

Household characteristics	Number of adults	Monthly expenditure	Woodlot ownership	Amount of farm fuelwood use	Selling of tree products
Number of adults	1	0.288***	0.086	-0.044	-0.055
		(0.001)	(0.226)	(0.541)	(0.437)
Monthly expenditure		1	-0.024	0.022	-0.034
			(0.733)	(0.756)	0.629
Woodlot ownership			1	-0.339***	-0.184**
				(0.001)	(0.009)
Amount of farm fuelwood use				1	0.281***
					(0.001)
Selling of tree products					1

Note: Probability values (p-values) in parentheses. ** $p < 0.01$; *** $p < 0.001$

There also was a significant positive correlation ($p < 0.05$) between amount of farm fuelwood use and selling of tree products. This correlation implies a household that collect much fuelwood from farms is likely to sell the surplus in markets. On the other hand, amount of farm fuelwood use was significant and negatively related to woodlot ownership ($p < 0.001$), implying that households that tend to obtain much fuelwood from their farms do not own woodlots, which are the most convenient agroforestry system for higher production of fuelwood. There was also a significant negative correlation between woodlot ownership and selling of tree products ($p < 0.05$), suggesting that woodlot products are not regularly sold on the market but products from scattered trees on farms such as fruit may be sold by the farmer.

Using binary logistic regression, many of the hypothesized variables in section 4.2.4 were removed by the likelihood ratio test (Forward: LR method) because they had no effect on the presence of trees on farms. In MAR model, no explaining factors were found. This means no single variable was correlated with whether the households had trees or not on their farms. Hence the MAR model suggests that all households have trees on farms regardless of their characteristics including gender of head of household, household size, monthly income, and number of salaried members of the household. However, the analysis of data of sample households in LAR indicated that number of adult members in households, monthly expenses, ownership of woodlots, amount of farm fuelwood use and selling of tree products on markets were significant factors affecting the likelihood of the household to plant and maintain trees on farms (Table 4-8).

The hypothesis that households that own woodlots do not keep scattered trees on farms is not supported; rather those households are found to maintain trees in other arrangements and locations in farmlands. The result is not surprising because the Rwanda agricultural survey in 2008 found that many agricultural households (34%) owned both scattered trees and woodlots (NISR 2010). Similarly, the selling of tree products on markets contributed to the presence of trees on farms. As opposed to households without trees on farms, tree planters tend to sell wood products on markets. The result showed a strong support to our hypothesis that the presence of markets of tree products is positively correlated with the existence of trees on farms. As expected, adult members of households are usually involved in agricultural activities and hence tend to plant and retain trees on farms.

Table 4-8 Results of maximum likelihood estimates of the determinants of tree planting and retention on farms in the low altitude region of Rwanda

Variables					95 % C.I. for EXP(β)		
	β	S.E.	Wald	df	Lower	Exp(β)	Upper
Number of adults members in the household	0.97**	0.35	7.46	1	1.31	2.62	5.25
Monthly expenses	- 0.45*	0.17	6.71	1	0.46	0.64	0.90
Presence of woodlot	1.35*	0.60	4.99	1	1.18	3.85	12.57
Amount of farm fuelwood use	- 0.43**	0.14	8.95	1	0.49	0.65	0.86
Selling of tree products	2.68*	1.24	4.62	1	1.27	14.51	166.22
Constant	1.28	0.89	2.07	1		3.61	
Model χ^2	34.28***						
Hosmer & Lemeshow R^2	3.34						
Cox & Snell R^2	0.22						
Nagelkerke R^2	0.33						
Overall accuracy of classification (%)	76.3						

* p<0.05; ** p<0.001; *** p<0.0001

In LAR, monthly household expenses had significant negative correlation with the presence of trees on farms, implying that a move from a lower to a higher monthly household expenses decreased the likelihood of keeping trees on farms. Similarly, amount of farm fuelwood use was inversely related to the presence of trees on farms. This implies that, if the amount of farm fuelwood is large, then the households tend to harvest all fuelwood trees on their farms, may switch to other trees species such those used in erosion control, without replanting. As a result, on-farm fuelwood collection may lead to the depletion of trees on farms.

A significant inverse correlation between the amount of farm fuelwood use and presence of trees on farms ($r = -0.184$, $p = 0.04$) was also found for households in the high altitude region (Table 4-9), although the trend is very small. Monthly frequency of fuelwood collection was positively associated with the season in which fuelwood was used more than average. The results of the logistic formulation presented in Table 4-10 confirm these correlations and give other predictor variables that affect the household preference to plant and retain trees on farms.

Of the variables included in the logistic regression model, monthly frequency of fuelwood collection and monthly expenditure on firewood were positively correlated to the likelihood of household choice to maintain trees on farms. These results are in disagreement with the hypothesis that households who collect fuelwood or purchase it from markets tend to plant less trees on their farms. The existence of a season in which much firewood was used exhibited the expected relationship with the presence of trees on farms. The majority of HAR households (71 % of all on-farm tree growers) were likely to keep trees on farms in order to guarantee the supply of firewood during the wet seasons.

Table 4-9 Correlations among characteristics of the households in the high altitude region of Rwanda

Variables	Amount of farm fuelwood use	Monthly frequency of fuelwood collection	Monthly expenditure on firewood	Season in which much fuelwood is used
Amount of farm fuelwood use	1	-0.082	0.172	-.184*
		(0.374)	(0.06)	(0.044)
Monthly frequency of fuelwood collection		1	0.012	0.212*
			(0.896)	(0.02)
Monthly expenditure on firewood			1	0.134
				(0.144)
Season in which much fuelwood is used				1

Note: Probability values (p-values) in parentheses. * $p < 0.05$

In the LAR and HAR models, the values of the χ^2 statistics, the Hosmer-Lemeshow statistic and R^2-values of both models indicated that the selected variables fit the estimated models well (Tables 4-8 and 4-10). The HAR model, however, was better than the LAR model because the R^2-values were the highest.

Table 4-10 Results of maximum likelihood estimates of the factors influencing the planting and retention of trees on farms in high altitude region of Rwanda

					95 % C.I. for EXP(β)		
Variables	β	S.E.	Wald	df	Lower	Exp(β)	Upper
Amount of farm fuelwood use	-0.81***	0.23	12.67	1	0.29	0.45	0.70
Monthly frequency of firewood collection	0.38**	0.14	7.44	1	1.11	1.46	1.91
Monthly expenditure on firewood	0.99**	0.29	11.29	1	1.51	2.68	4.76
Season in which much fuelwood is used	0.56*	0.25	4.88	1	1.07	1.74	2.86
Constant	-0.88	1.22	0.52	1		0.42	
Model χ^2	46.78***						
Hosmer & Lemeshow Statistic	8.96						
Cox & Snell R^2	0.4						
Nagelkerke R^2	0.55						
Overall accuracy of classification (%)	76.9						

* p<0.05; ** p<0.001; *** p<0.0001

4.3.4 General determinants of households' choice to keep trees on farms

In order to identify factors influencing the current practices of planting and maintaining trees on farms in the whole study area, the logistic regression model was developed from the pool of data collected across three regions. Of the cases used to create the model, 233 of the 241 (i.e. 97%) farm tree owners were classified correctly. Fourteen out of 91 (i.e. 15%) who didn't own farm trees were classified correctly. Overall, 75% of the cases were classified correctly.

Table 4-11 shows how a combination of household characteristics relates to the presence of trees in the entire study area. All explanatory variables correlate with the presence of trees on farms with different significant levels. Among significant explanatory variables, selling of tree products and amount of farm fuelwood appear to result logically from the presence of trees on farms; if these variables are excluded from the model, the remaining variables remain significant but the accuracy of classification reduces by about 2 %.

Table 4-11 Results of maximum likelihood estimates of the determinants of the existence of trees on farms in the entire study area

	Parameter estimate	S.E.	p-value	p-value[a]
LAR vs. HAR	0.97	0.28	0.001	0.001
MAR vs. HAR	1.05	0.30	0.001	0.001
Male vs. Female heads of households	-0.70	0.26	0.008	0.005
Number of household members in informal employment	0.93	0.41	0.022	0.02
Number of meals per day	0.60	0.24	0.013	0.006
Amount of farm fuelwood use	-0.18	0.07	0.006	
Selling of tree product	1.08	0.35	0.004	
Constant	-0.71	0.80	0.369	0.056
Model χ^2	55.8***			29.8***
Hosmer & Lemeshow Statistic	3.8			4.9
Cox & Snell R^2	0.11			0.06
Nagelkerke R^2	0.16			0.09
Overall accuracy of classification (%)	75.2			72.7

a. Significance excluding amount of farm fuelwood and selling of tree products on markets

*** p=0.001

Of the six variables included in the model, the number of household members in informal employment, the number of meals per day, the selling of tree products on market and the location of households were positively correlated to the presence of trees on farms. Somewhat surprisingly, the presence of male heads of households is inversely correlated to the existence of trees on farms. The negative and significant effect of this variable means that households headed by men appeared less likely to belong to the category of farm tree owners compared to households headed by women. In other words, households headed by women were more likely to own trees on their farms than households headed by men.

The inverse correlation between the amount of farm fuelwood use and the presence of trees on farms implies that fuelwood collections from own farmlands apparently reduces the chance of keeping trees on farms. This implies that, as on-farm fuelwood collection increases, the stock of trees on farms decreases and may become depleted.

4.4 Discussion

A wide range of tree products are collected by rural households. These products underscore the economic roles of trees in rural livelihoods and the preference for keeping various multipurpose tree species. The results of this study indicated that households were commonly motivated to keep trees on farms to meet their needs in food and firewood as well as in income from the selling of tree products. Of the present trees, fruit trees are worth mentioning because they are sources of food and income to farmers. Economic factors, therefore, were the strongest motivators of keeping trees as has been documented elsewhere (e.g. Entage and Suh 2004). Many studies (e.g. Clay and Lewis 1990; Drechsel et al. 1996; Mateete et al. 1997; Roose and Ndayizigiye 1997) indicated that soil erosion and low soil fertility were major impediments to increasing agricultural production. The importance of farm trees in conserving the natural resource base and biodiversity is increasingly recognized (e.g. Acharya 2006; Garrity and Stapleton 2011). Unfortunately, rural households seem to be unaware of all the importance of trees on farms. As reported by Salam et al. (2000), the household decision to grow trees on farm is influenced more by economic than environmental factors. More widespread knowledge of the environmental importance of trees on farms could have a positive impact on the households' decision to plant and maintain trees on farms.

The importance of the factors that influenced the presence of trees on farms were determined by considering statistically significant variables for each altitude region, and for all regions combined. In the MAR model, none of the variables studied explained ownership of trees on farms by rural households. The lack of significant predictor variables provides avenue for future research aimed at a better understanding of the determinants of the presence of trees on farms. Possibly, the presence of trees on more than 75% of MAR farms can be ascribed to the impact of agriculture and forestry development projects that promoted and widely disseminated agroforestry technologies in the region since the early 1970s.

The households in LAR and HAR have different socio-economic status and are located in different biophysical conditions as compared to the

MAR households. Therefore, different sets of variables where used to predict the presence of trees on farms. The model for the entire study area showed few common variables with one or two regional models. Our results indicated that amount of farm fuelwood use, selling of tree products and the number of meals per day were significant predictors of having trees on farms. These variables had different coefficients, indicating varying effects on the presence of trees on farms across regions.

These findings were partly consistent with theoretical considerations. The amount of farm fuelwood use was negatively correlated to the presence of trees on farms in both LAR and HAR. The direction of the relationship between the presence of trees on farms and amount of farm fuelwood use remained negative when the pooled data across the three regions were analysed for their effects on the presence of trees at country level. This effect indicates that rural households may not have extended the planting of trees on farms or did not replant, and that effectively the on-farm tree resource is being depleted. In addition, many tree species found on farms were not primarily used for fuelwood production. Hence fuelwood collection appears to be not the major driving factor for the choice to keep trees on farms. For example, across the three altitudinal regions, the majority of trees on farms were fruit trees for households’ consumption and for income. This result seems to agree with those of Degrande et al. (2006) who found that smaller farms had higher fruit tree densities, a relationship that was particularly strong in communities with good market access. The rural households are therefore not primary growing trees on farms for fuelwood but aim to producre various tree products that can generate extra income. As argued by

Arnold and Persson (2003), firewood is collected as a secondary product from trees on farms. Yet, the use of trees on farms for fuelwood supply without replanting or coppicing may result in decline or complete disappearance of trees on farms.

The exploitation of trees on farms may affect farm productivity e.g. through removals of nitrogen, when the trees are used for fuelwood (Gama-Rodrigues 2011). Thus, the use of farm fuelwood may cause an adverse impact on the nutrient status of the farms, and agricultural productivity may decline. Intensive use of farm fuelwood may therefore require additional nutrient inputs to maintain the productivity of the land.

In Rwanda, as in many countries of Africa, it was customary for trees to be established by men, with women responsible for food production (e.g. Den Biggelaar 1996; Mekonnen 1999). Yet, households headed by women appear to plant and retain more trees on farms than households headed by men. This results seem to oppose many studies focusing on gender roles in tree planting and agroforestry adoption (e.g. Mukadasi et al. 2007; Buyinza and Ntakimanye 2008; Deressa et al. 2009; Kideghesho and Msuya 2010). The significance contribution of female headed household in the likelihood of keeping trees as compared to male headed households may be explained by anticipated products from trees on farms such as fruit trees, which were predominant in agricultural lands. Apparently, women have gained an important role in on-farm tree planting, indicating a change in attitude toward this cultural taboo and toward ownership rights over land and planted trees on this land. Women heads of households are common in social units in all provinces of the country (NISR 2010). As a result of heading their own households, women have assumed new roles and are increasingly becoming the owners of trees on farms. A historical process of women undertaking roles and responsibilities of men in the absence of the latter has been reported for a number of societies (e.g. Allan 1965; Cliffe 1975). In this way, women have access to landownership, which result in interest in land resource management, including tree planting and maintenance on farms.

The significant effect of altitude regions in influencing households' decision to keep trees on farms underscored the importance of taking into account the uniqueness of each geographical location. This is because the regions vary in climatic conditions and other characteristics that are likely to have influence on the presence of trees. In this study the three altitude regions were very distinct in many aspects, including the amount of rainfall, soils, crop types, farm size and forest resources. Location dummy variables also had significant impact, reflecting the role of the agroecological context in explaining the presence of trees on farms. For example, in the high altitude region, more than 50% of agricultural households own farms smaller than the national average of 0.76 ha (NISR 2010). The small size of landholdings could be the reason for keeping less or no trees on farms as it is has been found in many farm and socioeconomic studies (ex. Zubair and Garforth 2006; Schuren and Snelder 2008; Sood and Mitchell 2009), which show that land availability is a significant factor influencing a community's decision to plant trees on a large scale. The high altitude region has also large forest cover (outside farms), which may explain the low level of the presence of trees on farms compared to other two regions. This corroborates with the finding that the availability of forest affects the planting of trees on farms (Vikram 2006; Rao and Reddy 2007). The proximity of rural highland households to forests may have led to farmers planting and maintaining less trees on farms, as they could access forest products from government owned forests.

4.5 Conclusion

The household-level survey results shows that rural households in Rwanda are mainly motivated to keep trees on farms for economic benefits, not for environmental purposes. Consequently, trees on farms should have clear economic benefits if agroforestry cover is to be increased. Rural households should be able to earn more income and produce wood and food for their own use, thus contributing to their improved livelihoods, in order to adopt Agroforestry systems. Expansion of tree planting on farms is only attractive to farmers when this contributes to achieving food and an extra household income, which should be recognized by policy makers and extension services. To maximize the benefits from trees on farms, extension workers should motivate households to plant and keep more trees on farms and raise awareness on multiple benefits of trees on farms, including their effects on the natural resource base and the environment.

This study indicates that different sets of socio-economic factors and attitudes in fuelwood production and use are associated with the household choice to keep trees on their farms. The determinants of the presence of trees on farm are region-specific, and cannot be easily generalized for all agricultural households at national scale. The current Rwandan forest policy promotes farm forestry. In the process of promoting tree planting and agroforestry practices, extension staff and development professionals should take into account the regional biophysical conditions as well as household characteristics. This may help to match tree species with regional conditions and to meet the interests of the households in tree products. The finding of this study therefore could be helpful in assisting the Rwanda government to effectively implement agriculture and forestry policies geared toward expanding agroforestry to 80% of the agricultural land. One focus of these policies could be to monitor the land use systems across the country. This would may lead to identification and mapping of sites within altitude regions that are relevant for tree planting. Specifically, forest policy should be based on evaluation of current farm forestry needs in each of the specific agroecological zones of the country, to strengthen tree planting practices. This may assist in the allocation of resources to increase national tree cover.

The issue of income and food from trees is of crucial importance. As long as farm trees produce products for selling, a policy formulated to improve commercialisation of farm tree products is bound to successfully influence the household decision to plant and keep more trees on farms. Overexploitation of trees on farms urgently require strategies for replacement planting and management in terms of fuelwood sustainability for instance using alternative sources of energy or expanding plantation of multipurpose trees. Another important factor that influence households’ farm tree planting decisions is the availability labour. The promotion of agroforestry technologies requiring less labour inputs in tree propagation, establishment and maintenance are likely to be adopted by many farming households.

In general, the results of the study bring up many factors that policies aiming at promoting farm tree planting and agroforestry may want to take into account. For instance, policy measures that enhance food security and income diversification in the households may, at the same time, enhance tree planting on farms. The results are also relevant to forestry (agroforestry) policy because they feature which category of tree species are important for rural households and for which purposes, for example to meet the needs in nutrition (fruit), or to address scarcity of fuelwood.

Encouraging tree planting on farms in order to meet the household needs is appropriate for all the categories of agricultural households in rural areas. Under the conditions of low income and small farm size, the households need to produce all products they need on a small area, thus enhancing competition between food crop and tree crop production. Notably in this case, the household tree management capacities need to be enhanced through awareness raising and provision of technical information. If farm size is large or income improves, the households may meet their tree products needs by planting more trees or produce some extra crop for the local markets. Income derived from the selling of crops then can be used to buy wood products, including fuelwood. Extension programmes should consider these issues related to farm size by focusing not only on subsistence and household uses but also on options for market-oriented activities because surpluses are apt to be marketed in many rural areas.

For effective dissemination of agroforestry technologies and their adoption by beneficiary smallholder farmers, development facilitators and extension services must be aware of the factors that contribute to the presence of trees on farms in the context of agricultural intensification. Their interventions might be more effective if implemented with actions supporting food security and commercialisation of tree products. While the positive effects of trees on farms on crop yields and environment are poorly understood by farmers, awareness raising and education programmes may result in positive attitudes for tree planting on farms. Building farmers' knowledge, especially for women, about trees on farms and their effects on crops and environment - through training and better access to technical information and tree seeds or seedlings - would increase tree cover in agriculture landscape. Given the interests of farmers in economic benefits from trees, it should be possible to build on them in order to diversify and intensify the production of crops, trees and livestock on sustainable basis and to alleviate poverty in rural areas. In these respects, interventions by government and donor-funded projects should be site (region) specific, to account for biophysical conditions and boundary socio-economic realities that motivate farmers to plant different tree species on their farms.

Chapter 5 Farm woodlots in rural Rwanda: purposes and determinants

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Abstract

The development of farm woodlots as an alternative source of livelihood for smallholder farmers in diverse biophysical and socio-economic conditions is a challenging issue in developing countries, such as Rwanda, where the majority of the population relies on subsistence farming. There is a need to understand why and when farmers decide to grow trees and woodlots on their farms. The objective of this study was to analyse the determinants and the purposes that enhance the propensity to own woodlots in low, medium and high altitude regions of Rwanda. Necessary information for this study came from a survey of 480 households across these regions. The results showed regional variations in the determinants of woodlot farming, demonstrating the importance of not extrapolating the results between regions. Pooled data across regions indicated that age of the householder, number of salaried household members, farm size, travel distance to fuelwood sources and household location in medium forest cover region had positive significant effects on the propensity to own farm woodlots. In contrast, household location in low forest cover region, ownership of livestock and monthly frequency of purchasing fuelwood were inversely related to ownership of farm woodlots. Many households planted eucalyptus woodlots for economic reasons, not for environmental purposes. Livestock and crop production were more attractive to rural households than woodlot farming. The findings of the study can be used by policymakers and extension services in order to promote sustainable land use practices by focusing on the challenges of competing land uses, farm size, unemployment, dependence on forests for fuelwood supply and subsistence farming.

Keywords: Agroforestry; Eucalyptus; Farm woodlot; Fuelwood; Logistic regression; Rural households

5.1 Introduction

Globally, forests provide important economic and environmental benefits. In addition, small woodlots on agricultural land play similar roles and are increasingly recognized for their contribution to solving energy problems, enhancing biodiversity conservation, addressing deforestation and mitigating climate change (e.g. Acharya 2006, Deressa et al. 2009, Dixit and Dixit 2010, Garrity and Stapleton 2011). For instance, as the rates of deforestation continue to rise in some tropical countries, governments are faced with the challenge of finding approaches which can reduce deforestation and provide rural livelihoods in addition to protecting the environment. Much of these policies focus on the promotion of farm forestry by providing incentives that encourage the households to establish and manage their own sources of wood and non-wood products on their farmlands. In densely populated countries such as Rwanda where the majority of their inhabitants survive on subsistence farming, there is a tendency to believe that ownership of woodlots is very limited, particularly for smallholder farmers. Agroforestry - intentional management of trees with agricultural crops - has the potential for accommodating trees and woodlots on agricultural land. This potential is enhanced by the spatial and temporal arrangement of crops and trees in order to reduce competition.

Small woodlots and trees in agro-forestry systems are part of Rwandan forest resources, but they have not been quantified so far (Ndayambaje and Mohren 2011). Nearly 70 % of agricultural households in Rwanda have trees on their farms (NISR 2010), hence many households collect wood products from farms and enhance crop yields and environmental protection through tree planting on farms. Hence, agroforestry practices by rural households produce large amount of wood; at the same time, they increase crop yields while protecting the environment.

On the demand side, farmers need various wood products, especially firewood, building poles and timber. Many studies in East Africa (e.g. Nyadzi et al. 2006, Kimaro et al. 2007, Ntakimanyire and Buyinza 2008) show that woodlot technologies provide wood products to farming households. These technologies include rotational woodlots that involve the growing of trees and crops in interrelated phases (Nyadzi et al. 2003). The benefits of rotational woodlots are more in wood products than in soil fertility restoration (Nyadzi et al. 2006). In traditional practice, wood production in woodlots competes with food production for the same space, undermining the sustainability of production especially on small farms. When farms are large, farmers can allocate parts of their land for growing woodlots. This practice, however, is only feasible if woodlot products are market driven (Dewees and Saxena 1997). Hence, market incentive could be one of the reasons for farm forestry especially where farms can accommodate both food and wood production.

In Rwanda, private woodlots consist of pieces of private land on which trees are cultivated, specifically as sources of firewood and building materials. The national agricultural survey in 2008 estimated that about 9 % of agricultural households owned woodlots and 34% owned both woodlots and scattered trees (NISR 2010). This demonstrates clearly that many households plant woodlots which offer practical responses to wood shortages and environmental degradation.

The Rwanda forest policy targets the promotion of farm forestry and forest extension. The success of the general policy on the development of farm forestry require many dimensions of these areas, more important are the motivations of farmers to adjust their behaviour with forest policy objectives. Many factors determine the farmers' willingness to grow trees; If the extension systems intend to convince farmers to grow more trees, these factors must first be understood.

In fact, many factors including household socio-economic characteristics, access to forest products and markets factors affect farmers' tree planting decisions (see Salam et al 2000, Amacher et al. 2004, Hansen et al. 2005). In their study in Bangladesh, Salam et al. (2000) showed that economic factors play a role than ecological factors in determining farmers' decisions to plant trees, in contrast to the findings of Emtage and Suh (2004) from the Philippines where tree planting was driven by the household needs for timber and building materials. Gebreegziabher et al. (2010a), from a study in Northern Ethiopia, reported that land size, age, and agro-ecology were among important factors that enhance the farmer tree planting decision, while increased livestock holding affected this decision negatively. In Central Ethiopia, Mekonnen (1998) showed that households with relatively higher income and higher proportion of off-farm income are likely to plant trees. Dewees (1995a) also found that household fuelwood demand and market prices are the most important determinants influencing farmers' decisions to plant trees in Malawi.

In Rwanda, few studies are available which focus on the determinants of farmers' decisions to plant trees on farms. This implies the need for additional studies to increase understanding of the factors that smallholder farmers consider in making decisions to grow trees and woodlots. Woodlot farming, however, has not been comprehensively investigated as a land use option that takes place under biophysical and socio-economic constructs and which much be understood in the context of subsistence farming.

In this paper, we address three questions. First, what are the most important purposes that households consider when deciding to establish farm woodlots? Second, what factors affect the decision whether to establish farm woodlots or not in the low, medium and high altitude regions of Rwanda? Third, what factors generalize the planting of farm woodlots at the national scale? It is argued that understanding the process by which farmers make decision to establish woodlots provide in-depth understanding of the general farmer motivations and perceptions and lead to an increase in the amounts of wood produced on agricultural lands. The hypothesis was that several household characteristics including gender of the household head, occupation of the household head, age, size of the household, farm size, monthly income, number of household members in formal employment, crop types, livestock ownership, forest cover and distance to fuelwood sources affect the decision to plant woodlots on farms. The results of the study are expected to provide an effective means for policy makers, development professionals and extension staff to promote farm forestry in order to meet the rising demand for wood products while contributing to sustainable land uses and environment protection in the country.

5.2 Methods

5.2.1 Study sites and selection of interview households

The focus of this study was the low, medium and high altitude regions of Rwanda. Each altitude region covers large and discontinued areas defined by altitude, rainfall and soil characteristics, hence forming different agroecological zones as described by Delepierre (1975). The low altitude region (LAR) covers the agroecological zones of Eastern Savannah, Eastern Plateau, Mayaga, Bugesera, and Imbo. This region extends over the entire area of the Eastern Province, the eastern part of Kigali City and the far south western part of the Western Province. It is a region with gentle slopes and altitude of less than 1,500 m. Rainfall is lower here than in the medium and high altitude regions. The mean annual rainfall varies from 800 mm to 1,000 mm. Drier and warmer than the rest of Rwanda, the low altitude region was traditionally reserved for pastoral uses. Though it is densely settled today, farms are larger than those found in the medium and high altitude regions. As for the rest of the country, about 90% of farmers practice subsistence farming on average farm size of 1 ha (NISR 2010). Households in this region rely principally on banana, sorghum, beans and cassava as food crops, and coffee as cash crop.

The medium altitude region (MAR) comprises the Central Plateau, the Granitic Ridge, Impala, and Banks of Lake Kivu. This region encompasses much of the Southern Province, and the south-western parts of the Western Province. It has an average altitude of 1,700 m with a maximum of 1,900 m. The rainfall varies between 1,000 mm and 1,250 mm. The average farm area per household is estimated at about 0.7 ha. It's a region of many undulating hills separated by well-watered marshes, which allow crop farming all seasons. The major cash crop is coffee, while favoured staples are beans, bananas, sweet potatoes, cassava and sorghum.

The high altitude region (HAR) is made up of the agroecological zones of the Congo Nile Ridge, Buberuka (non-volcanic) highlands and the volcanic highlands. This region is characterised by high mountains, very steep slopes, and susceptibility to erosion. The lower areas are located at approximately 1,900 m and higher ones at altitude equal or above 2,500 m. The annual rainfall ranges from 1,250 mm to more than 2,000 mm. The HAR has most volcanic, fertile soils in which major cash crops namely coffee, white potatoes and pyrethrum are produced. Food crops include potatoes, maize, sweet potatoes and beans. Much of the region is very densely populated, and farming is done on very steep slopes often higher than 100%. Farm sizes are usually lower than those in MAR and LAR; 65 % of agricultural households own about 0.6 ha.

The survey sites were selected according to the sampling procedure described by Ndayambaje et al. (2012). In order to select the survey sites, the stratification of the study area was done based on altitude regions and on administrative units of Rwanda. Considering the rural settings, the households within each of the three altitude regions have considerable heterogeneity in their socio-economic conditions. A sampling strategy was designed to eliminate regional sources of variation by focusing on a single area, the administrative Cell, but maximise neighbourhood level variation by sampling households from a setting with much local variation (Smith 1989).

Forty sample households were selected randomly from a Cell in each agroecological zone. In this sampling, the number of sample Cells equalled the number of agroecological zones, and the total number of random sample households from three to five agroecological zones was considered to be representative of a particular altitude region in terms of the different household characteristics within each Cell. For the entire study area, the total number of survey households was 480 of which 200 households were visited in LAR, 160 in MAR and 120 in HAR.

5.2.2 Data collection

Data collection was done on a per household basis using structured questionnaires which were filled by interviewers. The household heads either men or women were chosen as respondents since they had information regarding the socio-economic status, farming practices, and fuelwood supply and consumption in the households. Thus sample selection sought information from men as heads of the households or their wives but could not establish other gender categories such as widows. If the head of the household was not present, that particular household was rejected for interviewing and the next household was visited. Each interviewer surveyed 40 randomly distributed households in each cell within a single agroecological zone. The interviewer was also equipped with a GPS instrument to get data regarding the dimensions of farm woodlots and a spring balance to measure the weight of charcoal and bundles of firewood found in sample households at the time of the visit. The average weight of a bundle of wood splits and a bag of charcoal was 12.5 kg and 35 kg, respectively.

5.2.3 Analytical model

Binary logistic regression methods were used to model ownership of farm woodlots from several measures of household demographic and socio-economic conditions, agricultural production and fuelwood collection and use in LAR, MAR and HAR. The outcome variable, ownership of farm woodlots, was dichotomous, and was assigned a value of 1 if a household owned a farm-woodlot and a value of 0, otherwise (for not having a farm woodlot), and then explained in terms of predictor variables using binary logistic regression techniques. Seventy per cent of farm woodlot owners were used to create the model and the remaining farm woodlot owners were used to validate the model results.

The choice of the households to own farm woodlots was framed as a binary-choice model which assumed that individual households were faced between two alternatives and the choice depended on their characteristics including their socioeconomic status, locations and availability of forests in their neighbourhood. The probability of having a farm woodlot, $P(Y_i = 1)$, was cumulative density function evaluated at βX_i, where X_i is a vector of predictor variables and β is a vector that indexes an unknown parameter (Johnston and Albert 1999). The cumulative density function can be modelled using logistic probability function, which has the following form:

$$\text{Choice to own woodlot} = P(Y_i = 1) = \frac{\exp(\beta X_i)}{1+\exp(\beta X_i)} \qquad \text{[Eq. 1]}$$

The estimation form of the logistic transformation of the probability of household's choice to own farm woodlot, P(Yi = 1) can be represented as:

$$Log\left[\frac{P(Y_i=1)}{1-P(Y_i=1)}\right]=\beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\cdots+\beta_nX_n$$

or

$$Log\left[\frac{P(Y_i=1)}{1-P(Y_i=1)}\right]=\beta_0+\sum_{i=1}^{n}\beta_iX_i \qquad \text{[Eq. 2]}$$

where:

a) $P(Y_i = 1)$ is the probability of having farm woodlot by the i^{th} household in the sample ; it ranges from 0 to 1;

b) $[1-P(Y_i = 1)]$ is the probability of not having farm woodlots; it ranges from 0 to 1;

c) $[P(Y_i=1)/(1-P(Y_i=1))]$ denotes a monotonic transformation of P to odds of the ownership of woodlots on farms; it means the odds increase as the probability increases or vice versa. Its value ranges from 0 and positive infinity;

d) $Log[P(Y_i=1)/(1-P(Y_i=1))]$]) is a monotonic transformation of odds to log of odds, meaning that the greater odds, the greater the log of odds and vice versa; its value ranges from negative infinity to positive infinity;

e) β_0 is the intercept term,

f) $\beta_1, \beta_2, \ldots, \beta_n$ are the coefficients associated with each predictor variable $X_1, X_2, \ldots, X_n$.

The resulting value from Eq.1 varies between 0 and 1. A value close to 0 means that *Y* is very unlikely to have occurred, and a value close to 1 means that *Y* is very likely to have occurred. Each predictor variable has its own coefficient. The values of these coefficients in the logistic regression were estimated using the maximum likelihood estimation method.

The predictor variables referred in the equation above as X-variables are described in Table 5-1. Most of the variables are self-explanatory except for forest cover (X_{17}). The later variable was included in the model in order to determine the influence of the availability of forests in the neighbourhood on the households' decision to own woodlots on their farms.

Table 5-1 Description of the predictor variables used in the model predicting the presence of farm woodlots

Variable	Description
GENDER (X_1)	Binary variable = 1 if the head of the household is male, 0 otherwise
OCHEAD(X_2)	Binary variable = 1 if the main occupation of the household is agriculture, 0 otherwise
AGE(X_3)	Age of the head of the households, from value 1 = 16-20 years to value 10 = > 60 years.
HSIZE(X_4)	Total number of household members, from value 1 = 1-3 members to value 5= > 12 members.
NEMPLOY(X_5)	Number of household members in formal employment. from value 1 = none to value 5= > 6 persons.
INCOME(X_6)	Estimated monthly income during the past 12 months, from value 1 = < 5,000 Rwf to value 10 = > 70,000 Rwf.
NMEAL(X_7)	Continuous variable for the number of meals per day, ranges from 1 to 3 times per day
FARMSIZE(X_8)	Farm sizes in ha, with values ranging from 1 = landless to 5 = > 2 ha.

Table 5-1 (Continued)

Variable	Description
DISTANCE (X_9)	Binary variable = 1 if the distance to fuelwood source is far, 0 otherwise
BUYFWD(X_{10})	Frequency of fuelwood purchase per month, on a scale of 1 = no purchase to 7 = > 17 times.
FBUNDLE(X_{11})	Number of firewood head load bundles used per week, on a scale of 1 = < 5 bundles to 5 = > 16 bundles.
ROTUB(X_{12})	Binary variable = 1 if the household grows roots and tubers, 0 otherwise
CEREAL(X_{13})	Binary variable = 1 if the household grows cereals, 0 otherwise
BANANA(X_{14})	Binary variable = 1 if the household grows banana, 0 otherwise
CSHCROP(X_{15})	Binary variable = 1 if the household grows cash crops, 0 otherwise
LVESTCK(X_{16})	Binary variable = 1 if the household keeps livestock, 0 otherwise
FORCOVER(X_{17})	Forest cover in the region each household belongs to. Dummy variables: 1 if low otherwise 0, 1 if medium otherwise 0, and 1 if high 0 otherwise

The data on forest cover was obtained from the forest mapping that distinguished five forest cover classes based on forest area relative to the area of the district and compared across 30 districts (CGIS-NUR and MINITERE 2008). The first eight variables (X_1 to X_8) account for household's demographic and socio-economic factors affecting the growing of farm woodlots. The next three variables (X_9 to X_{11}) are used to measure fuelwood collection and use in the rural households.

Different crop types (Variables X_{12} to X_{15}) were included in the model in order to determine their effects on household choice to keep woodlots on farms. Similarly, since Rwandan farmers are also livestock breeders, livestock farming (X_{16}) was examined in the model to assess whether ownership of livestock influenced the household decision to keep a woodlot or not.

5.3 Results and discussion

5.3.1 Characteristics of the sample households

The percentage of farms presenting woodlots was high in the HAR (62 %), followed by MAR (47 %) and least in the LAR (28 %). For the entire study area, woodlot owners accounted for about 42 % and non-woodlot owners 58 %. For all the three regions, the average woodlot size was approximately 0.2 ha. Table 5-2 shows the distribution of tree species in farm woodlots across the three regions.

Table 5-2 Tree species grown in farm woodlots by rural households in the LAR, MAR and HAR

Tree species	% of households			
	LAR [n = 200]	MAR [n = 160]	HAR [n = 120]	All regions [n = 480]
None	72.5	53.5	38.3	57.6
Eucalyptus spp.	23.0	43.4	49.2	36.3
Grevillea	2.0		0.8	1.0
Eucalyptus spp. + Grevillea robusta	2.0	1.9	1.7	1.9
Eucalyptus spp. + Cupressus lusitanica			4.2	1.0
Eucalyptus spp. + Acacia spp.		0.6	3.3	1.0
Eucalyptus spp. + Cedrela spp.	0.5			0.2
Eucalyptus spp. + Pinus patula			2.5	0.6
Eucalyptus spp.+ Callitris spp.		0.6		0.2
Total	100.0	100.0	100.0	100.0

In general, eucalyptus woodlots occurred on 36 % of the total number of farms. The remaining woodlots consisted of *Eucalyptus spp.* in mixture with other tree species including *Grevillea robusta, Cupressus lusitanica, Cedrela spp.*, *Callitris spp.*, *Pinus patula* and *Acacia spp.* The first five tree species are timber species. *Acacia spp.* and *Callitris spp.* were either planted or found growing naturally in woodlots. With the exception of very young eucalyptus woodlots, all others were managed as simple coppices managed on very short rotations of about 7 years. Many woodlots were found on the infertile parts of farms and on steep slopes as reported by Balasubramanian and Egli (1986), and Mugabo (2003). It appeared that woodlot farming was done on unsuitable sites for crop production in the three regions. Some key characteristics of woodlot owner and non-owner households are presented separately for each altitude region and for the entire study area. Figure 5-1 provides a visual comparison of significant differences between the proportions of woodlot owners and non-owners according to some household characteristics, while Table 5-3 shows mainly the proportions of woodlot owners and non-owners that were not statistically different according to other variables examined in the study. With respect to various socio-economic characteristics, the proportions of woodlots owners and non-owners differed significantly ($p < 0.05$) in terms of cash crops and livestock farming, farm sizes, number of salaried household members, and the main occupation of the households' heads. The differences in proportions of woodlot owner categories due to gender of head of households and monthly income were insignificant for the three regions, and for the entire study area. With respect to household size, the proportions of woodlot owner and non-owner households did not differ significantly for two (LAR and MAR), but one region (HAR). For the household characteristics examined here, the proportions of woodlot owners and non-owners were not significantly differentiated by the size of households, monthly income categories of households, and the gender of the household heads. However, it is important to note that the proportions were not consistently significant or insignificant across the various values of some household characteristics.

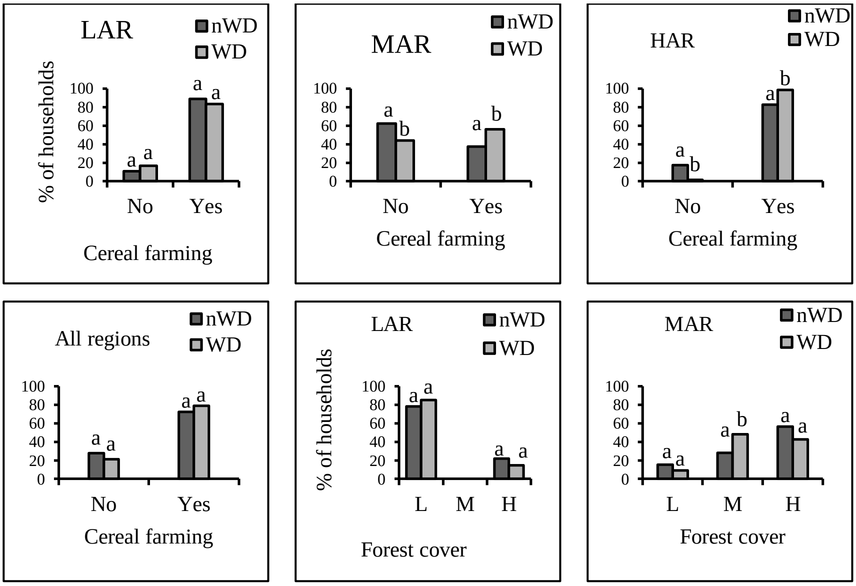

Fig. 5-1 Proportions of farm woodlot owner and non-owner households according to some household characteristics in the LAR, MAR and HAR and in the entire study area. Column proportions bearing the same letter within a category of a group variable are not significantly different at p <0.05 using the Bonferroni method.

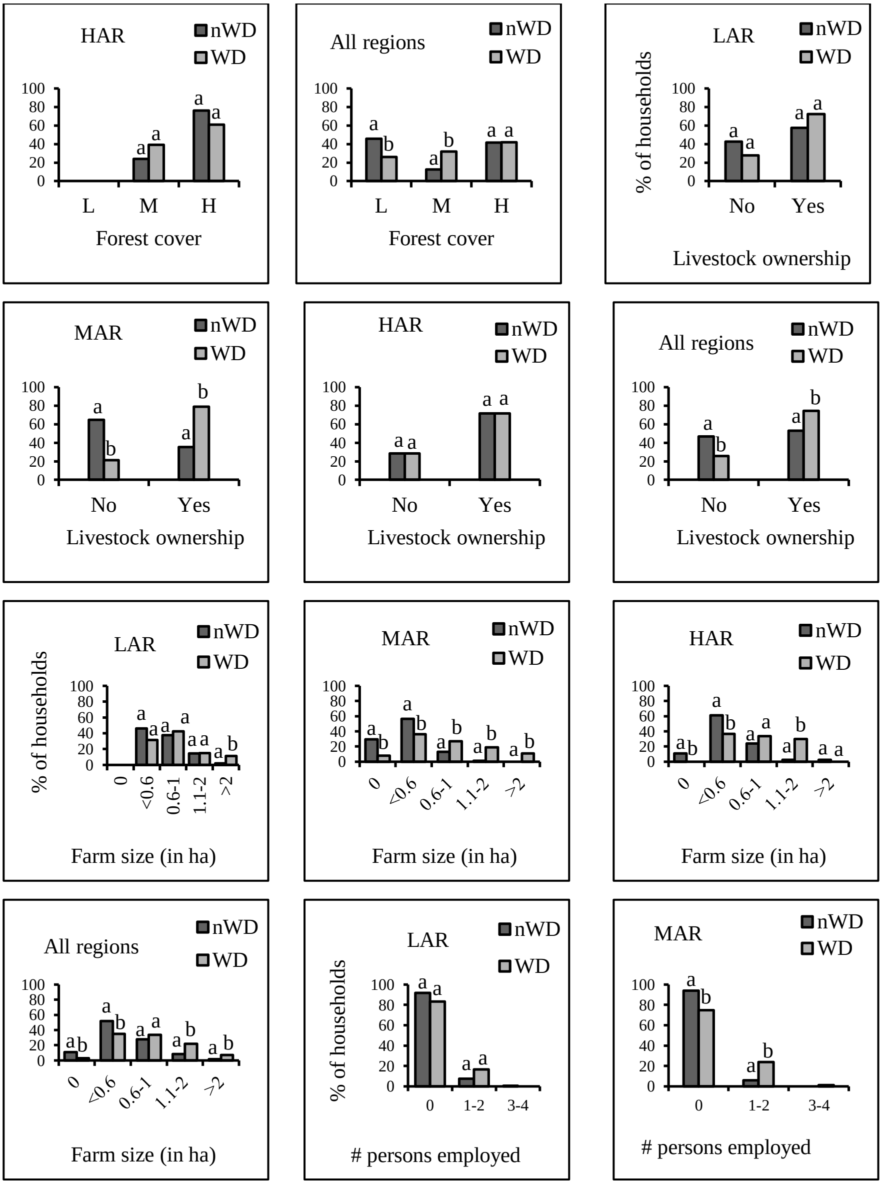

Figure 5-1 (continued)

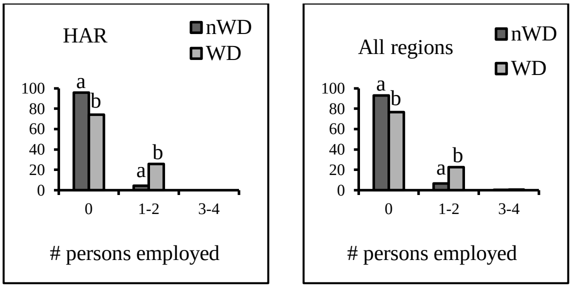

Figure 5-1 (continued)

Table 5-3. Percentage distributions of farm woodlot owners and non-owners according to some characteristics of households in the LAR, MAR and HAR and in the entire study area

Characteristics	Woodlots in LAR		Woodlots in MAR		Woodlots in HAR		Woodlots in the entire study area	
	No	Yes	No	Yes	No	Yes	No	Yes
Gender of heads of households								
Female	24.7_a	33.3_a	28.2_a	26.7_a	32.6_a	32.4_a	27.1_a	30.5_a
Male	75.3_a	66.7_a	71.8_a	73.3_a	67.4_a	67.6_a	72.9_a	69.5_a
Size of households								
1 - 3 persons	24.7_a	27.8_a	20.0_a	17.3_a	26.1_a	9.5_b	23.5_a	17.2_a
4 - 6 persons	49.3_a	44.4_a	48.2_a	54.7_a	45.7_a	40.5_a	48.4_a	46.8_a
7 - 9 persons	19.2_a	20.4_a	29.4_a	18.7_a	26.1_a	43.2_a	23.5_a	28.1_a
> 9 persons	6.8_a	7.4_a	2.4_a	9.3_a	2.2_a	6.8_a	4.7_a	7.9_a
Main occupation of head of households								
Agriculture	84.2_a	77.8_a	88.2_a	78.7_a	73.9_a	51.4_b	83.8_a	68.5_b
Other	15.8_a	22.2_a	11.8_a	21.3_a	26.1_a	48.6_b	16.2_a	31.5_b

Table 5-3 (continued)

Characteristics	Woodlots in LAR		Woodlots in MAR		Woodlots in HAR		Woodlots in the entire study area	
	No	Yes	No	Yes	No	Yes	No	Yes
Monthly income (Rwf)								
< 5 000	34.2a	27.8a	62.4a	53.3a	30.4a	41.9a	42.2a	42.4a
5 001 - 10 000	38.4a	37.0a	21.2a	24.0a	19.6a	29.7a	30.0a	29.6a
10 001 - 15 000	11.0a	16.7a	3.5a	4.0a	10.9a	10.8a	8.7a	9.9a
15 001 - 20 000	6.8a	1.9a	1.2a	4.0a	8.7a	2.7a	5.4a	3.0a
> 20 000	9.6a	16.7a	11.8a	14.7a	30.4a	14.9b	13.7a	15.3a
Number of daily meals								
1	15.8_a	14.8_a	17.6_a	13.3_a	32.6_a	4.1_b	19.1_a	10.3_b
2	80.1_a	77.8_a	82.4_a	81.3_a	56.5_a	82.4_b	76.9_a	80.8_a
3	4.1_a	7.4_a		5.3_b	10.9_a	13.5_a	4.0_a	8.9_b
Banana								
Grown	23.3_a	25.9_a	18.8_a	54.7_b			18.1_a	27.1_b
Not grown	76.7_a	74.1_a	81.2_a	45.3_b			81.9_a	72.9_b
Monthly frequency of purchasing fuelwood								
No purchase	67.4_a	82.4_b	55.4_a	75.4_b	43.5_a	72.6_b	59.8_a	76.2_b
< 2 times	9.9_a	5.9_a	20.3_a	7.7_b	17.4_a	6.8_a	14.2_a	6.9_b
2 - 5 times	7.1_a	2.0_a	6.8_a	7.7_a	17.4_a	17.8_a	8.8_a	10.1_a
6 - 9 times	8.5_a	3.9_a	6.8_a		6.5_a	2.7_a	7.7_a	2.1_b
10 - 13 times	3.5_a	2.0_a	1.4_a	3.1_a	8.7_a		3.8_a	1.6_a
14 - 17 times	1.4_a	3.9_a	1.4_a	4.6_a	2.2_a		1.5_a	2.6_a
> 17 times	2.1_a		8.1_a	1.5_a	4.3_a		4.2_a	$.5_b$

Table 5-3 (continued)

Characteristics	Woodlots in LAR		Woodlots in MAR		Woodlots in HAR		Woodlots in the entire study area	
	No	Yes	No	Yes	No	Yes	No	Yes
Distance to source of fuelwood								
Near	73.3_a	85.2_a	56.5_a	88.0_b	60.9_a	60.8_a	66.1_a	77.3_b
Far	26.7_a	14.8_a	43.5_a	12.0_b	39.1_a	39.2_a	33.9_a	22.7_b
Number of firewood head-load bundles used per week								
< 5 bundles	72.2_a	87.0_b	69.9_a	75.7_a	76.7_a	94.6_b	72.2_a	85.9_b
5 - 8 bundles	24.3_a	11.1_b	24.1_a	15.7_a	18.6_a	5.4_b	23.3_a	10.6_b
9 - 12 bundles	$.7_a$		3.6_a	5.7_a	2.3_a		1.9_a	2.0_a
13 - 16 bundles	1.4_a	1.9_a	2.4_a		2.3_a		1.9_a	$.5_a$
> 16 bundles	1.4_a			2.9_a			$.7_a$	1.0_a
Roots and tubers								
Grown	79.5_a	79.6_a	89.4_a	93.3_a	84.8_a	90.5_a	83.4_a	88.7_a
Not grown	20.5_a	20.4_a	10.6_a	6.7_a	15.2_a	9.5_a	16.6_a	11.3_a
Forest cover								
Low	78.1_a	85.2_a	15.3_a	9.3_a			45.8_a	26.1_b
Medium			28.2_a	48.0_b	23.9_a	39.2_a	12.6_a	32.0_b
High	21.9_a	14.8_a	56.5_a	42.7_a	76.1_a	60.8_a	41.5_a	41.9_a

Note: Within a region, proportions of woodlot owners and non-woodlot owners not sharing the same subscript are significantly different at $p < 0.05$ in the two test of equality for column proportions using the Bonferroni method. Tests assume equal variance

The means and standard deviations of the scores of the predictor variables above are presented in Table 5-4. Compared across regions, many predictor variables had different mean scores and different magnitudes of the standard deviations.

Table 5-4 Descriptive Statistics of scores of the predictor variables involved in estimating the model predicting the presence of farm woodlots in LAR, MAR, HAR and in the entire study area

Variable name			LAR N = 190		MAR N = 134		HAR N = 116		All regions combined, N = 440	
	Min	Max	Mean	SD	Mean	SD	Mean	SD	Mean	SD
AGE	1	5	3.01	1.48	3.16	1.37	2.94	1.46	3.04	1.44
GENDER	0	1	0.73	0.45	0.73	0.45	0.68	0.47	0.71	0.45
HSIZE	1	4	2.08	0.85	2.17	0.79	2.31	0.80	2.17	0.82
OCHEAD	0	1	0.83	0.38	0.84	0.37	0.60	0.49	0.77	0.42
INCOME	1	5	2.26	1.28	1.90	1.38	2.46	1.54	2.19	1.40
NMEAL	1	3	1.90	0.44	1.87	0.41	1.98	0.53	1.91	0.45
FARMSIZE	1	4	1.82	0.85	1.34	1.05	1.67	0.86	1.62	0.94
BANANA	0	1	0.24	0.43	0.36	0.48	0.00	0.00	0.22	0.41
BUYFWD	1	7	1.74	1.42	1.93	1.67	1.87	1.35	1.83	1.48
DISTANCE	0	1	0.24	0.43	0.29	0.45	0.39	0.49	0.29	0.46
FBUNDLE	1	5	1.30	0.66	1.39	0.75	1.15	0.44	1.29	0.65
CSHCROP	0	1	0.05	0.21	0.06	0.24	0.01	0.09	0.04	0.20
ROTUB	0	1	0.80	0.40	0.91	0.28	0.88	0.32	0.86	0.35
CEREAL	0	1	0.88	0.33	0.46	0.50	0.93	0.26	0.75	0.43
LVESTOCK	0	1	0.62	0.49	0.56	0.50	0.72	0.45	0.62	0.49
FORCOVER	1	3	1.40	0.80	2.38	0.70	2.67	0.47	2.04	0.89

This indicated variations in predictor variables that might have significant influence on farm woodlot model through the effects of the agroecological conditions and the household characteristics. For example, given the range of values of 1 to 5 that measure the range of farm sizes, households in the low altitude region have larger farms compared to midland and highland households. Cereal crops were also grown by many households in the highlands (maize) and in the lowlands (rice) but the proportion of lowland farmers who did not grow cereals were high compared to that in the highlands. Since large areas of forests are found in HAR (CGIS-NUR and MINITERE 2008), the forest cover scored highly in this region. For binary variables measured on scale of 0 to 1, the scores represent the corresponding proportions of households across the three regions. In general, the proportions were different between two or three regions. For the whole study area, male heads of households represented 71 %, the main occupation was agriculture for 77 % of heads of households, livestock breeding was made by 62 % and cereal crops were cultivated by 75 % of households.

5.3.2 Rural household purposes of keeping farm woodlots

The reasons why rural households were maintaining farm woodlots are presented in Table 5-5.

Table 5-5 Distribution of the rural households by main benefits from farm woodlots

Main benefits from woodlots	Frequency of households	Percentage of households
Firewood	97	47.5
Building materials	87	42.6
Income	11	5.4
Timber	3	1.5
Environmental protection	6	2.9
Total	204	100.0

Of 480 survey households, 204 (i.e. 43 %) had woodlots on their farms. Of the total number of woodlot owners, 48 % produced mainly firewood, and

43% targeted building materials. Rural households were also motivated to manage farm woodlots for other economic incentives including income from the selling of fuelwood, building poles and timber.

Farm woodlots were also owned for the purpose of environmental protection. By environmental protection, rural households meant the protection of soil from erosion and microclimate moderation. The rural households managing woodlots for these purposes were few (3 %), indicating that environmental issues were not important determinants of farm woodlot ownership. The household objectives of having woodlots were therefore different from the objectives of farmers in developed countries where environmental conservation is among the main motivators (e.g. Erickson and Deyoung 1993, Erickson et al. 2002, Wiersum et al. 2005). The lack of rural households' interests in environmental benefits of woodlots may be an obstacle to the environmental conservation. The environmental value of woodlots could not be achieved if many rural households see them as providers of wood products only. Since woodlots are very important part of the landscape, their use by many rural households for economic benefits may result in overexploitation of the resource leading to pressure on forests and environmental degradation.

5.3.3 Household characteristics affecting the presence of farm woodlots in the low, medium and high altitude regions

Table 5-6 presents the estimates of the coefficients of binary logistic regressions on the factors influencing presence of farm woodlots in the LAR, MAR and HAR. In general, the explanatory power of the variables as reflected by pseudo R^2 (Cox and Snell R^2, Nagelkerke R^2) was comparatively high for HAR model, followed by MAR and least for LAR, indicating that these variables had different significant effects on the presence of farm woodlots in these regions. The overall goodness of fit as indicated by the significance of the chi square statistic was very high for the HAR and MAR models at a value of 0.001. The results of the test for multicollinearity indicated that there was no collinearity among predictor variables in each region and these independencies resulted in the unbiased models.

In LAR, the coefficients of three variables were significant in explaining the presence of farm woodlots (Table 5-6). These were: the farm size, the travel distance to fuelwood sources and the number of firewood head-load bundles used per week.

In the MAR, four variables were significantly correlated with household choice to keep woodlots on farms (Table 5-6). These were: the presence of banana crop, travel distance to fuelwood sources, cropping of cereals, and farming of livestock.

In the HAR, five variables were significant in explaining the choice to keep farm woodlots. These were (Table 5-6): household size, number of meals per day, monthly frequency of fuelwood purchase, number of firewood head-load bundles used per week and cropping of cereals.

Different combinations of factors correlated with the presence of farm woodlots across regions. Farm size was positively and significantly associated with the presence of farm woodlots in the LAR only ($p < 0.05$).

Table 5-6 Logistic regression estimates of the effects of household characteristics on the presence of farm woodlots in the low, medium and high altitude regions

	LAR			MAR			HAR		
	β	S.E.	Exp(β)	β	S.E.	Exp(β)	β	S.E.	Exp(β)
AGE	0.17	0.13	1.18	0.34	0.21	1.41	0.45	0.24	1.57
GENDER	0.21	0.45	1.23	-0.03	0.63	0.97	0.05	0.70	1.06
HSIZE	0.10	0.23	1.10	-0.40	0.35	0.67	1.48**	0.53	4.39
NEMPLOY	0.41	0.57	1.50	0.87	0.89	2.38	2.09	1.46	8.11
OCHEAD	0.35	0.51	1.42	-0.73	0.77	0.48	1.33	0.88	3.79
INCOME	0.13	0.14	1.14	0.26	0.23	1.30	-0.12	0.22	0.89
NMEAL	0.29	0.45	1.33	-0.13	0.70	0.88	1.79*	0.85	5.98
FARMSIZE	0.48*	0.23	1.62	0.54	0.39	1.72	0.76	0.49	2.15
BANANA	0.49	0.47	1.63	-1.50*	0.67	0.22			
BUYFWD	-0.24	0.16	0.79	-0.16	0.17	0.85	-1.59***	0.43	0.20
DISTANCE	1.08*	0.48	2.93	1.42*	0.64	4.13	0.48	0.86	1.62
FBUNDLE	-1.16*	0.53	0.31	0.55	0.37	1.73	-1.87*	0.83	0.15
ROTUB	0.46	0.48	1.59	0.57	0.89	1.76	0.22	0.93	1.24
CEREAL	0.97	0.56	2.64	-1.58*	0.64	0.21	-4.11*	1.86	0.02
LIVSTCK	-0.21	0.42	0.81	-1.73**	0.60	0.18	-0.87	0.83	0.42
FORCOVER									
LOW	-0.30	0.60	0.74	-0.44	0.86	0.65	0.25	0.94	1.28
MEDIUM				-0.74	0.80	0.48			
Constant	-3.45*	1.56	0.03	-0.78	2.13	0.46	-5.91	3.26	0.00
Model χ^2	30.4*			76.3***			81.7***		
Hosmer & Lemeshow statistic	5.6			9.2			4.7		
Cox & Snell R^2	0.15			0.43			0.51		
Nagelkerke R^2	0.22			0.58			0.69		
Classification accuracy (%)	75.3			79.9			82.8		

* $p < .05$; ** $p < .01$, *** $p < .001$

This relationship indicated that an increase in farm size increased the probability that households own woodlots on their farms. The result corroborates the findings by Lovell et al. (2010) that large farms have a great potential to accommodate tree habitats. In the low altitude region of Rwanda, particularly in the Eastern Province, farm sizes are comparatively large than in the medium and high altitude regions of Rwanda, hence many lowland households keep farm woodlots. For the MAR and HAR models, farm size had no significant effect on presence of woodlots. However, the positive sign of the coefficient of farm size in the MAR and HAR models suggests a positive association between farm size and woodlot presence.

The travel distance to fuelwood sources was positively and significantly correlated with the presence of farm woodlots in LAR and MAR ($p < 0.05$). This implied that, as the distance to fuelwood collection increased, the probability of household ownership of farm woodlots increased also. In other words, long distance to fuelwood sources constrained lowland and midland households to grow and maintain woodlots on their farms. This result seems to oppose to the finding by Brouwer et al. (1997) that an increasing distance to woodlands forces households to collect fuelwood further and to collect lower quality wood from nearby sources. A long walking distance to the fuelwood sources requires more energy for household members to complete this task, and therefore becomes a burden to rural people, especially women and children. In addition, the forest policy precludes forest depletion by regulating wood harvesting and fuelwood collection from forests and by promoting farm forestry. Fuelwood collection from public forests, which is illegal, forces many households to alter their customary behaviour in fuelwood collection by planting their woodlots that are sustainable and easily accessible for fuelwood collection.

The frequency of purchasing fuelwood was negatively and highly significantly correlated to ownership of farm woodlots in the HAR ($p < 0.001$). This relationship suggested that, the more frequent a household purchased fuelwood, the lower was the probability of having farm woodlots. In other words, farm woodlot owners purchased fuelwood less frequently than non-woodlot owners. In Rwanda, both formal and informal markets for fuelwood (firewood, charcoal) exist. Well-off households buy fuelwood partly because they lack their own farm fuelwood sources or if they do, the size of the resource is small in order to meet their fuelwood needs. Purchased fuelwood is expensive; hence low income households could not buy fuelwood from local markets. As a result, they grow and maintain farm woodlots which provide fuelwood on sustainable basis.

The number of firewood head-load bundles used per week was also negatively and significantly correlated with household ownership of farm woodlots in LAR and HAR ($p < 0.05$), which may reflect the negative effect of fuelwood collection on ownership of farm woodlots in these regions. As the number of firewood head-load bundles used per week increased, the chance that rural households own farm woodlots decreased. In general, non-woodlot owner households collect fuelwood from outside their farms. Since small woody materials are collected, the households depend on firewood collected in the form of many head-load bundles in order to acquire sufficient energy for cooking. The use of small quantities of firewood by woodlot owner households can partly be ascribed to more suitable wood for energy and the use of wood burning stoves.

Among crop predictor variables, banana had a significant effect on the presence of farm woodlots in MAR only ($p < 0.05$) and cereal cropping significantly influenced the presence of farm woodlots both in MAR and HAR at $p < 0.05$. For the two crop types, the coefficients were negative, implying that growing banana and cereals decreased the chance of having farm woodlots both in MAR and HAR. The inverse relationship is to be expected as food production on small farms outcompete wood production. Although no significant effects of these variables were found for the LAR model, the positive correlation implied a positive attitude of lowland farmers towards keeping of farm woodlots. Since lowland farmers own larger farms compared to their counterparts in MAR and HAR, they were more likely to maintain farm woodlots.

In some countries in East Africa such as Tanzania and Uganda, rotational woodlots increase crop and wood biomass yields (e.g. Kimaro et al. 2007, Buyinza et al. 2008). In Rwanda, agricultural crops are not grown in rotation with woodlots, which reduce the dual advantage of increasing wood and food production. With increasing pressure on lands for food production, land scarcity led many midland and highland households to exploit degraded sites for food production, which resulted in reduced propensity to keep farm woodlots.

It is evident that available land use options favour the production of food crops more intensively. Banana crops characterise the farming systems in many tropical countries and specific tree species are associated in banana plantations. The basic primary production is food and the integration of trees aims primarily at increasing banana yields because tree biomass in banana agroforestry is low (Kibria and Saha, 2011). In addition, pressure on land for subsistence farming does not allow the practice of rotational tree blocks that enhance the yields of subsequent crops including cereals.

Livestock farming was consistently negatively correlated with presence of farm woodlots in the LAR, MAR and HAR. The significant inverse relationship between livestock farming and the presence of farm woodlots in MAR indicated that livestock farmers were less likely to grow woodlots. Hence, livestock farming is an important factor driving rural households to divert from having woodlots in MAR. Livestock farming requires pastureland, which is also managed on marginal lands. Regardless of the level of significance, the negative sign on the coefficient of livestock farming for the three models suggest that livestock farming was unlikely to be practiced alongside woodlot farming. For this matter, woodlots and pastures are competing for the same land, where livestock grazing is more attractive to many farming households.

Since agroforestry is an interdisciplinary approach to land use from a set of integrated land uses (Sinclair 1999a), the integration of livestock farming in agroforestry is also possible through managed woodlots, fodder banks, pastures and forage from managed live fences, hedgerows and other planted trees in farmlands. In the MAR, therefore, land is only available for agricultural production but with much crop-livestock integration. Many studies (e.g. Daneshmandi and Azizi 2009, El-Rokiek and Eid, 2009) reported that *Eucalyptus spp.* inhibit the germination and growth of vegetation on the ground layer. The lack of silvopastoral practices in the study area may partly be caused by the lack or low availability of fodder of high nutritive qualities for livestock grazing in the eucalyptus woodlots.

The size of the household was positive and very significantly correlated with ownership of farm woodlots in HAR, implying that large households were more likely to own farm woodlots. Since the household size has a positive correlation with the quantity of energy consumption (e.g. Mallik 2006) and farmers tree growing decisions depend on socio-economic characteristics (e.g. Predo and Fransisco 2006), the relative high fuelwood needs for food preparation translated into the option for producing large amounts of fuelwood into farm woodlots. This agrees with the result presented earlier that fuelwood is the primary objective of owning farm woodlots. The number of daily meals taken in the households had a similar effect in HAR - a rise in the number of meals significantly increased the likelihood of having farm woodlots. A higher number of daily meals in HAR implied the need to increase the frequency of cooking meals and hence rural households addressed fuelwood demands by having woodlots. Although not significant, the positive sign on the coefficient of the number of daily meals in LAR model suggested that an increase of the number of meals taken in the households was correlated with an increase of the probability of having woodlots. On the opposite, fewer daily meals turned out to be negatively correlated to household ownership of farm woodlots in the MAR, meaning that midland households were unlikely to keep farm woodlots. These households may be in state of fuelwood scarcity that is addressed by taking meals fewer times daily, thus reducing the frequency of burning scarce fuelwood. Since many households in MAR are food insecure households (e.g. WFP 2006), agricultural production is the most important concern.

5.3.4 Household characteristics affecting the presence of farm woodlots in the entire study area

For the entire study area, the log-likelihood ratio (LR) test showed that the estimated model, including a constant and a set of eight explanatory variables, can describe the presence of farm woodlots. Table 5-7 presents the parameter estimates for the model. The model obtained correct predictions of the presence of farm woodlots of 78% of the farms included in the estimation. The household characteristics that positively and significantly influenced the planting of woodlots on farms were: age of the heads of households, number of salaried household members, farm size, distance to fuelwood sources and location dummy of the households in the medium altitude region (Table 5-7). Factors that were negatively and significantly correlated with the presence of farm woodlots were: monthly frequency of purchasing fuelwood, livestock farming and location dummy of the households in the low altitude region (Table5-7). Among significant and positive factors, the number of salaried household’ members had a larger impact (larger regression coefficient) on household ownership of farm woodlots in the entire study area. In agricultural households where many of the members are involved in paid employment, it is likely that long term production systems such as woodlot farming, be practised. With increase in the number of salaried persons in the households, household agricultural labour decreases but employment increases the propensity to keep woodlots.

Table 5-7 Logistic regression estimates of the effects of household characteristics on the presence of farm woodlots in the entire study area

			95% C.I. for EXP(β)		
	β	S.E.	Lower	Exp(β)	Upper
Age of head of households	0.21*	0.09	1.05	1.24	1.46
Gender of the heads of households	0.23	0.26	0.75	1.26	2.10
Household size	0.05	0.15	0.79	1.05	1.40
Number of household members in formal employment	1.12**	0.38	1.45	3.05	6.43
Main Occupation of heads of households	0.54	0.30	0.94	1.72	3.12
Monthly income	-0.05	0.09	0.81	0.95	1.13
Number of meals per day	0.37	0.28	0.83	1.44	2.51
Farm size	0.36*	0.15	1.08	1.44	1.91
Banana crops	-0.26	0.32	0.42	0.77	1.44
Monthly frequency of purchasing fuelwood	-0.28**	0.09	0.63	0.76	0.90
Distance to source of fuelwood	0.61*	0.26	1.10	1.85	3.10
Number of firewood head load bundles used per week	-0.40	0.22	0.44	0.67	1.03
Root and tuber crops	0.24	0.34	0.64	1.27	2.49
Cereal crops	-0.58	0.32	0.30	0.56	1.04
Livestock farming	-0.66*	0.26	0.31	0.52	0.86
Estimate of forest cover					
Low	-1.24***	0.28	0.17	0.29	0.50
Medium	1.04**	0.36	1.39	2.82	5.75
Cash crops	-0.42	0.56	0.22	0.66	1.98
Constant	-1.96	1.05		0.14	
Model χ^2	142.6***				
Hosmer & Lemeshow statistic	15.6				
Cox & Snell R^2	0.28				
Nagelkerke R^2	0.37				
Classification accuracy (%)	78.0				

* p < .05; ** p <.01, *** p < .001

Given that total income in household increases, the immediate needs of the households can be met from off-farm labour, which impacts positively on the decision to own farm woodlots. Our results corroborate many adoption studies (e.g. Patel et al. 1995, Hyde et al. 2000, Pattanayak et al. 2003) that concluded that larger income households adopt agroforestry technologies.

Farm woodlots require other sources of income for households to achieve their desired objectives. In addition, total income from the members of the households enable them to pay for silvicultural activities and management operations as well as to compensate, through market supplies, for food which otherwise would be lost through woodlot farming.

The entire study area model showed statistical result that indicate a positive effect of forest cover categories on household choice to own farm woodlots. Compared to households in locations with high forest cover, households in location with medium forest cover were likely to own farm woodlots. This is probably explained by large proportion of the total public forest area in some regions. In area with medium forest cover, farm woodlots contribute significantly to the total forest cover. In contrast, the coefficient of the low forest cover was negatively and highly significantly related to the presence of farm woodlots in the whole study area. This indicated that many households in areas with low forest cover were less likely to own woodlots on their farms. Although not significant, the negative signs of the coefficient of forest cover categories in the model predicting the presence of woodlots in the LAR and MAR indicated that there were few farm woodlots in these regions.

The travel distance to source of fuelwood was also an important determinant of the presence of farm woodlots in the entire study area. Yet this variable was significant in the LAR ($p < 0.05$) and MAR ($p < 0.05$), but with larger coefficients indicating large effects which were probably due to differences in biophysical conditions across the three regions. The large significant positive coefficients reflected that forests in LAR and MAR were located away from many households. This pattern had a positive influence on the rural household choice to keep farm woodlots for the purpose of fuelwood production instead of walking long distance to gather the resource from public and private forests. This result seems to corroborate the findings from many studies (e.g. Mekonnen et al. 2007, Duguma and Hager 2010) that reported an increasing tree planting practices with increasing distances from public forests. However, this result contradicts results from other studies (e.g. Nibbering 1999, Jenbere et al. 2012) that household exposure to forest practices and improved access to seedlings and technical assistance result in increased tree planting. In the context of our study, the contrasting results imply that woodlot farming is not necessarily encouraged by scarcity of wood products (including fuelwood) but also by several other factors that affect the farmers' decision to have woodlots or not on their farms.

As expected, farm size had positive and significant influence on the presence of farm woodlots, suggesting that land availability is an important factor that determines the farming of woodlots as a profitable form of agroforestry. The farm size had also positive effect on household choice to keep farm woodlots in LAR (Table 6) where household farms were comparatively large. This effect, reinforced by the entire study area model, suggested that large farm owners were capable of having farm woodlots at regional and national scale. The positive correlation between the farm size and the choice to keep woodlots has also been found by several studies in Ethiopia (e.g. Bewket 2003, Teshome 2004, Jenbere et al. 2012). Under conditions of very small farms, farmers do not own woodlots; their choices are understandable because many households intensify agricultural production on small farms in order to feed their families. Households with smaller farms such as those in MAR and HAR, are less likely to produce wood products as a land use option. Nyadzi et al. (2003) argue that farmers with land shortages do not have enough land to practice agroforestry. This is particularly likely in Rwanda given the small average farm size of 0.76 ha. Though the results of this study are line with the finding that farm size and the choice to plant trees on farms are positively related (Den Biggelaar and Gold 1996, Salam et al. 2000, Abebe 2005, Tolera et al. 2008), the relationship between number of employed persons in the households and the choice to maintain farm woodlots indicate that such relationship could be reversed by employment or total income in the households. Low income and small farm owners are the likely the only category of households that depends on forests regardless of the social and the ecological consequences implied by this behaviour.

It is worth to note that the age of the heads of households was positive and significant in the model linking household characteristics to ownership of woodlots for the entire study area. This relationship was not identified for LAR, MAR and HAR, but the sign of the coefficient was consistently positive. Age is one of the demographic characteristics of households that influence the adoption of agroforestry (e.g. Neupane et al. 2002, Kabwe et al. 2009, Gebreegziabher et al. 2010a, Buyinza and Mambede 2008). Farm woodlots are likely to be planted by older heads of households than younger ones because the older households have been exposed to the benefits of the trees through awareness programs of the forestry department and extension staff over many years of their life. With age, older household heads realize the importance of woodlots in wood supply and environmental protection; hence they take the decision to grow them on their farms. Moreover, experience most often comes with age, hence experienced household heads may be more proactive with regard to the growing of woodlots than inexperienced household heads.

As expected, we found a negative association between the monthly frequency of purchasing fuelwood and the presence of farm woodlots in the whole study area and in HAR. This suggested that households that purchased fuelwood more frequently were less likely to own farm woodlots. This is in agreement with the findings by Bensel and Remedio (1995) that the frequency of fuelwood purchase is high among low income households. In general, the frequent use of purchased fuelwood implies the household budget. Because of income constraints, rural households hardly buy enough fuelwood to last them for a long time. Non-woodlot owners are prompted to buy small amounts of fuelwood more frequently, hence reduce the hardship associated with the collection of large volumes of firewood by incurring expenses on firewood (Chirwa et al. 2008). Since the demand for firewood is also high in high-income households (Gebreegziabher et al. 2010b), well-off households are capable of buying fuelwood over gathering it from other sources including their own woodlots.

In Rwanda, livestock breeding is an important component of agricultural production. Livestock farming was significantly negatively related to ownership of farm woodlots in the whole study area, as it was found individually for MAR. Livestock farmers were less likely to own woodlots on farms, which indicated that livestock grazing competed for land with woodlot farming. Correlation analysis revealed that farm size was positively related to the livestock farming ($r = 0.30$, $p < 0.001$), meaning that as farm size increases, livestock farming is more likely. Therefore, the significant negative correlation between livestock farming and woodlot farming indicate that part of the farmland in the study area is devoted more to livestock farming than to woodlots.

Many authors (e.g. Dev et al. 2006, Appiah and Pappinen 2010, Stewart et al. 2011) reported that woodlots provide both environmental and social benefits. The integration of livestock and woodlot in farming systems may provide diverse and increased benefits to livestock farmers. Livestock production may increase through management of pastures in order to meet the fodder demand by livestock breeders. As a land use option, the growing of farm woodlots can produce wood and fodder through silvopastoral practices.

Using the pooled household-level data across regions, the growing of the different crop types appeared insignificant in predicting the presence of farm woodlots. This can partly be explained by the main household preference of growing food crops on small farms than producing tree crops. In addition, woodlot farming is feasible on farm parts unsuitable for food crop and livestock farming, implying that woodlot farming is not spatially affected by the various crop types that require fertile soils for enhanced productivity.

5.4 Conclusion

In Rwanda, rural households own woodlots on their farms mainly for economic reasons and much less for environmental purposes. Many agricultural households are increasingly managing eucalyptus woodlots on the parts of their farms unsuitable for food production and livestock grazing in order to produce mainly fuelwood and building materials. The common use of woodlots for economic benefits may result into environmental degradation. This suggests that policy makers and extension programme planners need to develop education programmes for the farmers focusing on expansion and sustainable use of woodlots, and beneficial ecological effects of woodlots. Measures are needed to promote management practices that enhance productivity and sustainability of farm woodlots, and it will be important to link economic benefits to environmental gains from woodlots.

The study revealed that ownership of farm woodlots by rural households is correlated with a set of interacting factors that differ from one region to the other. This variability demonstrates the importance of not extrapolating findings between regions. The differences are mainly caused by differences in the household decision environment which includes: regional socio-demographic and economic characteristics of the households;

biophysical conditions; historical development of the region; and the availability of forest resources. The analysis of pooled household-level data enables only to generalize the factors that are relevant for national development and extension. Based on the results of the study, it seems reasonable to conclude that in order to promote farm forestry, it is crucial that interventions be region specific, population-specific and forest resources specific. There should be locational and socio-economic based plan strategies besides measures to reduce dependence on fuelwood collection from forests.

Since farm woodlots contribute largely to the total forest cover in the country, their exploitation by farm owners for the supply of fuelwood and building materials could result in ecological problems including destruction of carbon sinks, soil erosion, greenhouse effect and global warming. It is therefore necessary to identify regulatory measures that could facilitate the growing and harvesting of farm woodlots while minimizing possible detrimental environmental impacts. Development professionals and extension services should carry out mass education on the importance of growing woodlots and the dangers of unsustainable exploitation of woodlots. Further research may explore options for integrating woodlot farming with agricultural production by enhancing the economic, social and environmental attributes of farm forestry. Since woodlot farming is competing for space with food production and livestock breeding, it might be useful to investigate the economic returns from farm forestry and agriculture. Among the social factors, gender differences are evident in how farms are used, which has important implications for establishing and managing woodlots. Further studies focussing on gender analysis within the households can be useful in determining the associations between woodlot farming, gender and land ownership status.

Finally, the research demonstrated that, among several factors, the main challenge for farm woodlot ownership is land size, unemployment and the priority of the farmer to produce food and livestock feeds on small farms. Thus, the place for woodlot farming is on the least productive arable land only when farms are large. Renewed focus on woodlot may provide a pathway for crop and livestock production as a strategy to maximise the profitability and sustainability of land-use. Choosing between agriculture and tree crops may require the forest policy to adopt strategies that might include mainstreaming farm forestry in agricultural policies, promoting best management practices of trees and woodlots on farms, building capacity of farmers, providing incentives for tree planting, and developing and disseminating farm forestry in a unified extension system for all agroecological zones of the country.

Chapter 6 Woody biomass on farms and in the landscapes of Rwanda

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Submitted

Abstract

Scattered trees and woodlots are a prominent feature of agricultural landscapes of Rwanda. However, little is known about their characteristics and their contribution to farmers' wood needs. Here, we present the results of a survey of (a) the abundance, composition, and size of trees and woodlots in the low, medium and high altitude regions of Rwanda, (b) total woody biomass and biomass for fuelwood at farm and landscape levels, and (c) opportunities for their sustainable use. Scattered trees occurred in all landscapes at minimum densities ranging from 20 to 167 trees ha^{-1}. Of the 56 tree genera recorded, a handful of tree species dominated, with the ten most common species accounting for over 70 % of all trees recorded. Most of them provided fuelwood, fruit and timber to farm owners. Woodlots occurred on about 40 % of the survey farms and consisted for 90% of eucalyptus coppice. Woody biomass dry weight of scattered trees on agricultural landscape was 0.7 ton ha^{-1} in low altitude region (LAR), 3 ton ha^{-1} in medium altitude region (MAR), and 1 ton ha^{-1} in high altitude region (HAR). Dry weight woody biomass in woodlots (< 0.5 ha) was the highest in MAR (221 ton ha^{-1}), followed by that in HAR (205 ton ha^{-1}) and least in LAR (96 ton ha^{-1}). About 80 % of total woody biomass in trees and woodlots on farmland was useable biomass for fuelwood, indicating that the production of fuelwood on agricultural land was important. Woody biomass on agricultural land was higher than that in forest plantations, and was potentially sufficient to reduce the gap between fuelwood supply and demand when the entire agricultural area was taken into account. In order to achieve this on agricultural land, while contributing to food security and environmental conservation as well,

smallholder farmers must be provided with incentives to grow woodlots and to adopt agroforestry systems, thereby considering the trade-offs with agricultural production. Strategies to encourage smallholder farmers to increase the use of agroforestry have to account for the farmers' ecological and socioeconomic conditions.

Keywords: Biomass; Farm; Fuelwood; Agricultural landscape; Scattered trees; Woodlots.

6.1 Introduction

Rwanda's rural landscape is characterized by many elements, of which crop fields, trees and woodlots are predominant. Traditionally, farmers have retained a number of indigenous trees on their private farmlands (Habiyambere 1999), and trees on farms (i.e. agroforestry systems) have always been present. The first agroforestry projects in Rwanda started in the 1970s; since then, agroforestry systems have been improved by introducing new technologies and by promoting the planting of exotic and indigenous multipurpose tree species. In 1995, more than 153 tree species were recorded on farms (Den Biggelaar 1996). These occur in different locations on farms and are managed for various purposes, so as to ensure minimal competition for water, light and nutrients with agricultural crops. A recent analysis of fuelwood demand and supply in Rwanda (Ndayambaje and Mohren 2011) described the current and potential forms of agroforestry suitable for Rwanda, with respect to fuelwood production. Many of these practices offer options for increasing crop and wood yields, and help achieve environment protection.

In the various land-use systems of Rwanda, farm trees are a source of human food, fuelwood, stakes for climbing crops (e.g. beans, peas), timber, building poles, fodder for livestock and other materials. Nowadays, trees on farms are recognized for contributing to sustainable agriculture, enhancing environmental protection, conserving biodiversity and sequestering carbon (Acharya 2006; WAC 2007; Leaky 2010; Garrity and Stapleton 2011). They thus help meet farmers' needs in terms of sustainable production of crops, livestock, exchange commodities, energy and diverse tree products for sustaining rural livelihoods (Arnold 1997; Chew 2001). They can also contribute to environmental protection within the agricultural landscape, and to the sustainable development and reduction of greenhouse gas emissions in the atmosphere. Evidently, there are always trade-offs with agricultural production, as trees also occupy sparse growing space, notably relevant on small farms, and compete with agricultural crops for water and nutrients that may be short in supply. Here, we aim to determine the total biomass of trees and woodlands in the agricultural landscapes in Rwanda, as to understand the potential of trees and woodlots in agroforestry systems.

In Rwanda, the planting of trees and woodlots on farms is encouraged in order to reduce pressure on the remaining forests. The high rate of deforestation is being curbed by campaigns against unsustainable use of forests, and by promoting tree planting by smallholder farmers across the country. With limited land area for expanding forest plantations, parts of private farmland are being afforested, and farmers are now being encouraged to take up agroforestry and establish woodlots. There have been many studies to ascertain why farmers have planted trees together with crops (e.g. Den Biggelaar 1996; Ndayambaje et al. 2012), but in general, farmers plant more trees if they see benefits and have land available.

While there is an increasing recognition that that trees and woodlots on Rwandan farms play economic and environmental protective roles within the agricultural landscapes, little is known about the abundance of trees or of their biomass in the different regions of the country. Available studies on tree species diversity and tree products (e.g. Den Biggelaar 1996) often do not quantify the biomass that trees and woodlots provide, so it is difficult to compare product use across the different topographic regions. In addition, there is little information on the distribution of trees and woodlots within the agricultural landscape, and on their environmental and productive functions. This contrasts with the literature on agroforestry, where the value of farm tree cover is assessed in order to understand its contribution to forest resource and biodiversity conservation (e.g. Alam and Sarker 2011; Fifanou et al. 2011), improvement of rural livelihoods (e.g. Jamnadass et al. 2011; Moreno-Calles et al. 2012), and global relevance in terms of carbon sequestration and reduction on greenhouse effects (e.g. Jose 2009; Torres et al. 2011).

We set out to determine the main characteristics and biomass of trees and woodlots on individual farms and in entire agricultural landscapes in Rwanda, to describe the occurrence of trees and woodlots, and to investigate whether biomass in trees and woodlots varies from one altitude region to another. Specifically, our research focused on (a) the abundance, species composition, and sizes of trees and woodlots on farms in the low, medium and high altitude regions of Rwanda, (b) total aboveground woody biomass on farms in agricultural landscapes of the three altitude regions, and (c) tree and woodlot biomass currently present on farms and in the three landscapes, suitable to provide fuelwood for farmers. The analysis is based on two scales of assessment of trees and woodlots, using two different approaches for the estimation of woody biomass at farm and landscape level. By using the information collected in the low, medium and high altitude regions, the current woody biomass is described and compared with the woody biomass in forest plantations or forest stands having an area of $\geq$ 0.5 ha. For the purpose of this study, the term “tree” refers to woody perennials with a single main stem and definite crown. It is also used to designate a “shrub”, defined as a woody perennial without a main stem and definite crown (Gschwantner et al. 2009). However, since the methods for estimating biomass of overstory trees (large trees) and shrubs on agricultural land are different, the terms tree and shrub were often distinguished, by explaining how for each growth form, measurements and wood volume calculations were performed.

6.2 Data and methodology

6.2.1 Study area

Trees and woodlots on farms were assessed for three different study areas representing the low, medium and high altitude regions of Rwanda (Fig. 6-1). Each altitude region is large, but not necessarily homogeneous since it is sometimes separated by landscapes of different biophysical attributes belonging to a different altitude region. Thus an altitude region consists sometimes of unconnected agroecological zones of similar biophysical features (Fig.6-1). It may include 3 to 5 homogenous agroecological zones defined by altitude, rainfall, and soil characteristics (Delepierre 1975; Gasana 1991b). Figure 6-1 shows these agroecological zones and how they are distributed over the country. The low altitude region (LAR) has gentle slopes and altitude of less than 1500 m. In the medium altitude region (MAR), the average altitude is 1700 m with a maximum of 1900 m. The high altitude region (HAR) comprises areas above 1900 m (to a maximum of just over 2500 m).

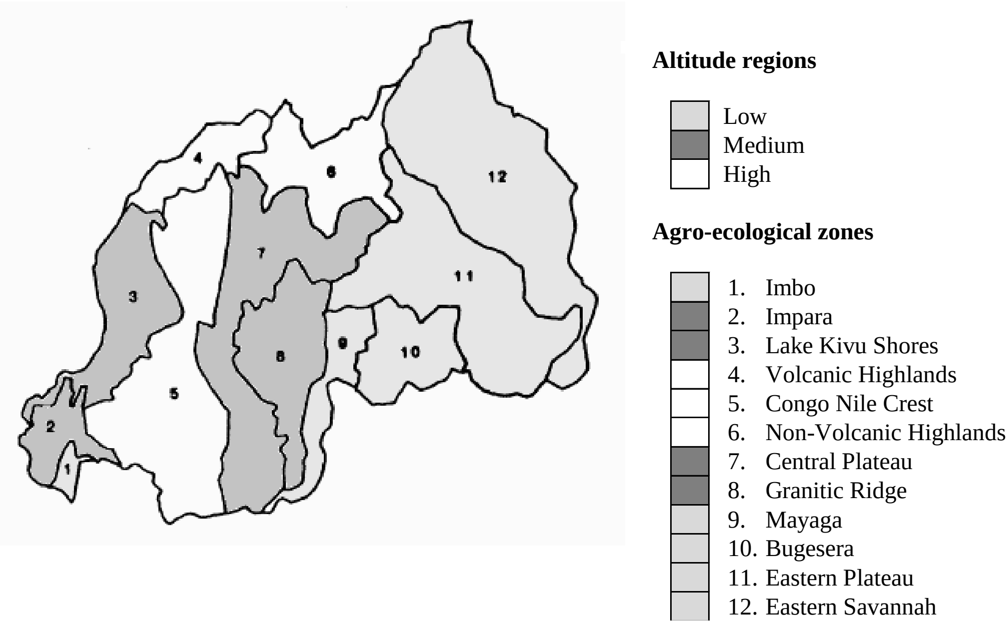


Fig. 6-1 Altitude regions in Rwanda and their corresponding agro-ecological zones

The three altitude regions have different biophysical and production characteristics (Table 6-1), which influence the diversity and productivity of both crops and livestock. The LAR, covering an area of 7 117 km^2 in the eastern Province of Rwanda, has a population density of about 100 – 300 inhabitants per km^2. It is dominated by the farming of sorghum, cassava, and beans, and cattle and goat herding. According to the forest inventory and mapping results by ISAR and MINITERE (2008), and CGIS-NUR and MINITERE (2008), the LAR has much less forest cover than the other two regions (i.e. only 6 % of total national forest area).

Table 6-1 Biophysical and production characteristics of the low, medium and high altitude regions in Rwanda

Characteristics	Low altitude region (LAR)	Medium altitude region (MAR)	High altitude region (HAR)	References
a) Biophysical characteristics				Delepierre 1975; Gasana 1991b
Area (km^2)	7 117	6 790	4 820	
Altitude (m)	900 – 1500	1500 - 1900	1900 - 2500	
Rainfall (mm)	800 – 1000	1000 - 1250	1250 - 2000	
Soil types	Ferrasols, nitosols, vertisols	Nitosols, ferrasols, leptosols, lixisols	Nitosols, ferrasols, andosols	
b) Population density in 2009 (number of people km^{-2})	226	453	513	NISR 2009; own calculations
b) Farming systems				
Main cash crops	Coffee, banana	Coffee	Tea, coffea, white potato, maize	Olson 1994; Djimde et al. 1988
Food crops	Banana, sorghum, beans, peanuts, cassava, maize	Sweet potato, cassava bean, maize, banana, soybeans	White potato, maize, bean, wheat, sorghum	

Table 6-1 (continued)

Characteristics	Low altitude region (LAR)	Medium altitude region (MAR)	High altitude region (HAR)	References
Livestock	Cattle, goats	Cattle, pigs, goats, sheep, chicken	Sheep, goats, cows	
Average farm size (ha)	1.1	0.7	0.6	NSIR 2010; own calculations
Forest cover, as % of total forest area	5.5	37.6	56.8	CGIS-NUR and MINITERE 2008; own calculations

The MAR which covers all the Southern Provinces of Rwanda, covers an area of 6 790 km^2 and has a population density ranging from 320 to 400 inhabitants per km^{-2}. Typically, the MAR produces cereals, roots and tubers, coffee and livestock. The forest area (assessed as forest stands larger than 0.5 ha) is about 38 % of the total forest area of Rwanda.

The HAR, extending over the Western and Northern Provinces of Rwanda on an area of 4 820 km^2, has a higher population density (400 - 500 inhabitants per km^{-2}) than in the LAR and the MAR. It is the region where the major natural forests are found (e.g. Nyungwe, Gishwati and Birunga forests); it accounts for 57 % of the total national forest area. Deforestation in this region increased largely due to reduction in size of Gishwati forest from 28 000 ha in 1970’s to 316 ha in 2006 as a result of forest clearing for large scale cattle ranching projects, particularly cattle grazing within the forest, agriculture expansion and settlement (Kanyamibwa 1998; Gatera 2001;

Plumptre et al. 2001). The sloping land in this region is intensively cultivated for the production of white potatoes, maize, beans, wheat and sorghum.

6.2.2 Data collection methods for trees and woodlots on farms

Trees on farms

Data on trees and woodlots on farms were collected in 2007 and 2008 through farm surveys. For each altitude region, 93 - 194 farms were randomly selected, using a stratified sampling procedure described by Ndayambaje et al. (2012). In this sampling scheme, the sampling unit were the three altitude regions in which all the component agroecological zones were taken as strata, further considered for a random selection of a single low-level administrative unit[8] known as “Cell”. Then a random sample of 30 - 50 farms and their owners were selected per cell and within each agroecological zone for the inventory of trees and woodlots and for collecting data on the uses of the trees recorded on the farms. In total, a stratified random sample of 457 farms was included in the study.

The percentages of sample farms in which trees and shrubs were recorded for each altitude region are given in Table 6-2. Baseline field data were collected on tree species, number of individual trees of each tree species, tree diameter and height, tree use by farm owners, and farm size. Since many shrubs were coppiced on farms, the measurements included number of stems per stool, basal diameter, diameter at 1 m above ground and

[8] The Republic of Rwanda is divided into four administrative provinces and the city of Kigali, further subdivided into 30 administrative districts, and then into 416 sectors, and again into 2148 cells. The district is the basic political-administrative unit of the country. The cell is the smallest politico-administrative unit of the country and hence closest to the people.

the total height of a randomly selected single stem. A simple random sampling method was used to select small, medium or large diameter stem to be measured. This was done by picking a token from a box of three ones coded for the selection of the three diameter size categories of the stems. Farm owners or their representatives reported on the main uses of the trees and shrubs on the farms.

Table 6-2 Number of farms surveyed and percentages of farms where trees and woodlots were present in the low (LAR), medium (MAR) and high altitude regions (HAR)

Data collected	LAR	MAR	HAR	Total
Number of farms surveyed	170	193	94	457
Number of farms on which trees were present	117 (69%)	111 (57%)	46 (49%)	274 (60%)
Number of farms on which woodlots were present (%)	15 (9%)	46 (24%)	24 (26%)	98 (21%)
Number of farms on which trees and woodlots were present	38 (22%)	36 (19%)	24 (25%)	85 (19%)

In order to estimate volume , the following measurements were recorded: (1) stem basal diameter; (2) stem diameter at 1m from the ground or from the point of sprouting; (3) stem total length; and (4) stem mid-diameter, measured on the stem mid-way between the base of the coppiced stem and tip.

Farm woodlots

Woodlot size was measured using GPS instruments. Data were collected on all trees in a circular plot of 3.40 m radius (i.e. 36.3 m^2) in the centre of the woodlot. Their diameters were measured; if the woodlot was almost as large as the plot, the diameters of all trees were measured. Multi-stemmed coppice stems were taken as individual stems. Total height of individual trees was derived using diameter– height relationships published by ISAR and MINITERE (2008) for the nationwide forest inventory (Table 6-3). Most of the woodlots were managed as coppice stands. Stems originating from one stump were systematically considered as individual trees.

Table 6-3 Diameter–height relationships used to determine individual tree height of tree species inventoried in farm woodlots. These relationships were developed by ISAR and MINITERE (2008) during a nationwide inventory of the forest plantations in Rwanda . D stands for diameter at breast height in cm and H is total height of the tree in m.

Tree species	Diameter– height equations	n	R^2	SE
Grevillea robusta	$H = 1.8149 + 1.3642 \times D - 0.3304 \times D^2 + 0.00046 \times D^3$	68	0.86	2.35
Pinus patula	$H = 1.97189 \times D^{0.7282}$	7926	0.78	0.14
Eucalyptus spp. (coppice)	$H = -0.2096 + 1.2253 \times D - 0.0101 \times D^2$	8314	0.91	1.74
*Other**	$H = 2.3999 \times D^{0.6306}$	352	0.83	0.14

* Other tree species include *Cedrela serrata* and *Cupressus lusitanica*

6.2.3 Scattered trees and woodlots in agricultural landscapes

Since each of the three altitude regions covers a large and disconnected area, a study area of 10 000 ha was delineated within each of the various agroecological zones making up a particular altitude region. In line with the number of agroecological zones, the study area representing the LAR, MAR and HAR, was 50 000 ha, 40 000 ha and 30 000 ha, respectively (Table 6-4). These study areas were demarcated on aerial photographs of 0.25 m resolution, available at the Rwanda National Land Centre in 2008/2009 for the purpose of land registration.

The agricultural landscapes on aerial photographs were extracted from the study areas by excluding the area elements of forests, water bodies, plantations, wetlands, built-up areas, and degraded unfarmed land. Table 4 shows the net area of the agricultural landscape derived from a land cover analysis of aerial photographs of the different agroecological zones of the three altitude regions. Trees and woodlots were classified in each agricultural landscape: scattered trees were classified as points and woodlots as polygons. ArcCatalog was used to create all layers and ArcMap supported data visualization, editing and exploratory analysis. Trees and woodlots were digitized on-screen to obtain the tree numbers and woodlot sizes in each agricultural landscape.

6.2.4 Estimation of aboveground woody biomass

Woody biomass of trees on farms

Aboveground woody biomass on farms was estimated from the volume of trees and average oven-dry wood density of each species. The low number of trees per farm and the diversity of tree species in the agricultural landscape large made it impractical and time-consuming to carry out destructive measurements for individual volume equations. The following formula was therefore used to compute the volume of the tree bole:

$$V_{tree} = (\pi \times D^2 \times H \times 0.5)/40\,000 \qquad (1)$$

Table 6-4 Study area and area of forests, wetlands and water bodies, agricultural lands and other lands derived from a land cover analysis of aerial photographs of different agroecological zones of the three altitude regions

Altitude regions and agroecological zones	Study area (ha)	Forest area ≥ 0.5 ha	Wetlands and water bodies (ha)	Other land [ha]	Agricultural land [ha]	Farmland as % of study area
Low altitude region						
Bugesera	10 000	3051	4701	1095	1153	12
Eastern Plateau	10 000	2935	66	3530	3469	35
Eastern Savannah	10 000	1639	1094	3682	3585	36
Imbo	10 000	347	1434	4115	4104	41
Mayaga	10 000	908	864	4025	4203	42
Total	*50 000*	*8880*	*8160*	*16 447*	*16514*	*33*
Medium altitude region						
Central Plateau	10 000	1429	996	3690	3885	39
Granitic Ridge	10 000	2152		3861	3987	40
Impala	10 000	2693	79	3578	3650	37
Lake Kivu Shores	10 000	2658	488	3399	3455	35
Total	*40 000*	*8932*	*1562*	*14 528*	*14977*	*37*
High altitude region						
Volcanic highlands	10 000	978		4347	4675	47
Non-volcanic highlands	10 000	1053	2761	3055	3131	31
Congo Nile Crest	10 000	2422	5	3670	3903	39
Total	*30 000*	*4453*	*2766*	*11 071*	*11 709*	*39*

where V_{tree} is the volume of wood in the tree bole (m^3), D is the diameter over bark at breast height (cm), H is the total height of the tree (m). A form factor of 0.5 was applied to each tree in order to account for the taper effect of diameter and height measurements on the tree volume. The branch volume was calculated as being 30 % of the tree bole volume, in accordance with the findings by Saint-André et al. (2005), and Segura and Kanninen (2005). The total tree volume was determined by summing branch volume and tree bole volume.

The volume of shrubs was calculated differently, by assuming that each stem comprised two components: (1) a perfect cone of height equal to half the stem length, with basal diameter equal to stem mid-diameter; (2) a perfect frustum of a cone of height equal to half the stem length, with basal diameter equal to stem basal diameter, and top diameter equal to stem mid-diameter.

The standing volumes of trees per farm and per hectare of farm worked out here, do not provide the best approximations of volume of trees on farms, as these trees are pruned, lopped and pollarded. But in the absence of any other reliable methods we adopted this technique, which may nonetheless provide a good comparative basis for volume estimates of trees on farms over the three altitude regions of Rwanda.

Biomass of trees on farms was estimated separately for each altitude region, because of large differences in tree species and their characteristics (size, abundance, use), and environmental conditions (soil, precipitation, elevation). Since many tree species were occurring in agroforestry systems, it was impractical to estimate tree biomass by developing biomass equations via destructive sampling. Average wood densities of the various tree species found in the literature were used to estimate the woody biomass on the farms. This assumes that wood gravity is distributed identically within and between trees of the same species, following Chave et al. (2005) in estimating carbon stocks and balance in tropical forests. The total tree volume was converted to biomass dry weight according to the following formula:

$$B = V_{tree} \times D \tag{2}$$

where B is the biomass in ton tree^{-1} and D is wood density in ton m^{-3}).

To estimate the aboveground woody biomass of fruit trees without destructive measurements, the following equation given by Brown et al. (1989) was used:

$$Y = exp(-2.4090 + 0.9522\ ln(D^2 \times H \times W)) \tag{3}$$

Where Y is the average aboveground woody biomass dry weight for a fruit tree (kg); D the diameter at breast height (cm); H, tree height in m and W, the wood density (ton m^{-3}). The wood density was calculated as the average value of five fruit species found in Rwanda (*Persea americana*, *Psidium guayava*, *Mangifera indica*, *Annona cherimola*, and *Arthocarpus heterophyllus*) giving a value of 0.62 ton m^{-3}, and was applied to fruit species for which no information on wood density was available in the literature (Brown 1997; Orwa et al. 2009; Chave et al. 2009).

The standing aboveground woody biomass per farm was calculated as the total sum of biomass of all trees present. Next, the biomass per hectare of farm was estimated, based on farm sizes in each altitude region. The standing woody biomass was further evaluated for the different types of trees, as defined by their main uses by the farm owners. Specifically, biomass for fuelwood was derived from the total tree biomass by considering tree species farmers used solely for fuelwood. Since large trees with a diameter equal or greater than 30 cm are not cut for fuelwood (Top et al. 2006), fuelwood biomass was assumed to be made up of stem section that is not commercial due to defects, known as non-merchantable section, and branches , accounting for about 30 % of the total aboveground biomass (Saint-André et al., 2005; Segura and Kanninen 2005). This biomass proportion was included in the estimation of biomass currently available for fuelwood.

Woody biomass in farm woodlots

Volume equations developed by Deleporte (1987a, 1987b), Pleines (1987), and ISAR and MINITERE (2008), were used to estimate the standing wood volume of individual trees of different tree species such as *Eucalyptus spp.*, *Cedrela serrata*, *Grevillea robusta*, *Pinus patula* and *Cupressus lusitanica* (Table 6-5). The volume equation for eucalyptus coppices, however, was established for the merchantable volume which is calculated for the stem section that has a commercial potential. A volume proportion of 30 % of the stem wood volume was applied to account for the volume of branch wood. The aboveground woody biomass in a woodlot was obtained by multiplying the individual tree volume by the overall wood density of the tree species in the woodlot.

Table 6-5 Individual tree volume equations for five tree species in Rwanda

Tree species	Volume equation (m^3)	n	R^2	Reference
Cedrela serrata	$V = (182.65 - 5.482 \times D - 24.9 \times H - 0.0701 \times D^2 + 1.7777 \times (D \times H) + 0.004679 \times (D^2 \times H)) \times 10^{-3}$	263	0.99	Deleporte, 1987
Cupressus lusitanica	$V = (121.6 - 22.845 \times D + 1.9909 \times D^2 - 0.012 \times D^3) \times 10^{-3}$	263	0.97	Deleporte, 1987
Grevillea robusta	$V = (-11.93 + 3.0386 \times D + 0.2063 \times D^2 \times 10^{-3})$	38	0.95	Deleporte, 1987
Pinus patula	$V = 8.42 \times 10^{-4} \times D^2 - 7.354 \times 10^{-3} \times D + 2.506 \times 10^{-2}$	181	0.93	Pleines, 1987
Eucalyptus spp. (coppice)	$V = 0.0001738 \text{ x } D^{1.920048} \text{ x } H^{0.484466}$		0.87	ISAR and MINITERE, 2008

Since eucalyptus species in a woodlot were not identified, a wood density of 770 kg m^{-3} was used as the average value of eight common eucalyptus species in planted forests and woodlots in Rwanda (*E. tereticornis, E. camaldulensis, E. grandis, E. globulus, E. saligna, E. microcorys, E. maculata*, and *E. maideni*). The wood density values of these species were obtained from NAS (1983), Pynton (1979) and Orwa et al. (2009).

The aboveground woody biomass was determined for an average woodlot and per hectare for each altitude region. Biomass for fuelwood included all eucalyptus trees with a diameter of less than 30 cm. Above this size, only 30 % of the total tree biomass was included in order to account for wood in branches and non-merchantable section of the trees, following the findings by Saint-André (2005), and Segura and Kanninen (2005). The biomass for fuelwood in timber trees (e.g. Pine, Grevillea, Cypress) that were mainly found inter-planted with eucalyptus trees, was assumed to account for only 30 % of their total standing woody biomass.

Woody biomass in the agricultural landscapes

Standing woody biomass in the agricultural landscapes of the low, medium and high altitude regions of Rwanda was estimated for scattered trees and woodlots. Since estimates of biomass were tree species-specific and based on detailed farm assessment in a specific altitude region, average values of biomass per ha were assumed to be suitable for determining woody biomass in each of the three agricultural landscapes. An estimate of the current biomass of scattered trees in the landscape was derived from the per-hectare estimates of farm tree density and woody biomass by applying proportions. Biomass for fuelwood on farms was estimated similarly. An agricultural landscape was therefore considered as a large-scale farm, excluding land unsuitable for tree and crop farming.

Using screen digitizing and exploratory analysis in ArcGis, woodlot size was recorded. Data from woodlot surveys were used to establish the relationship between woodlot area and tree density for each altitude region. A power transformation applied to number of trees in woodlots and woodlot area gave a better prediction of the number of trees in woodlots (Fig. 6-2). The model created was only applicable for predicting the number of trees in woodlots up to 0.5 ha in size. Using the model, it was possible to calculate the number of trees ha^{-1} for woodlot in each landscape. The woodlot biomass at landscape level was estimated by simulating the relationship between number of trees in the woodlot and woodlot size, and multiplying the result by the average tree biomass in a woodlot. The woody biomass for each landscape was estimated by summing up the biomass values of all the woodlots.

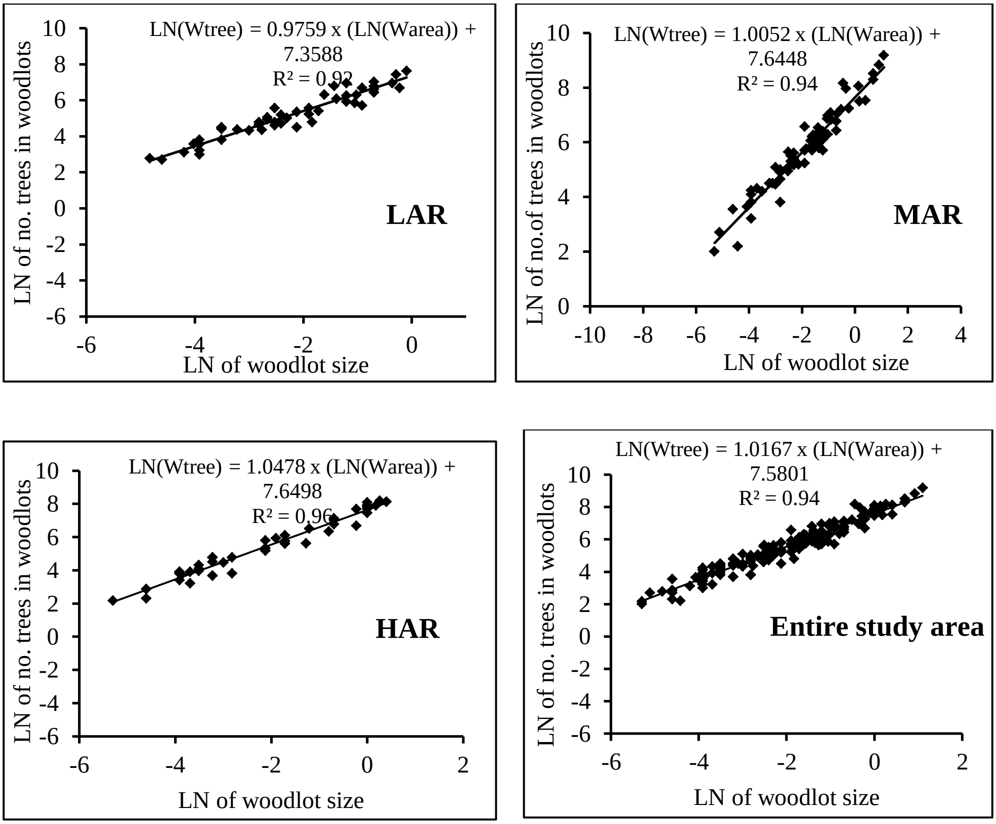


Fig. 6-2 Relationship between number of trees per woodlot (W_{tree}) and the woodlot size (W_{area}) in the LAR MAR HAR and across the three altitude regions. Power transformation was applied to the two variables in order to achieve linearity. LN stands for the natural logarithm of the parameter in brackets.

6.2.5 Statistical analysis

Data analysis focused on density, volume and biomass of trees and woodlots on farms in the three study areas representing the LAR, MAR and HAR. Frequency analyses were applied to the data in order to determine the presence of trees and woodlots on farms. Descriptive statistics (means, standard errors and 95 % confidence intervals) for the tree and woodlot characteristics were calculated and presented for each study area and for each agricultural landscape. Volume and biomass values were determined for each individual tree and mean values calculated for each stratum (farm, study area, landscape). To compare farm sizes, woodlot sizes, tree densities, volume and biomass values across the three study areas and landscapes, one-way ANOVA was used followed by Tukey test at $p < 0.05$. GENSTAT Statistical Software 14th edition was used for the analysis.

6.3 Results

6.3.1 Abundance, species composition and size of trees on farms

Scattered trees on farms are a noticeable feature in the study areas representing the low, medium and high altitude regions and occurred in 79 % of the farms surveyed (Table 6-2). A total of 3086 trees were inventoried in the 457 farms across these study areas, representing 56 tree genera (Table 6-6). The highest number of tree genera was recorded in the LAR (40 tree genera), followed by the HAR (30 tree genera) and least in the HAR (29 tree genera) The number of tree species per farm ranged from 2 on farms in MAR to 4 on farms in the LAR. Farms in the LAR had the highest overall number of tree species ($F = 31.94$, $p < 0.001$) (Table 6-6).

Table 6-6 Characteristics of trees on farms inventoried in the study areas representing the LAR, MAR and HAR of Rwanda. Means in the same row with the same letter are not significantly different ($p<0.05$) according to one-way ANOVA test followed by pairwise comparison using the Tukey test for $p < 0.05$

	LAR	MAR	HAR	Across the three regions
Total farm area inventoired in ha ((±SE)	125.4	109.7	19.6	254.7
Average farm size in ha (±SE)	0.81±0.07 b	0.75±0.07 b	0.28±0.10 a	0.68±0.12
Average number of trees per farm (±SE)	20±1 c	6±1 a	14±2 b	13±2
Total number of trees on farms inventoried	2013	701	372	3086
Mean density of trees ha^{-1} of farm (±SE)	69±11 b	20±11 a	168±17 c	65±18
Total number of tree genera recorded on farms	40	29	30	56
Average number of tree species per farm (±SE)	3.97±0.17 b	2.39±0.17 a	2.95±0.19 a	3.14±0.10
Mean diameter (± SE) in cm	15.6±0.8 a	29.2±0.4c	21.2±1.2 b	22±1.4
Mean height (± SE) in m	8.4±0.4 a	14.7±0.4 b	8.7±0.6 a	10.9±0.7
Mean volume of trees (± SE) in m^3ha^{-1}	7.8± 1.3 a	12.2± 1.4a b	14.5±2.0 b	10.8±2.2
Mean weight of trees (± SE) in kg ha^{-1}	4.5± 0.7 a	6.9±0.8 b	7.6 ±1.1 a	6.0±1.2

Scattered trees occurred at very low frequencies on farms in all three altitude regions, ranging from a mean of 20 trees ha^{-1} in MAR to 168 trees ha^{-1} in HAR (Table 6-3). There were significant differences in the average number of trees per ha across the three altitude regions, with HAR having a significantly higher average number of trees per hectare than MAR and LAR (Table 6-6), but LAR has significantly higher tree density than MAR($F = 27.4$, $p < 0.001$). The difference between the three altitude regions in terms of number of trees per hectare and farm size was reflected in significant differences in number of trees per farm across these regions, with LAR having the highest number of trees per farm, followed by HAR and least for MAR ($F = 32.4$, $p < 0.001$) (Table 6-6).

There were also differences across altitude regions in the size distribution of trees present (Fig. 6-3). On the LAR and HAR farms, the diameter distribution was skewed towards trees with small diameters (Fig. 6-3A, 6-3C). The distribution of tree diameters in the MAR was distinct from that of the other two regions because of the large number of farm trees with large diameters (40 % of trees had diameters exceeding 30 cm) and few trees with small diameters (Fig. 6-3B).

The overall mean tree diameter was larger in MAR than in the LAR and HAR, but LAR farms had smaller diameter trees than those in the HAR (Table 6-6). There were also differences in tree height across the altitude regions. Trees were taller in the MAR than in the LAR and HAR, but the farms in the LAR and HAR had trees of similar height (Table 6-6). Better height growth in the MAR could partly be explained by fertile soils and the predominance of overstory trees on farms including *Grevillea robusta*, *Cedrela serrata* and *Persea Americana*.

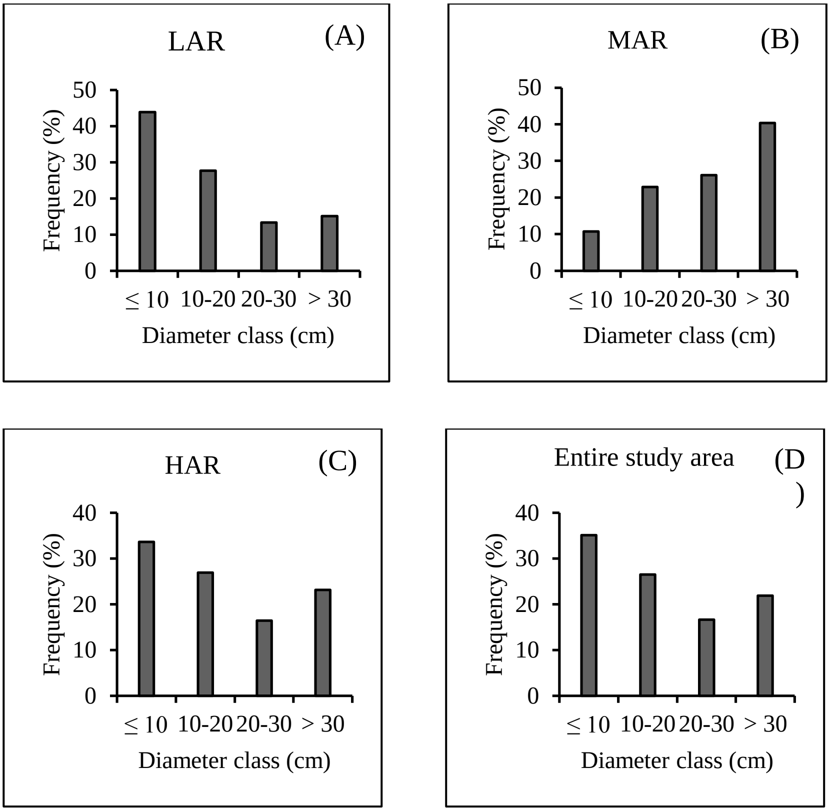


Fig. 6-3 Distribution of diameters of scattered trees on farms in the LAR, MAR, HAR, and in the entire study area. Data are based on 2013 trees in the LAR, 701 in the MAR, 372 in the HAR, implying 3086 trees for the entire study area. The data represent the % of trees found in each diameter class

Many of the tree species recorded on farms were present in low numbers: in each altitude region, 10 tree species were more common and represented about 70 % of the total number of farm trees (Table 6-7). This pattern of overall large number of tree species in each region and a dominance of a few most common species was evident in all three regions.

Table 6-7 A summary of the ten most common tree species on farms and their respective main uses in each of the three altitude regions and in the entire study area

LAR			MAR			HAR			Across the three altitude regions		
Tree species	% farms	% trees n =2488	Tree species	% farms	% trees n = 957	Tree species	% farms	% trees n = 541	Tree species	% farms	% trees n = 3986
G. robusta[ac]	47.8	23.8	*P. americana*[b]	42.1	21.2	*P.americana*[b]	36.7	17.2	*P. americana*[b]	40.5	13.1
P. americana[b]	41.1	9.1	*G. robusta*[ac]	29.2	26.4	*Ficus spp.*[ac]	19.2	5.9	*G. robusta*[ac]	32.7	23.1
Mangifera indica[b]	21.7	3.6	*Eucalyptus spp.*[cd]	14.6	10.4	*Erythrina abyssinica*[ae]	14.2	5.4	*Ficus spp.*[ac]	12.3	3.8
Senna spectabilis[cd]	17.9	6.5	*Ficus spp.*[ac]	8.2	3.6	*Grevillea robusta*[ac]	13.3	14.2	*Eucalyptus spp.*[cd]	11.3	8.5
Vernonia amygdalina[c]	17.4	5.6	*Citrus lemon*[b]	7.3	3.2	*Carica papaya*[b]	11.7	4.8	*C. papaya*[b]	10.2	3.5
Carica papaya[b]	16.4	3.8	*Psidium guayava*[b*]	6.9	2.5	*Vernonia amygdalina*[c]	10.0	5.7	*M. indica*[b*]	9.3	2.5
Markhamia spp[ac].	16.4	3.3	*Calliandra calothyrsus*[c]	5.6	7.9	*Cedrela serrata*[a]	10.0	5.0	*V. amygdalina*[c]	9.1	4.4
Euphorbia tirucalli[c]	14.5	7.2	*E. tirucalli*[c]	5.2	3.7	*C. lusitanica*[a]	9.2	4.6	*Markhamia spp.*[ac]	8.8	3.0
Ficus spp.[ac]	13.0	3.4	*Markhamia spp.*[ac]	4.3	2.9	*Dahlia spp.*[c]	9.2	6.8	*E. tirucalli*[c]	7.5	5.4
Eucalyptus spp.[c d]	12.1	9.2	*Cupressus lusitanica*[a]	4.3	2.4	*Alnus spp.*[cf]	6.7	2.4	*S. spectabilis*[cd]	6.6	4.1
Total		75.5	Total		84.3	Total		72.1	Total		71.3

Note: Many farms have more than one tree species so percentages do not add up to 100

[a] Timber; [b] Fruit for food and income; [b*]Fruit for food only; [c] Fuelwood; [d] Building material; [e] Supports for beehives; [f] Bean stakes

The commonest tree species was *Grevillea robusta*, a tree used mainly for timber, accounted for over 20 % of all of the trees recorded across the three regions and was present in more than 30 % of the total number of farms surveyed. The other two very common tree species were *Persea americana* (avocado), a tree species producing fruits for food and income (Ndayambaje et al. 2012), which accounted for 13 % of trees recorded and which was common in about 40 % of farms in all three regions; *Ficus spp.* mainly used as timber and fuelwood, was more common in the HAR and LAR than in the MAR and totalled to 4 % of all trees across the three altitude regions. Nearly all scattered trees on farms were species commonly used by farming households for one or more purposes (fuelwood, fruit, timber, building materials: Table 6-7 and Table 6-8).

Table 6-8 Percentage of trees on farms that provide different products in each study site in the LAR, MAR, HAR, and across these three altitude regions based on farm tree inventories (2488 trees in LAR 957 trees in MAR 541 trees in the HAR and 3986 trees across the three regions)

Tree uses	LAR	MAR	HAR	Total (across the three regions)
Fuelwood	44	26	36	39
Fruit	17	32	25	21
Timber	12	21	18	15
Timber and fuelwood	7	5	8	7
Building materials	5	6	2	5
Other[a]	15	10	11	13

a. Other uses of trees include: banana supports stakes for climbing crops (mainly beans) fencing supports for beehives cultural importance erosion control fodder soil improvement boundary marking ornament medicine income and any combination of these uses with or without those listed in the above table.

Firewood species accounted for about 39 % of all dispersed trees (Table 6-8) in all three altitude regions, but were most common on the LAR farms, followed by the HAR farms, and with very few in the MAR; this pattern reflects the importance of farm fuelwood as an energy source for cooking in these regions. Over a fifth of all trees in the three regions were species that provided fruit. In the MAR, fruit species (particularly *Persea americana*) accounted for 33% of all trees. With the exception of the LAR, over 15 % of the trees recorded in each altitude region were timber-producing. The abundance of trees and the species composition on farms reflected the different interests of farmers in trees and the extent of tree planting on farms. All regions shared the same basic set of common species, with the two most abundant species in each region being *Grevillea robusta* and *Persea americana* (Table 6-7). Excluding *Eucalyptus spp.*, which was widespread in all three regions, the species composition of HAR was distinct, with indigenous or naturally regenerating trees (such as *Dahlia spp.*) predominating. HAR was also characterised by higher occurrence of *Ficus spp.* which represented about 6 % of the trees in this region.

Classified by use, the overall proportion of fuelwood volume to total volume was about 40 % (Fig. 6-4A-B). The average volume per hectare was also different, with HAR having a significantly higher volume ha^{-1} than the LAR but not from the MAR. The LAR and MAR farms had statistically similar average volumes per ha (Fig. 6-4A). The average standing volume of trees per farm differed significantly between the three regions ($F = 0.6$, $p = 0.028$), with the lowest volume recorded on HAR farms (Fig. 6-4A).

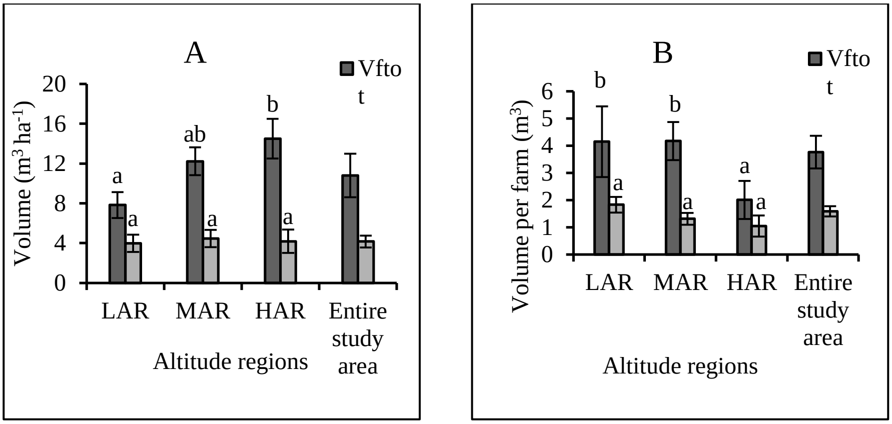
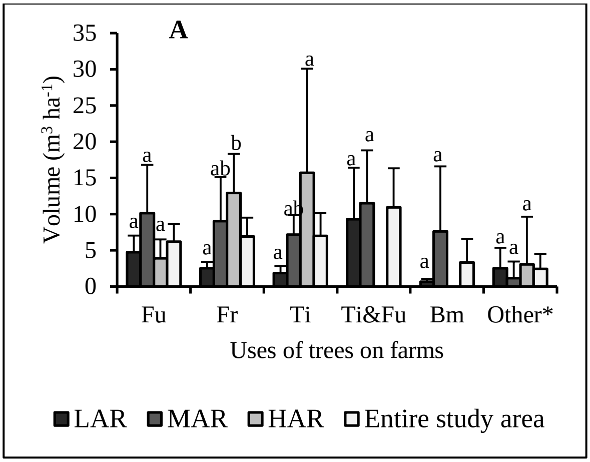


Fig. 6-4 Relationship between total standing wood volume and volume of fuelwood trees per hectare of farmland (A) and between total standing wood volume and volume of fuelwood trees per farm (B) in the LAR, MAR, HAR, and across the three altitude regions. V_{ftot} denotes the standing volume of all trees on farms V_{ffwd} denotes the standing tree volume of fuelwood species. The error bars represent the 95 % confidence intervals around the mean values of V_{ftot} and V_{ffwd}. The same letter above the bars across the altitude regions implies non-significant differences for the parameter on the Y-axis according to one-way ANOVA test followed by multiple comparisons using the Tukey test at $p < 0.05$.

There were no significant differences in average volume of fuelwood per farm (Fig. 6-4B) and per hectare (Fig. 6-4A) across regions. The volume of fuelwood trees was the same in the three regions: 3 m^3 per farm on average (Fig. 6-5). The volume of trees used for both timber and fuelwood was the highest but was not significantly different between the three regions (Fig. 6-5).



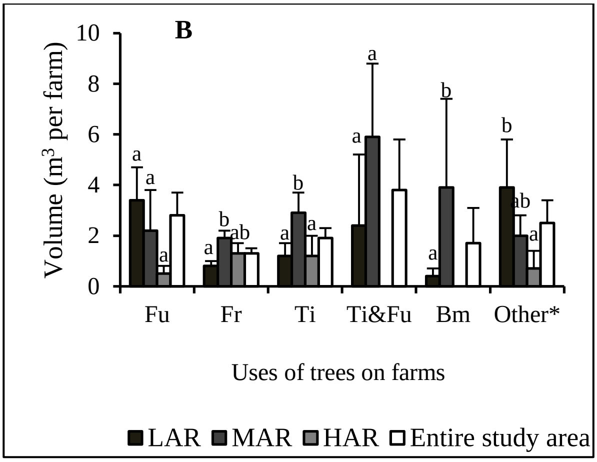


Fig. 6-5 Volume (m^3) of wood by uses of trees per hectare (A) and per farm (B) in LAR, MAR, HAR and in the entire study area. Fu denotes fuelwood, Fr denotes fruit, Ti denotes timber, Ti&Fu denotes timber and fuelwood, and Bm denotes building materials. The category "other" encompasses other uses of trees on farms such as bean stakes fences fodder erosion control soil improvement ornament supports of banana bunches and beehives cultural importance and various combinations of these uses with main uses including timber building materials and fuelwood. Error bars represent 95 % confidence interval.

6.3.2 Abundance, species composition and size of farm woodlots

Farm woodlots occurred on 31%, 43% and 51 % of the total number of farms surveyed in the LAR, MAR and HAR respectively (Table 6-2). Eucalyptus was easily the most dominant species in woodlots and was present in about 90% of the survey woodlots in each of the three altitude regions (Table 6-9).

Table 6-9 Percentage distribution of farm woodlots according to tree species composition in the three altitude regions singly and together based on farm surveys[a]

Types of farm woodlots	HAR n = 48	LAR n = 53	MAR n = 82	Entire study area n = 183
Acacia mearnsii	4.2			1.1
Acacia sp.	2.1			0.5
Cupressus lusitanica			1.2	0.5
Eucalyptus sp.	89.6	90.6	91.5	90.7
Eucalyptus sp. + Cedrela		1.9		0.5
Eucalyptus sp. + Grevillea		1.9	3.7	2.2
Eucalyptus sp. + Pinus patula	2.1			0.5
Grevillea robusta		5.7	3.7	3.3
Pinus patula	2.1			0.5
Total	100	100	100	100

The total number of woodlots for each region is the sum of number of farm having woodlots only and number of farms having both scattered trees and woodlots as presented in Table 6.2.

Grevillea robusta occurred in many LAR and MAR woodlots, reflecting the species was preferred by many farmers in these regions. Although the total number of woodlots per region differed, the mean woodlot size did not differ significantly between regions. It was 0.23 ha in the LAR, 0.35 ha in the MAR and 0.35 ha in the HAR. The overall mean woodlot size was 0.32 ha (Table

6-10). The average number of trees ha^{-1} of woodlots was significantly higher in the MAR and HAR than in the LAR (Table 6-10). There were significant differences in tree density across the three altitude regions, with the MAR and HAR having higher tree densities than the LAR ($F = 6.12$, $p = 0.003$). In general, large woodlots had more trees per unit area. The mean density of trees in a woodlot in the LAR was about 1800 trees ha^{-1}, compared with over 2000 trees ha^{-1} in the MAR and HAR.

There were no statistically significant differences within regions in the number of trees present in the survey woodlots. The number of trees per woodlot was 404 ± 163 in LAR, 816 ± 131 in MAR and 782 ± 172 in HAR (Table 6-10). The large standard errors are partly attributable to differences in environmental conditions and to management practices of eucalyptus coppices. Eucalyptus was easily the most dominant species in woodlots in the three altitude regions, regardless of woodlot size. Of the total number of survey woodlots, a small percentage of woodlots consisted of *Acacia spp., Grevillea robusta, Pinus patula* and *Eucalyptus spp.* planted in mixture with Acacia, Pinus, Cedrela or Callitris (Table 6-9).

Another prominent structural attribute of the woodlots was the diameter distribution of trees in the three altitude regions. Diameter distribution was skewed towards trees with smaller diameters in 68 % of woodlots in the LAR and 46 % of woodlots in the MAR where average woodlot diameters were less than 10 cm (Fig. 6-6).

Table 6-10 Main characteristics of woodlots present on farms in the LAR, MAR and HAR of Rwanda. Means in the same row with the same letter are not significantly different ($p<0.05$) according to one-way ANOVA test followed by pairwise comparison using the Tukey test for $p < 0.05$.

	LAR	MAR	HAR	Total (across regions)
Number of farm woodlots	53	82	48	183
Mean woodlot size (±SE) in ha	0.23 ± 0.06a	0.35 ± 0.05a	0.35 ± 0.07a	0.32 ± 0.03
Mean tree diameter ((±SE) in cm	10.1 ± 1.1a	13.7 ± 0.9b	16.1 ± 1.2b	13.3 ± 0.6
Mean total tree height ((±SE) in m	9.1 ± 0.7a	12.7 ± 0.9b	13.5 ± 0.8b	11.9 ± 0.4
Mean number of trees in woodlot	403.6 ± 163.2a	815.8 ± 131.2a	782.0 ± 171.5a	687.6 ± 88.4
Mean density of trees ha^{-1} (±SE)	1759.4 ± 97.2a	2195.1 ± 78.1b	2000.0 ± 102.1ab	2017.8 ± 53.8
Mean wood volume (±SE) in m^3	56.7 ± 98.6a	285.6 ± 79.3a	301.8 ± 103.7 a	223.6 ± 53.4
Mean wood volume ha^{-1} (±SE)	210.3 ± 76a	448.9 ± 61.1b	457.9 ± 79.9b	382.2 ± 41.5
Average tree weight (±SE) in kg/tree	57.7 ± 8.2a	107.3 ± 5.8b	111.3 ± 8.1 b	96.1 ± 4.1

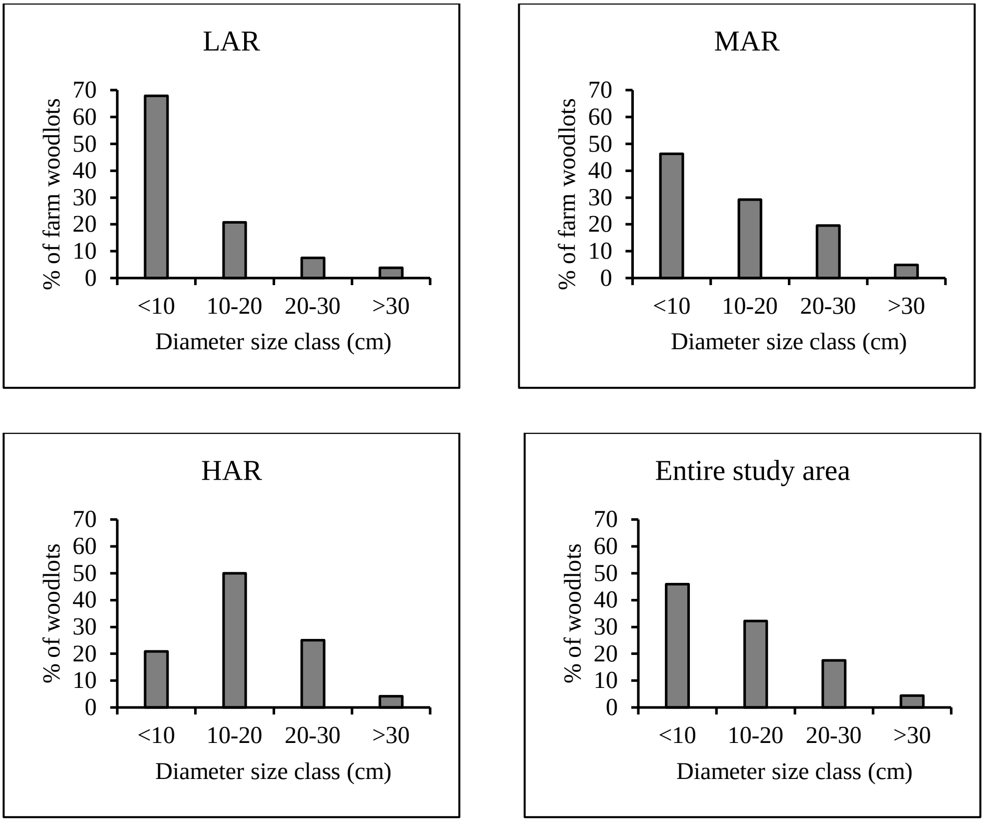


Fig. 6-6 Distribution of diameters of farm woodlot trees in the LAR, MAR, HAR, and in the entire study area. Data are based on 53 woodlots in the LAR, 82 in the MAR, 48 in the HAR, and 183 woodlots for the entire study area. Data represent the % of woodlots with overall mean diameter belonging to each diameter class.

In the HAR, 50 % of woodlots had medium diameters of 10 to 20 cm. The overall mean diameter and mean height of woodlots in the MAR and HAR were significantly larger than those in the LAR woodlots (F = 7. 24, $p < 0.001$ for tree diameter; F = 10.48, $p < 0.001$ for tree height) (Table 6-10).

The total standing wood volume ha^{-1} of woodlot was also different within and across regions, with large volume in HAR and low volume in the

LAR (Fig. 6-7A). Per hectare figures of standing wood volume indicated a high proportion of fuelwood volume for HAR (about 80 %), followed by MAR (67 %) and least for the LAR (60 %). On the other hand, the average standing wood volume in woodlot was not significantly different across the three regions (Fig. 6-7B). It ranged from about 58 to 302 m^3 per woodlot. However, Nearly 64 % of the standing wood volume was available as fuelwood volume in each woodlot.

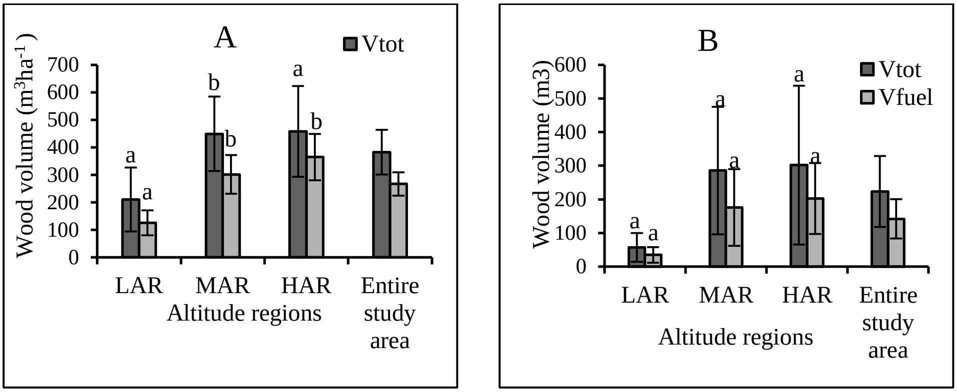


Fig. 6-7 Relationship between total standing wood volume and volume of fuelwood trees per hectare of woodlot (A) and between total standing volume of trees and fuelwood trees in a woodlot (B) in the LAR, MAR, HAR, and across the three altitude regions. V_{tot} denotes the standing total of all trees in woodlot and V_{fuel} denotes the standing tree volume of fuelwood trees in woodlots. The error bars represent the 95 % confidence intervals surrounding the mean values of V_{tot} and V_{fuel} in their respective units. The same letter on the top of the bars across the altitude regions implies non-significant differences for the parameter on the Y-axis according to one-way ANOVA test followed by multiple comparisons using the Tukey test at $p < 0.05$.

6.3.3 Aboveground woody biomass of scattered trees and woodlots on farms

Scattered trees on farms

At farm level, there were significant differences between regions in aboveground woody biomass of scattered trees ($F = 4.1$, $p = 0.02$), with the MAR and LAR farms having the same quantity but more than HAR (Fig. 6-8). In all regions together, 42 % of the total aboveground biomass ha^{-1} of

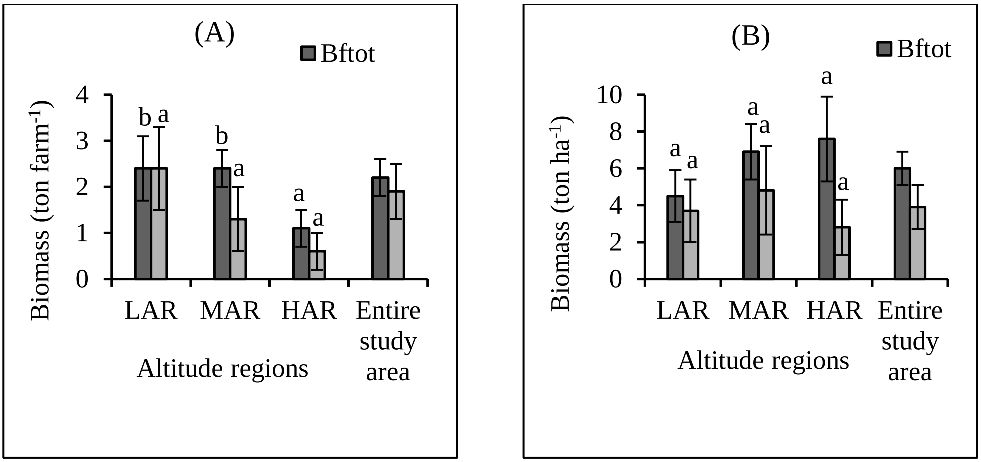


Fig. 6-8 Relationship between present total aboveground woody biomass and biomass for fuelwood per farm (A) and per hectare of farm (B) in the LAR, MAR, HAR, and in the entire study area. Bftot denotes the total aboveground biomass and Bf_{fuel} denotes the aboveground biomass for fuelwood. The error bars represent the 95 % confidence intervals surrounding the mean values of Bftot and Bffuel. The same letter above the bars across the altitude regions implies non-significant differences for the parameter on the Y-axis according to one-way ANOVA test followed by multiple comparisons using the Tukey test at $p < 0.05$.

scattered trees was for fuelwood use. There were no significant differences in farm total tree biomass per ha (Fig. 6-8B). The mean for farm woody biomass dry weight was 4.5 ± 1.4 ton ha^{-1} in the LAR, 6.9 ± 1.5 ton ha^{-1} in the MAR and 7.6 ± 2.3 ton ha^{-1} in the HAR. The analysis of the pooled farm-level data across regions gave the overall average tree biomass of 6 ± 0.9 ton ha^{-1} at 95 % confidence interval.

Similarly, woody biomass dry weight accumulated in fuelwood species did not differ significantly among regions (Fig 6-8A&B). The overall biomass for fuelwood was 2 t $farm^{-1}$ or 4 t ha^{-1}. The variability of fuelwood trees across regions was not reflected in the amount of woody biomass, probably because of differences in the size distribution of fuelwood trees. Compared to the total standing woody biomass, the share of fuelwood species per hectare of farm was 82 % for the LAR, 70 % for the MAR and 37 % for the HAR.

Farm woodlots

Total woody biomass dry weight per hectare was higher for the MAR than the LAR, but both the HAR and LAR had the same biomass (Fig. 6-9A). But both the MAR and HAR had higher biomass for fuelwood per ha than the LAR ($F = 12.2$, $p < 0.001$) since about 70 % of woodlot trees in the LAR had small-diameter trees (Fig. 6-6). Standing fuelwood biomass in the woodlots was in the order of 66 ton ha^{-1} in the LAR, 177 ton ha^{-1} in the MAR and 188 ton ha^{-1} in the HAR. The mean standing fuelwood biomass was different among the three regions, with the LAR having a lower biomass ha^{-1} than the HAR and MAR. Both the MAR and HAR woodlots farms showed statistically identical standing fuelwood biomass per hectare (Fig. 6-9A).

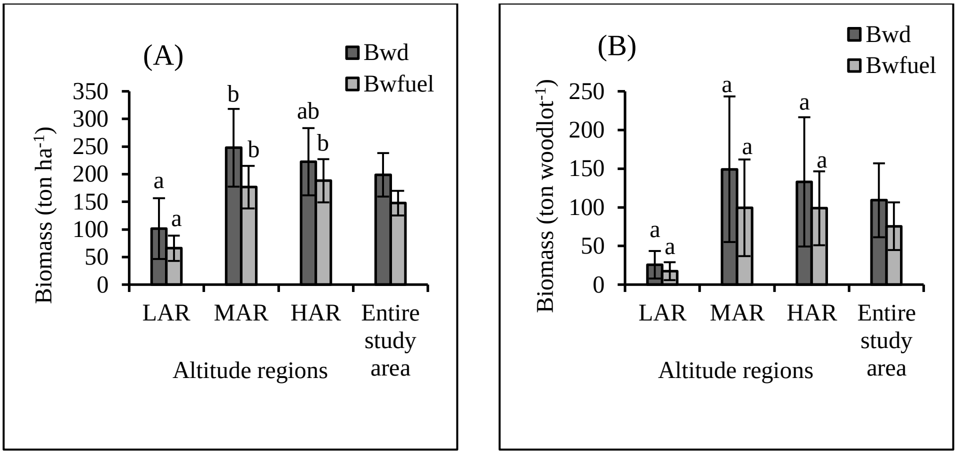


Fig. 6-9 Standing total and fuelwood biomass per hectare (Fig. 6-9A) and per woodlot (Fig. 6-9B) in the LAR, MAR, HAR, and across the three altitude regions. B_{wd} denotes the total standing biomass per woodlot and per ha and B_{wfuel} denotes the standing fuelwood biomass per woodlot (tons) and per hectare (ton ha^{-1}). Error bars represent 95 % confidence interval around the mean biomass per woodlot and per hectare. Column bearing the same letter across the three regions are not significantly different according to one-way ANOVA test followed by Tukey test at $p < 0.05$.

The mean woody biomass dry weight in woodlots was 26 ± 17.8 ton for the LAR, 149 ± 94 ton for MAR and 133 ± 84 ton for HAR at 95 % confidence interval. For the entire study area, it averaged 109 ± 48 ton. The aboveground biomass useable as fuelwood was less: about 74 % of the total standing biomass across the three regions. There were no statistically significant differences in total biomass accumulation and biomass for fuelwood per woodlot among these regions (Fig. 6-9B), pointing to the large variation in the data.

Fuelwood biomass or the amount of woody biomass dry weight usable as fuelwood accounted for 74 % of the total aboveground biomass in woodlots across the three regions. It represented 65 % in the LAR, 71 % in the MAR and 85 % in the HAR. The non-fuelwood biomass from woodlots was low in the HAR, followed by that in the MAR and the LAR.

6.3.4 Characteristics and aboveground biomass of different types of trees on farms

Table 6-11 summarizes the average tree biomass, the number of trees per hectare, and the average aboveground biomass per hectare for the main types of trees found in the three altitude regions of Rwanda. The individual average tree weights across the different types of trees on farms ranged from 195 to 294 kg, with the low tree biomass found for shrubs used for various products and services including stakes for climbing crops and banana, fodder for livestock, fencing, green manure and medicine. The individual tree biomass for fuelwood did not differ significantly among regions. The large standard errors imply significant variation in tree diameters; one reason for the large differences was that timber species were often used as fuelwood.

The individual tree biomass of tree species producing timber, fruit and building materials varied between farms and across two or three regions. The number of trees per hectare of farmland differed only slightly within the different types of trees across the three regions, with the exception of the trees producing timber and fruit. The latter generally accounted for the greatest number of large trees per hectare. Thus, the average biomass ha^{-1} was largely a function of average tree weight: timber and fruit tree species accumulate large amounts of woody biomass, whereas fuelwood species and tree species producing building materials accumulate small amounts of biomass.

Table 6-11 Individual tree biomass number of trees per hectare and average biomass per hectare for the main types of trees on farms in the LAR, MAR and HAR of Rwanda. Means in the same row with the same letter are not significantly different according to one-way ANOVA test followed by Tukey at $p < 0.05$

Types of trees	LAR	MAR	HAR	Across the three regions
1) Fuelwood species				
Tree biomass (±SE) in kg	258.8 ± 53.9 a	434.9 ± 76.8 a	91.4 ± 129.5 a	293.5
No. trees ha^{-1} (±SE)	21 ± 4 a	16 ± 5 a	26 ± 9 a	20
Farm tree biomass (±SE) in ton ha^{-1}	2.9 ± 0.9 a	5.8 ± 1.3 a	2.5 ± 2.1 a	3.9
2) Timber species				
Tree biomass (±SE) in kg	139.8 ± 17.6 a	664.9 ± 27.5 c	238.1 ± 32.1 b	282.7
No. trees ha^{-1} (±SE)	22.6 ± 3.5 b	8.5 ± 3.5 a	43.4 ± 4.9 c	21.1
Farm tree biomass (±SE) in ton ha^{-1}	2.7 ± 1.1 a	4.5 ± 1.1 ab	7.5 ± 1.5 b	4.4
3) Fruit species				
Tree biomass (±SE) in kg	109.0 ± 16.6 a	392.7 ± 22.0 c	280.8 ± 32.7 b	221.5
No. trees ha^{-1} (±SE)	17.9 ± 3.4 ab	11.8 ± 1.1 a	27.8 ± 5.3 b	17.3
Farm tree biomass (±SE) in ton ha^{-1}	1.4 ± 1.1 a	4.8 ± 1.1 ab	7.0 ± 1.6 b	3.7
4) Building materials				
Tree biomass (±SE) in kg	48.5 ± 34.0 a	828.8 ± 54.3 b	36.7 ± 187.9 a	263.5
No. trees ha^{-1} (±SE)	28.6 ± 15.5 a	5.3 ± 19.2 a	32.5 ± 52. 4 a	20.1
Farm tree biomass (±SE) in ton ha^{-1}	0.4 ± 1.3 a	4.9 ± 1.5 a	1.0 ± 1.2 a	2.1
5) Other [a]				
Tree biomass (±SE) in kg	190.6 ± 62.7 a	170.1 ± 150. 7 a	236.7 ± 142.9 a	194.5
No. trees ha^{-1} (±SE)	24.3 ± 8.9 a	2.7 ± 13.1 a	16.1 ± 11.1 a	17.1
Farm tree biomass (±SE) in ton ha^{-1}	1.2 ± 0.8 a	0.6 ± 1.1 a	1.6 ± 1.0 a	1.2

[a] The category “Other” includes tree species that provide banana supports stakes for climbing crops (mainly beans) fences supports for beehives cultural importance erosion control fodder soil improvement boundary marking ornament and medicine

Fuelwood species, species producing building materials and tree species for uses other than timber and fruit did not differ significantly in woody biomass accumulation within the three altitude regions. Across these regions, biomass accumulation increased in the following sequence: timber species, fuelwood species, fruit species, tree species producing building materials, and other tree species serving different functions from the formal uses.

6.3.5 Characteristics and aboveground woody biomass of scattered trees and woodlots in the landscapes

Scattered trees in the agricultural landscapes

Agricultural land accounted for about one-third of the total sample area per region (32 % in the LAR, 35 % in the MAR and 36 % in the HAR). Scattered trees occurred throughout the agricultural landscapes of the low, medium and high altitude regions, with much variation within each landscape (Fig. 6-10).

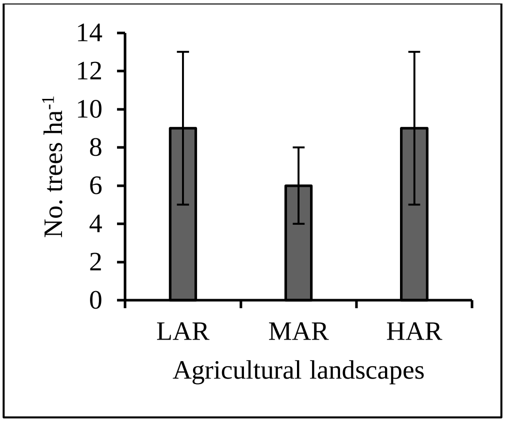


Fig. 6-10 Number of dispersed trees ha^{-1} in the LAR, MAR, and HAR landscapes. Error bars represent standard deviations.

In the LAR landscape, 123 443 trees were recorded on the 15 901 ha of arable land, corresponding to a density of 8 trees ha^{-1}. The overall average figure hides a large degree of variation: the Eastern Plateau, for instance, had an average of 3 trees ha^{-1} while the Eastern Savannah had 11 trees ha^{-1}. Scattered trees in the landscape occurred most frequently in Bugesera: 14 trees ha^{-1} (Table 6-12). The MAR agricultural landscape had the least scattered trees ha^{-1}: 85 837 trees were digitized over an area of 14 038 ha, equivalent to 6 trees ha^{-1} (Table 6-12).

Table 6-12 Density and aboveground biomass of dispersed trees in the LAR, MAR and HAR landscapes of Rwanda

Landscapes	Arable land (ha)	No. trees recorded	Number of trees ha^{-1}	Biomass (ton ha^{-1})
LAR				
Bugesera	1083	14 691	14	1.4
Eastern Plateau	3413	10 198	3	0.3
Eastern Savannah	3557	37 631	11	1.1
Imbo	3966	25 373	6	0.7
Mayaga	3882	35 550	9	1.0
Total	15 901	123 443	8	0.9
MAR				
Central Plateau	3565	30 379	9	3.5
Granitic Ridge	3726	19 712	5	2.1
Impala	3458	14 158	4	1.7
Lake Kivu Shores	3289	21 588	7	2.7
Total	14 038	85 837	6	2.5
HAR				
Volcanic Highlands	4185	57 499	14	2.0
Non-volcanic Highlands	2962	24 288	8	1.2
Congo Nile Crest	3545	19 961	6	0.8
Total	10 693	101 748	10	1.3

Considerable variation in the densities of scattered trees existed within the MAR agricultural landscape. The range was from 4 trees ha^{-1} in Impala to 9 trees ha^{-1} in the Central Plateau. In HAR landscape there were about 10 scattered trees per hectare: 101 748 trees were recorded over an area of 10 693 ha (Table 6-12). Within this landscape, the Volcanic Highlands had the highest number of trees ha^{-1} (14 trees ha^{-1}), followed by the Non-volcanic Highlands (8 trees ha^{-1}) and the Congo Nile Crest (6 trees ha^{-1}).

Based on the mapped scattered trees in the sample agricultural landscapes, the average aboveground live biomass for each category of landscape was calculated (Table 6-12). The difference in standing biomass was clear for the three types of landscapes, with the live biomass in MAR landscape being 2-3 times that estimated in the HAR and LAR landscapes. The aboveground live biomass was highest in the MAR landscape, where there were few trees ha^{-1} and many trees were large (Fig. 6-10). There was no consistent trend between biomass of scattered trees at farm level and biomass at landscape level (Fig. 6-11).

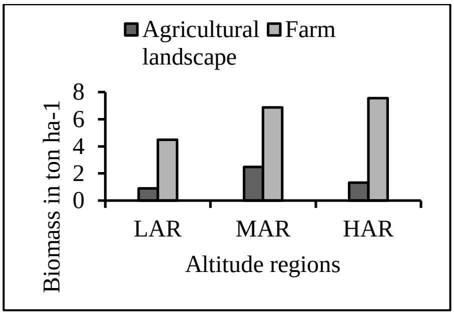


Fig. 6-11 Relationship between biomass on individual farms and biomass in the landscapes within and across the LAR, MAR and HAR regions of Rwanda.

Unexpectedly, biomass accumulation in scattered trees in the HAR landscape was uncorrelated with the standing biomass of scattered trees at farm level.

Woodlots in the agricultural landscapes

Some 23 % of the total study area was covered by forests (> 0.5 ha) and woodlots (<0.5 ha). This figure differs by only 4 % from that reported by FAO (2010c), but is about twice the forest cover value of 10 % in the forest mapping report by CGIS-NUR and MINITERE (2008) which excluded small stands of < 0.5 ha from mapping. In our study, small woodlot (< 0.5 ha) cover alone accounted for about 10 % of the total wooded lands. Table 6-13 gives the areas of forests (> 0.5 ha) and woodlots (< 0.5 ha) and their corresponding proportions of the land areas in the low, medium and high altitude regions. Taken together, the proportion of area occupied by forests and woodlands increased going from MAR, to LAR, and to HAR.

Table 6-13 Area and cover of wooded land in study landscapes of LAR, MAR and HAR by forest and woodlot sizes

			Wooded land (ha)				Woodlot cover	
Land-scapes	Sample area (ha)	Estimated land (ha)	Forest > 0.5 ha	Woodlot < 0.5 ha	Total (ha)	% land area	% land area	% total wooded land
LAR	50 000	41 840	8880	612	9492	23	2	6
MAR	40 000	38 438	8932	940	9872	26	2	10
HAR	30 000	27 234	4453	1017	5470	20	4	19
Total	120 000	10 7512	22 265	2570	24 835	23	2	10

Whereas the majority of natural forest occurs in HAR, more woodland cover was recorded in the LAR, because here there were savannah woodlands and small forest stands (< 10 % tree cover) that did not meet the

FAO (2005) criterion of > 10 % tree cover and so were excluded from the CGIS-NUR and MINITERE forest inventory. The overall average figure of 23 % woodland cover also hides a large degree of variation within the three types of landscape. Wooded land cover ranged from 20 % in HAR landscape to 26 % in MAR landscape. Small woodlot (≤ 0.5 ha) cover ranged from 2 % to 4 % of the land and represented 6 %, 10 % and 19 % of the total wooded lands in the low, medium and high altitude landscapes.

Some characteristics of woodlots in the three agricultural landscapes are presented in Table 6-14. The mean woodlots sizes were statistically different between these landscapes. The mean number of trees in woodlots was also different, with many trees present in the MAR woodlots, followed by the HAR and LAR woodlots. There were significant differences in tree densities between landscapes: the MAR landscape had a higher tree density than the LAR and HAR; the LAR landscape had significantly less dense woodlots than the HAR landscape (Fig. 6-12).

The aboveground biomasses per woodlot and per hectare were significantly higher for the MAR than the HAR and LAR landscapes. The HAR landscape had the second highest biomass per woodlot and per ha and had significantly more biomass than the LAR (Fig. 13).

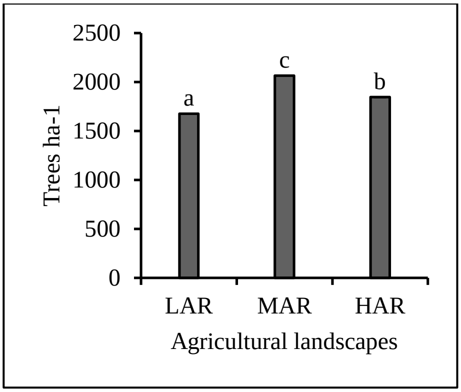


Fig. 6-12 Estimates of the number of trees ha^{-1} in woodlots (≤ 5 ha) in the LAR, MAR and HAR landscapes. Data are based on 4801 woodlots in the LAR; 6263 woodlots in the MAR and 9105 woodlots in the HAR. The same letter above the bars across the altitude regions implies non-significant differences for the parameter on the Y-axis according to one-way ANOVA test followed by multiple comparisons using the Tukey test at $p < 0.05$

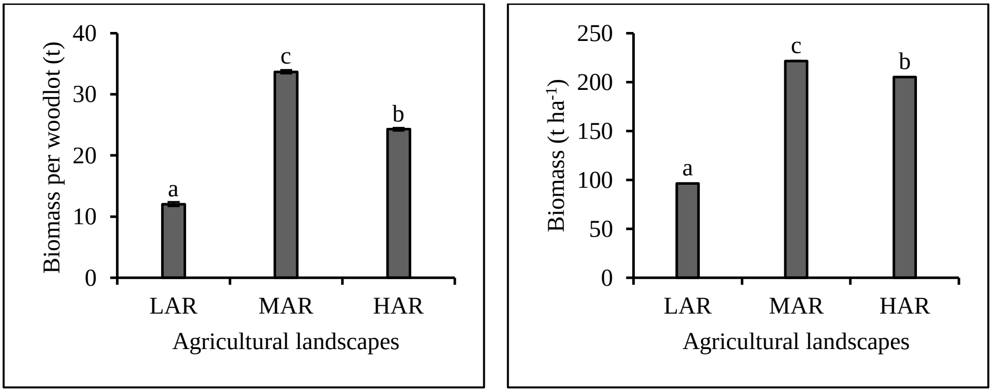


Fig. 6-13 Estimates of aboveground biomass per average woodlot size and per hectare of woodlot in the LAR, MAR and HAR landscapes. The error bars represent the standard errors. Columns bearing the same letter across the altitude regions are not significantly different according to one-way ANOVA test followed by Tukey test at $p < 0.05$. Biomass estimates are based on 4801 woodlots in the LAR, 6263 woodlots in the MAR, and 9105 woodlots in the HAR.

6.3.6 Estimates of total farm woody biomass in the agricultural landscapes of the low, medium and high altitude regions

Table 6-14 shows the cultivated land area and the present total amount of aboveground woody biomass and biomass for fuelwood accumulated in scattered trees and woodlots (< 0.5 ha) in each of the three agricultural landscapes.

Table 6-14 Estimates of total aboveground biomass and biomass for fuelwood stored in scattered trees and woodlots in the agricultural landscapes of the LAR, MAR and HAR of Rwanda

Agricultural landscape	Area under agroforestry (x 10^6 ha)	Woodlot area (ha)	Total biomass (x 10^6 t)			Fuelwood biomass (x 10^6 t)		
			Trees	Woodlots (<0.5 ha)	Total	Trees	Woodlots (<0.5 ha)	Total
LAR	0.23	10 675	0.15	1.02	1.18	0.08	0.67	0.74
MAR	0.25	16 295	0.76	3.60	4.36	0.30	2.56	2.85
HAR	0.19	17 831	0.21	3.66	3.86	0.45	3.07	3.52
All	0.67	44 800	1.12	8.28	9.40	0.83	6.29	7.12

Applying the mean woody biomass in scattered trees and woodlots on farms to the agricultural land area of each altitude region gave total accumulations of aboveground biomass estimated at 1.1 M t (M t = million tons) in the LAR, 4.4 M t in the MAR and 4.0 M t in the HAR. Based on biomass proportions between total aboveground biomass and biomass for fuelwood in each agricultural landscape, total biomass for fuelwood (from scattered trees and woodlots) were estimated to be, in descending order, 3.5 M t in the HAR, 2.9 M t in the MAR and 0.7 M t in the LAR. Across the three agricultural landscapes, the total aboveground woody biomass accumulated in scattered trees and woodlots was 9.4 M t, of which 7.1 M t were estimated to be for fuelwood use.

6.4 Discussion

6.4.1 Differences in scattered trees and woodlot cover between the three altitude regions

Differences in tree and woodlot cover between the three altitude regions reflect the combination of farmers’ interests, land use options, management strategies, farming systems and socioeconomic conditions of the farm households. For example, the medium altitude region had a much greater abundance of tall trees with large diameters than the other two regions, suggesting that here more upper storey trees producing timber and fruit have been planted than in the other regions. In contrast, much smaller trees predominated in the low and high altitude regions, suggesting that many of the trees were younger, or are maintained as shrubs under current management, by pruning and coppicing. More frequent and intensive planting of shrub species used in soil erosion control in the highlands may partly explain their predominance on farms in the high altitude zone. The reason for the many tree species on the LAR farms was that most smallholder farmers had planted or retained indigenous species characteristic of the semi-arid environment, including many shrub species. Though a large area of the LAR had been deforested and cleared for crop production and livestock farming in the 1960s, some tree species of the savannah woodlands were left standing on farms by farm households because of their productive and service functions.

The current densities, size and composition of scattered trees on farms reflect the combination of both historical and current management decisions made by households about which trees to plant and at what densities in order to avoid competition with crops. The present agroforestry systems in Rwanda reflect actions by agroforestry projects since the 1970's, focusing on particular areas of the country and promoting different agroforestry technologies using different approaches. For instance, given a choice, farmers might have preferred some species over the others, for instance fruit trees or Eucalyptus or Grevillea instead of, for example, Leucaena, Calliandra or Acacia.

In all three regions, despite an overall abundance of tree species, the composition of trees on farms was heavily skewed towards a subset of species, with the top ten tree species in region representing more than 70 % of all trees. In particular, the three altitude regions were dominated by a handful of useful tree species (particularly fuelwood, fruit and timber) which were commonly found on many farms. Hence, trees were valued for different purposes. This agrees with findings of studies on the importance of agroforestry systems in contrasting biophysical and cultural contexts elsewhere in Africa (e.g. Erakhrumen 2009; Isaac et al. 2009; Zerihun and Kaba 2011), but also in India (Sourabh et al. 2009; Palsaniya et al. 2010; Banyal et al. 2011), Europe (e.g. Baldy et al. 1993; Mary et al. 1998; Sinclair 1999b) and USA (e.g. Barbieri and Valdivia 2010), where farmers have planted trees because of their attributes, despite their competitiveness with crops (Palsaniya et al. 2010, Tang et al. 2012).

The importance of farm trees in providing fuelwood to farmers in the present study, is corroborated by many other studies that have shown that agroforestry systems were the best alternative to produce wood products and to conserve natural resources (Okubo et al. 2010; Quinion et al. 2010; Saha et al. 2010; Mehta et al. 2011; Stille et al. 2011). In the three altitude regions, the high proportion of fuelwood trees on farms reflects farmer strategies to secure energy for cooking. In all three regions most agricultural households depend on fuelwood for cooking, so it is no surprise that many scattered trees are used as fuelwood. In addition, some fuelwood is collected from tree species not primarily grown for fuelwood; Den Biggelaar (1996) also observed that fuelwood is a secondary product from trees in Maraba and Karama communes located in the medium altitude region of Rwanda. In fact, this study indicated that many trees on farms were valued for fruit and timber. On smaller farms, planting more trees to meet fuelwood needs might conflict with other farm priorities such as the production of food crops.

In the present study, having non-fuelwood trees on the farm was an important consideration Our finding is in line with that of Balasubramanian and Egli (1986) that fruit trees form an integral part of the farming systems in Rwanda. Farmers were also greatly interested in the production of timber. The difference in tree density and biomass production between the three regions indicates differences in tree species, growth rates and management practices. For instance, the low tree density ha^{-1} and high biomass production of timber trees in MAR result from the presence of large trees of Grevillea, Ficus and Markhamia. Wide spacing of timber trees provide merchantable wood volume (Bertomeu 2012), with only little loss of crop yields. To improve the productivity of tree-intercropping systems, spacing must be wide to minimize competition, and appropriate tree species and crops must be grown and tree management improved.

6.4.2 Aboveground woody biomass in the agricultural landscapes

The estimated average aboveground woody biomass in scattered trees and woodlots in Rwanda is 9.4 M ton. There is large variation between the agricultural landscapes of the LAR, MAR and HAR (Table 15). The MAR landscape accounted for 46 % of the woody biomass in the three regions, with the HAR landscape accounting for a further 41 % and the LAR landscape for only 13 %. The importance of woodlots, as opposed to scattered trees is clear, with farm woodlots contributing about 88 % of the total aboveground biomass in agricultural landscape. This corroborates the finding by Henry et al. (2009) that in smallholder farming systems elsewhere in Africa (e.g. Kenya), woodlots produce more biomass than other agroforestry systems.

The estimated aboveground woody biomass for the three landscapes (ranging between 1.2 and 4.4 M ton) were notably lower than the estimates for tropical agroforestry systems presented by Albrecht and Kandji (2003). This is most likely because these authors were only focusing on agroforestry plots while this study considered a mixture of agroforestry systems and cropping systems. In addition, the variability in aboveground biomass was important in the three altitude regions together and separately, with the MAR landscape contributing a large amount of biomass in scattered trees and woodlots to the total. Pressure on natural resources and land fragmentation are more common in the MAR and HAR (MINECOFIN 2007), where aboveground farm woody biomass is high. Hence, the greater the population density, the more the farms are devoted to biomass production despite their small size. Although we did not analyse differences in aboveground woody biomass between farms, it can be assumed that farmers' socioeconomic conditions will influence the quantity of farm woody biomass.

Our results indicated that the biomass stock on average was 6 ton ha^{-1} for scattered trees on farms, and about 200 ton ha^{-1} for farm woodlots. ISAR and MINITERE (2008) estimated that the stock of forest plantations was 13.4 M m^3 for the entire country. Assuming a specific weight of 500 kg m^{-3}, this figure translates to 6.7 M ton for a forest plantation area of 114 900 ha. This is equivalent to approximately 58 ton ha^{-1} without accounting for the biomass in branches and non-merchantable sections of the trees. If these are included on the basis that they account for 30 % of the merchantable volume (Saint-André et al., 2005; Segura and Kanninen, 2005), woody biomass stock in forest plantations increases to76 ton ha^{-1}. Since our study finds that total standing woody biomass in trees and woodlots on farms is 9.4 M ton, an inevitable conclusion is that in Rwanda, there is in total more woody biomass on agricultural land than in forest plantations. This can partly be explained by scattered trees and woodlots being more productive per unit area, probably because of good management, good soil, species composition and higher growth rates. Our total aboveground woody biomass on agricultural land falls within the range of 6 – 48 M ton estimated for the total national wood stock (Gibbs et al. 2007). Based on findings of the study and our estimates of woody biomass dry weight stock from literature, biomass stock on agricultural land is higher than that in forest plantations across the three altitude regions of Rwanda (Table 6-15).

Table 6-15 Estimates of woody biomass stock in trees on farms, woodlots, forest plantations and other wooded lands in Rwanda

	Woody biomass dry weight (ton ha^{-1})		
	LAR	MAR	HAR
Scattered trees on farms	4.5	6.9	7.6
Woodlots on farms	96	221	205
Forest plantations[a]	50	58	97
Other wooded lands[a]	1.5	0.5	0.4

a. Woody biomass stock estimates based on findings by Drigo and Nzabanita (2011).

Woody biomass stock in HAR forest plantations is larger probably due to forest plantation area being larger than in LAR and MAR. Low biomass stock exists for all tree systems in LAR.The low standing total woody biomass in the LAR landscape demonstrates that although farms here tend to be larger, insufficient trees and woodlots have been planted on the agricultural land, perhaps due to inadaptability of the tree species, lack of tree germplasm, and lack of awareness of agroforestry technologies by farmers. In general, our results reveal an inverse relationship between farm size and the amounts of woody biomass. For instance, in the HAR landscape, where average farm size is below the national average of 0.76 ha, there was more biomass than in the LAR landscape, where farms are comparatively large (average 1.0 ha). Similar relationships between farm size and productivity have been found in many studies (Dyer 1997; Thapa 2007; Chand et al. 2011). In the case of trees and woodlots on farms, however, the observed increase in biomass is not the result of inputs or more fertile land on the small farms but arises from the smallholder farmers taking measures to intensify agricultural production while also producing fuelwood, timber and fruit. The current land inheritance practice that results in fragmentation of holdings will ultimately result in farms being so small that they cannot be valuable sources of wood products anymore.

6.4.3 Biomass for fuelwood and opportunities for sustainable harvesting

Most of the standing aboveground woody biomass is in the MAR, where the biomass stocks in scattered trees and woodlots are higher than in the other two regions. Our study showed that about 76 % of the total biomass from farms was useable biomass for fuelwood, implying that the production of fuelwood on agricultural land is important. The notable differences in fuelwood production per ha between the three regions indicate the fuelwood supply situation. In the LAR, where the standing woody biomass in scattered trees and woodlots is low, fuelwood supply can be assumed to be inadequate. Whereas the MAR and HAR households may depend on farm fuelwood, LAR farmers are likely to use fuelwood collected from existing forests, and may use fuelwood obtained from outside their region, or may use larger proportions of agricultural residues in the mix of fuelwood to satisfy their energy needs for cooking.

Comparing this situation with the availability of forests in the three regions, it is clear that households in the MAR and HAR, where forest cover is moderate to extensive (CGIS-NUR and MINITERE 2008), adapt to fuelwood scarcity and to the ban on collecting fuelwood from forests by maintaining more trees and woodlots on their farms. This is a common strategy in rural households in developing countries, particularly in Africa (e.g. Johnsen 1999; Bisong et al. 2007; Akther et al. 2010).

The question is whether the woody biomass on farms can satisfy domestic needs for fuelwood for cooking. The estimated standing fuelwood volume available across the altitude regions of Rwanda was about 15.6 M m^3. Given an estimated population of 10.8 million in Rwanda in 2011 (NISR 2012a), this gives an average per capita volume of about 1.44 m^3 – a figure much higher than the annual fuelwood consumption per capita (0.67 m^3 year-1) reported in many studies (e.g. MINAGRI 1983; Karenzi 1994; Hategeka 1997a). Hence, even allowing for some underestimates in the biomass figures across the three regions, the amount of biomass for fuelwood could cover for about three years of fuelwood demand..

The large amounts of biomass accumulated in timber and fruit species might largely be the non-fuelwood biomass from large-diameter trees. It seems possible that overexploitation of farm trees and woodlots for fuelwood might not only initially reduce fuelwood trees but, if fuelwood is scarce, might later result in biomass from timber species being systematically harvested for fuel. Then the woody biomass on farms would not be sustained. Since tree size correlates strongly with aboveground biomass (Chiba 1998), the loss of timber trees may reduce the standing farm woody biomass. The branches lopped systematically to reduce crop shading by timber trees are an important source of fuelwood: branch biomass is estimated to be between 30 and 50 % of the total wood biomass of timber trees in agroforestry systems (Jensen, 1995).

This study did not distinguish fuelwood biomass in trees from that in shrubs. The latter is dominated by small multipurpose trees cultivated at very high densities and sustainably harvested over many cycles. Their cumulative biomass production for fuelwood has been found to be higher than fuelwood biomass of upper storey trees (Naugraiya and Sunil 2001; Gill 2005). The prunings in agroforestry can be used for fuelwood and the pruning itself encourages the growth of multiple stems. In this way, management practices may enhance biomass production on farms and sustainable harvesting of biomass for fuelwood.

Given the amount of standing biomass on farms for fuelwood which has not been accounted for in the national energy balance (Ndayambaje and Mohren 2011), the estimated annual fuelwood shortfall of 4.5 M m^3 in Rwanda (MINITERE 2004) can be re-examined in order to provide a more accurate figure of the fuelwood demand and supply in the country while providing information on a regional basis. Our results indicate that there were regional variations in the quantity of biomass for fuelwood, with low biomass production in the LAR. The high income from the selling of fuelwood reported for the Western and Southern Provinces of Rwanda (LTS 2010), which are mostly located in the HAR and MAR respectively, indicates that farm households earn income from the selling of fuelwood from their farms, particularly from woodlots where woody biomass production is high.

Most farm woodlots consist of eucalyptus managed as simple coppices. Using the productivity data in forest plantations estimated by Drigo and Nzabanita (2011), the mean annual increments in farm woodlots would be some 8.4 ton $ha^{-1}year^{-1}$ in the LAR, 10.1 ton $ha^{-1}year^{-1}$ in the MAR and 11.2 ton $ha^{-1}year^{-1}$ in the HAR. Applying these to woodlot areas presented in Table 6-14, the total gross increment in woodlots would be 0.09 M t yr^{-1} in the LAR, 0.16 M ton $year^{-1}$ in the MAR and 0.20 M ton $year^{-1}$ in the HAR. Thus, the amount of fuelwood potentially available on a sustainable basis could be 0.06 M ton $year^{-1}$ in the LAR, 0.12 M ton $year^{-1}$ in the MAR and 0.17 M ton $year^{-1}$ in the HAR. It is clear that the sustainable production of fuelwood increases consistently from the low to high altitude regions. However, the figures presented here must be treated with caution, because only small woodlots (< 0.5 ha) were included in the estimation.

Scattered trees on farms were also sources of wood, particularly of fuelwood. Trees considered in this study included individual trees planted on cropland especially as agroforestry, along farm boundaries and contours, roadsides and other similar areas, though agroforestry extends to trees in pasturelands, trees on non-government lands, and in general to all trees outside forests (Den Biggelaar 1996, REMA 2010). The data showed these scattered trees to be an important resource, planted for a variety of uses such as the production of fuelwood, fruit, timber and building materials. Based on total standing woody biomass of scattered trees (Table 6-14) and estimates of proportions of total woody biomass used as fuelwood (Fig. 6-8) in each of the three landscapes, and assuming that the productivity of scattered trees is 1.5 m^3 ha^{-1} $year^{-1}$ as per estimate by Samyn (1993), the annual wood production would be 0.3 M ton in the LAR and in the HAR, and 1.0 M ton in the MAR. Of these estimates, annual sustainable production of biomass for fuelwood would be 0.2 M ton in the LAR, 0.4 M ton in the MAR, and 0.1 M ton year^{-1} in the HAR, together accounting for 0.7 M ton year^{-1} on national basis.

On the basis of the above assumptions, the total, sustainable biomass production in scattered trees is small and could increase with increased tree planting on farms. Generally, sustainable biomass for fuelwood from trees and woodlots on farms can be increased if the productivity of present wood stocks is increased. Producing more biomass for fuelwood in the three altitude regions may be achieved through agricultural intensification which, in addition to the use of improved seeds and fertilizers, may involve the planting of fast-growing multipurpose trees on contours and field boundaries in order to control erosion and to stabilize terraces. The other remedial action to reduce the gap between fuelwood demand and supply would be to expand the planting of woodlots, particularly in the low altitude regions, and to enhance the productivity of eucalyptus coppice, which is now very low, as reported in many studies (ISAR-MINITERE 2008; Drigo and Nzabamwita 2011; Nduwamungu 2011).

6.5 Conclusion

Scattered trees and woodlots are key features of the agricultural landscapes in the three altitude regions of Rwanda. They occur at different densities and cover, and have a valuable productive role for the smallholder farmers. Many tree species were recorded on smallholder farms, but they occurred as few individuals only and were largely for the production of fuelwood, fruit, timber and building materials.

The value of the trees on farms, as reflected by their product categories, represents a resource that can be built upon to promote and disseminate agroforestry species, yet farm inventories reveal low densities of trees. This presents an opportunity for increasing the number of trees for energy production on agricultural land. In order to increase agricultural production and farm biodiversity, let alone increase wood products, smallholders probably need to be made more aware of the productive and ecological functions of trees and woodlots on farms. In addition, incentives related to payment for ecosystems services may encourage the smallholder farmers to extend the planting of trees on their farms.

Our results underline the importance of the cultivation of trees and woodlots for wood production on small farms in Rwanda, even in densely populated areas like the HAR. This provides an opportunity for agroforestry to contribute to agriculture intensification. For instance, the production of fuelwood and other wood products from banana and coffee agroforestry systems can be traced back to agricultural intensification. However, with economic development and income growth, smallholder farmers might change their behaviour in fuelwood consumption by either using purchased fuelwood or modern fuels such as electricity and gas, which might reduce their involvement in tree planting on their farms. Hence the degree to which farmers rely on agroforestry systems may be reduced following the relative demand for fuelwood and farmers' access to other sources of energy for cooking meals.

Programmes aimed at controlling erosion, promoting terracing practices on sloping land and protecting watersheds may result in all regions becoming more forested than today, but the trade-offs with agricultural production still need to be assessed in more detail. More investment in agroforestry and woodlot development might be required in the lowlands, where there was less tree and woodlot cover than in higher areas. As a mitigation strategy to relieve pressure on existing natural vegetation in the lowlands, the conversion of croplands and pastures to agroforestry might be an opportunity that may help increase crop, forage and wood yields while further reducing soil degradation.

Compared to forest plantations, woody biomass dry weight on agricultural land is higher: under conditions as in Rwanda up to about twice that in forest plantations (> 0.5 ha). Of the total standing woody biomass on farmland, the proportion of biomass for fuelwood is important and is about 1.5 times the amount of fuelwood consumed in Rwanda. The quantification of aboveground biomass revealed regional variations: from a landscape perspective this is important for increasing tree and woodlot cover. The high standing woody biomass in the MAR and HAR means these regions have high potential for fuelwood and carbon accumulation in the aboveground components of trees and woodlots.

Notable differences exist in the contribution of scattered trees and woodlots to total biomass and biomass for fuelwood across regions, with woodlots representing 83 to 95 % of total biomass stock in each region. Programmes and projects aiming at reducing fuelwood shortages may succeed if they support smallholder farmers in creating agroforestry systems and planting woodlots that produce fuelwood without compromising food production, for example by planting fertiliser trees that improve crop yields through biomass transfer and nitrogen fixation. Intensive planting of trees on small farms in the pursuit of soil conservation practices may be easier to promote among farmers, but woodlots may be more difficult to promote, as they can be targeted only at degraded areas on farms where energy production does not compete for space with food production.

Since the amounts of woody biomass on farms significantly varied between regions, trees and woodlots on farms will have different importance for bridging the gap between supply and demand of fuelwood. With improved productivity, farm trees and woodlots can significantly contribute to the balance between fuelwood demand and supply. But this can be achieved only if the productivity of trees and woodlots is increased through tree species choice and quality management practices (e.g. pruning, pollarding, lopping) that affect the distribution between leaf biomass and wood biomass in agroforestry systems and woodlots. At the same time, an increase in fuelwood production should not be at the cost of food crops on smallholder farms, except when and where wood production is economically more attractive than crop production.

In a view of the variations in tree and woodlot cover across the regions, and in order to achieve sustainable production of fuelwood, the programmes aiming at sustainable supply of energy will be more likely to succeed if they account for differences between regions, and are adapted to local conditions. On a more technical level, given the current situation, efforts must be made to promote improved tree species, improved tree and woodlot management, the extended planting of trees and woodlots on farms in ways that sustainably increases both crop and wood yields on small farms, while at the same time considering alternative sources of energy and using improved wood burning stoves to allow efficient use of the agricultural land for further development.

Chapter 7 General Discussion and Synthesis

7.1 Introduction

Developing countries often strongly rely on woodfuel as the major source of energy for cooking and heating. In Africa, 90 % of the total wood removal from the entire continent consists of fuelwood (FAO 2011), and in Sub-Saharan Africa, 90 % of the households use fuelwood for cooking (Maiangwa 2010). Many studies argue that agroforestry supplies large amounts of woodfuel and thus contributes to reducing deforestation (e.g. Francez and Rosa 2011; Kilpatrick 2011; Rahman et al. 2012). This is also true for developing countries, such as Rwanda, where the majority of the population relies on subsistence agriculture on small farms and where the forest resource per capita is small.

In Rwanda, different forms of agroforestry have been promoted in order to increase the national forest cover, which would result in more economic and ecological benefits for the entire country. However, many studies report a persisting scarcity and over-exploitation of natural resources and environmental degradation (e.g. Hategeka 1997b; Gasana 1997; MINITERE 2003), and agroforestry may also compete with the corresponding crops for scarce resources such as water and nutrients. Reports by the forest department indicate that the existing forest resources in Rwanda fail to counterbalance the demand and supply of wood, including fuelwood. Since scattered trees and woodlots are also present on agricultural land, there is need to understand their role in meeting the fuelwood needs by the households.

This thesis, therefore, seeks to analyse fuelwood supply and demand in Rwanda based on the needs for fuelwood of rural households and the availability of fuelwood from woodlots and trees on farms. It uses household socio-economic surveys to assess why and when farmers are planting trees and woodlots on farms. It uses also farm woody biomass inventories to quantify woody biomass on agricultural land and biomass for fuelwood in different regions of Rwanda. In so doing, the thesis addresses the research questions set out in the first chapter.

7.2 Forests and agroforestry in Rwanda: their impact on the balance between supply and demand of fuelwood

In Rwanda, many households face fuelwood shortages, and the gap between supply and demand of fuelwood is reported to increase each year (Murererehe 2000, MINIFOM 2010). This has significant consequences for Rwanda forests and agroforestry systems as more supplies from them would reduce this gap. The analysis of fuelwood demand and supply indicated that agroforestry systems were able to meet a large part of the demand for fuelwood (Chapter 2). In many national energy studies (e.g. MINAGRI 1983, MINITRAPE 1992, Murererehe 2000, GTZ and MARGE 2008), trees and woodlots on farms are not included in the estimation of the energy balance in the country, which results in the underestimation of the biomass for fuelwood and overestimation of the effect of fuelwood consumption on the sustainability of forests, and neglect of the importance of trees in agroforestry systems for fuelwood supply. Our review (Chapter 2) revealed flaws in the methodologies and sampling designs adopted by foresters and fuelwood researchers, with the implication that some of the data of fuelwood consumption and forest stock may be inaccurate. These flaws include the consideration that all wood consumed comes from forests only, and the estimation of the gap between wood consumption and forest stocks based of population figures only. The estimation of the balance between demand and supply of wood is biased since it is based on the assumption that fuelwood is harvested from forests to meet energy demand in an unsustainable way, leading to deforestation. But by now, ample evidence exists to prove that this assumption is false(e.g. Pandey 2002). The indications are that major causes of deforestation include the conversion of forest to agricultural land and settlement sites (Chapter 2), rather than overexploitation from fuelwood harvesting. Other conditions relevant to wood supply from forests are changing; sustained yields of wood or the amount of wood that can be harvested from forests without degrading them is increasing since 2002 (MINIFOM 2010) and tree plantations are being established on a large scale. The increment in existing forests together with new plantation establishment may compensate for wood removal from forests, allowing the forest system to match removal.

Under conditions of low forest cover per capita of 0.03 ha, and almost full dependence on fuelwood to supply energy for cooking, one might expect rapid deforestation and depletion of woodlots and trees on farms. However, the loss of forest area in Rwanda over the past four decades was not caused by fuelwood consumption but rather by changes in land use driven by other developments in society (Chapter 2).

As the problem of fuelwood scarcity becomes more severe, households may be forced into a number of coping strategies, which include, for instance, the adoption of agroforestry practices and the consumption of crop residues. Hence, the need for more surveys to assess the strategies adopted to alleviate the fuelwood problem in Rwanda. Such research should also identify other problems the households face, so that an integrated approach to the fuelwood problem can be developed.

Some forms of agroforestry, such as woodlots and scattered trees on agricultural land show high potential for fuelwood production because of their high biomass production (Chapter 6). Woodlots and multifunctional trees and shrubs on farms may produce substantial amounts of fuelwood because of their rapid growth, nitrogen fixing ability, coppicing ability, productivity rates and efficiency of nutrient use (Mead 2005; Breman and Kessler 1995). Because of these characteristics, we concluded that agroforestry may contribute significantly to reducing fuelwood shortage among agricultural households, without heavy reliance on forests. The extent to which this can be achieved depends on the tree species and provenances used, the biomass production rates, the management practices (e.g. lopping, cutting) and on the farming systems that may or may not enable the production of fuelwood without compromising crop yields.

Also within the Rwanda forest sector, there are a number of opportunities that may contribute to the provision of fuelwood on sustainable basis. Activities such as afforestation of degraded hill tops, riparian areas along roads and rivers, around lakes and marshlands might contribute to environment protection while producing fuelwood. These areas account for about 215,000 ha (CGIS-NUR and MINITERE 2008). These areas are currently not covered with trees probably due to limited financial resources for afforestation and reforestation activities, and lack of adapted tree species to highly eroded, rocky and degraded sites. Efforts to address fuelwood shortage and environmental degradation may involve an evaluation of the current status of potential sites for expanding forest plantation area in consideration of ecological aspects, tree species suitability to different sites and availability of financial resources to implement afforestation and tree planting projects in the country. In this way, Rwanda may gain long-term economic, environmental and social benefits from an expanded forest cover. Afforestation of marginal areas would provide an additional tree cover of up to 10 %. There are also opportunities for increased fuelwood supply through improving the productivity of existing forest plantations and woodlots which is now as low as 6 - 10 m^3 ha^{-1} $year^{-1}$ (ISAR and MINITERE 2008; Drigo and Nzabanita 2011). In addition, sustainable harvesting of existing forests and woodlots might provide a continuous supply of wood products. In the most extreme case, unproductive forests and woodlots may be clear-felled and replanted with short rotation tree species suitable for fuelwood.

7.3 Importance of the household characteristics on the choice of fuelwood sources

In rural areas of Rwanda, there are three different fuelwood sources: forests, farms, and markets (Chapter 3). I examined the influence of demographic, socioeconomic and location variables on the probability of choosing amongst these sources, and particularly determined the conditions of choosing between these fuelwood sources. Chapter 3 provided a framework for the choice of fuelwood source and the impact of fuelwood collection from farms and forests on the sustainability of the resource.

The multinomial logit model indicated that an increase in farm size increased the probability of household fuelwood collection from farm (Chapter 3, Table 4). This implies that larger farms are able to meet their fuelwood demands from agroforestry practices. The positive relationship between farm size and the propensity of household choice of fuelwood collection from farms is reported in many studies (e.g. Cooke et al. 2008; Damte and Koch 2011). Socio-economic circumstances, therefore, influence the choice of fuelwood sources. Since such socio-economic circumstances of households are changing over time, a fuelwood supply and demand model must allow household fuelwood choice to respond to changing circumstances over time. For instance, if the rural households are constrained by land shortage and insufficient income, they may choose to collect fuelwood from forests as the only means to meet their fuelwood demands. Similarly, high fuelwood collection efforts in the face of labour constraints in the livelihood activities could drive many farmers to resort to market purchase of fuelwood. Unfortunately, the majority of the Rwandan population is poor (i.e. about 60 % earn less than US$1 per day), hence cannot afford to pay for market fuelwood. This explains partly the low choice of markets as viable option to large families since they will need to buy large amount of fuelwood frequently and at high costs. Markets for fuelwood are common in Rwanda and constitute a significant motive for farmers to take up farm forestry (Chapters 4&5). Fuelwood production by large farm owners, therefore, can be an important source of income in rural areas if fuelwood markets are well organised, and cost of fuelwood is affordable for smallholder farmers.

The household fuelwood choice model predicted many households collecting fuelwood from farms (Chapter 3, Table 3-6). This result can be considered as one of the inputs for evaluating the impact of land ownership on farmers' decision around fuelwood and the implication of this on rural energy problems and agroforestry practices and conservation of forests. Rwandan farmers have already adopted the planting of trees and woodlots on their farms (Chapter 4 & 5) to varying degrees in different regions. The practice of fuelwood production on farms, whilst not an easy solution, offers a perspective for the conservation of forests.

Many studies indicate that an increase in household size is inversely correlated with the total amount of fuelwood consumed in the household (e.g. Abebaw 2007; Gupta et al. 2009) and the probability of choosing a fuel (Rao and Reddy 2007), but its effect on the probability of choosing between two or more fuel sources is not clear. In our study, the household size was positively associated with the probability that the households buy fuelwood from markets. As the number of members in a household increases, fuelwood demand increases, and is partly met by market purchase (Chapter 3, Table 4). Larger households are more likely to have extra income (for example children's income) that can be used to buy fuelwood from markets and thus save time and energy spent in collecting fuelwood from alternatives sources. Since the total amount of fuelwood demands by larger households is large, consumption of fuelwood from farms may decrease tree cover , leading to land degradation and reduced crop yield. The fuelwood market enables larger rural households to cope with these problems.

Some studies argue that smaller households collect fuelwood from forests and agroforestry in a more sustainable way (Akther 2010). Our study suggests that sustainable management of forests and agroforestry systems may also be achieved through larger household choice of buying fuelwood from markets rather than relying singly on fuelwood collected from farms. Fuelwood markets, therefore, may enhance the sustainability of agroforestry systems, but in this case fuelwood must be sold at affordable prices and produced from sustainable sources as well.

Our study aimed to establish whether household location in any of the three altitude regions (lowland, midland and highland) did influence the choice of fuelwood. It appears that households in low and medium forest cover areas depend more on forests for fuelwood collection than their counterparts in the high altitude region (Chapter 3, Tables 3-4). In the high altitude regions, forest resources are more abundant and more evenly distributed throughout the landscape, which results in short distances between fuelwood collector households and the forests. Contrary to expectation, highland households depend less on forests and meet their fuelwood demands more by collecting fuelwood from their farms(Chapter 3, Table 3-4), suggesting that proximity of forests in the immediate surroundings of the households, although not examined in this study, may not determine household fuelwood collection from forests. The results reported in this thesis support partly findings of other studies (e.g. Heltberg et al. 2000; Cooke et al. 2008, Dampte and Koch 2011) that find fuelwood substitution between forests and farms when market fuelwood becomes expensive. However, the substitution effect is not supported by this thesis when forests become inaccessible. The reforestation programmes in the past few years in the high altitude regions of Rwanda could have resulted into the beneficial management practices of farm forestry and increased awareness of the economic, social and environmental implications of agroforestry and forest management in the region. As such any policy to expand area under agroforestry will have reduced the propensity for fuelwood collection from forests, possibly leading to reduced pressure on forests, when household prefer to collect fuelwood from their own farms.

Other factors affecting the decision to choose a fuelwood source included gender, source of income and monthly income. Female-headed households chose to collect fuelwood from forests while male-headed households chose farms (Chapter 3, Tables 3&4). This is in contrast with anticipation that women headed households would be growing fuelwood trees on their farms in order to reduce their burden in fuelwood collection from distant forests. Perhaps, this may be due to the fact that even if the women are strongly concerned with energy for cooking meals, the need for producing more food for their families would deter them from planting fuelwood trees in favour of other crops including fruit trees as found in many studies (e.g. Den Biggelaar 1996; Mekonnen 1999, Buyinza and Ntakimanye 2008; Deressa et al. 2009; Kideghesho and Msuya 2010). Women-headed households tend therefore to produce more fruit trees on their farms than male-headed households, and consequently they are unlikely to collect fuelwood from their farms but will rely fuelwood from forests instead.

Though male-headed households plant trees and woodlots on farms more than female headed households (Shackleton et al. 2008), there is a need to understand the role of fuelwood in the livelihood strategies of men versus women. The decision of female-headed households to collect fuelwood from forests may be driven by the need to meet the household needs, while the decision of male-headed households to choose farm fuelwood may focus on economic benefits. Meeting the two contrasting demands for fuelwood require different solutions that affect for instance the issues of land use and management, access to resources, the development of agroforestry and woodlots, and short term solutions to the problem of fuelwood shortage until trees and woodlots on farms reach maturity.

The literature on household fuel choice suggests that income is responsible for increased choice of modern fuels such as electricity and gas (e.g. Gupta and Köhlin 2006; Farsi and Filippini 2007). Our results indicate that in rural areas, increased monthly income led the households to move away from collecting fuelwood from forests. This provides evidence that income in subsistence households is an important determinant of the choice of fuelwood between forests and alternatives sources. Farms and markets are the only sources of fuelwood at least for 40 % of the Rwandan population above the poverty line.

In this study, source of income had a positive effect on household choice of fuelwood from markets, in support of the expectation that if households, especially in rural areas, are predominantly dependent on subsistence farming they are less likely to use market fuelwood than their counterparts who have off-farm jobs. Off-farm income has a negative effect on the choice of fuelwood from farms and forests, in support of the expectation that households committed to income generating activities are more likely to use fuelwood alternatives, that is market fuelwood. Households associated with commercial farms, however, can derive higher income from farming activities (Asogwa et al. 2012; Poczta et al. 2012), thus enhancing their ability to purchase goods from markets, including fuelwood. In this context, government policies towards food security and energy issues in rural Rwanda may focus on promoting commercial farming, diversifying sources of income, organising and developing fuelwood markets, and accelerating the economic growth especially of poor households in rural areas. Incentives on tree planting on farms among smallholders may also be envisaged since the agricultural land becomes an important fuelwood source to farming households.

7.4 Factors affecting the presence of trees and woodlots on farms

Trees and woodlots are prominent features in many landscapes worldwide. Their ecological, social and economic importance is obvious and has been widely documented (e.g. Manning et al. 2006; Liagre 2009; Ashton et al. 2011). In Rwanda, the drivers and purposes for planting trees and woodlots on farms are still poorly defined and understood by policy makers and extension staff. Thus, in chapter 4 and 5 of this dissertation, we examined household determinants of the likelihood of planting trees and woodlots on farms under different socioeconomic and location attributes. The next sections discuss the relationships between such characteristics and the likelihood of planting trees on farms or not on one hand, and the likelihood of growing farm woodlots or not on the other hand.

Purpose and determinants of maintaining trees on farms

In the results reported here, multiple economic benefits including fuelwood, timber, food and income were the most important reasons for planting trees on farms (Chapter 4, Table 6). This finding supports the notion that farmers rarely grow trees on farms for the single purpose of supplying fuelwood (e.g. Den Biggelaar 1996; Jama et al. 2008). We found that rural households integrated fruit trees in farming systems, suggesting their interests in diversifying the sources of subsistence and income for their livelihoods. This result is in agreement with that of Bucagu et al. (2012) that fruit trees are commonly grown by farmers in subsistence farming systems in Rwanda. Given the economic interests in trees, the benefits from tree planting on farms appears to be as important as those from agricultural crops with which the trees compete for resources. We found evidence that the supply of fuelwood was one of the most important purposes underlying the presence of a diversity of tree species (Chapter 4, Table 6). In view of substantiating this observation, this thesis shows that 37 to 82 % of the total woody biomass on farm was biomass for fuelwood (Chapter 6).

Table 7-1 shows how and what factors enhance the likelihood of planting trees in the low, medium and high altitude regions and across the three regions of Rwanda. I expected that different sets of factors influenced farmer’s decision to keep trees on farms because of differences in socio-economic status and ecological conditions. In general, the findings revealed a consistent effect on the presence of trees, although the same factor did not necessarily affect the decision of keeping trees in all the three regions in the same way. For instance, the influence of the amounts of farm fuelwood use on the presence of trees was common for two regions (Table 7-1).

Table 7-1 Effects of socio-economic factors on the likelihood of planting trees on farms in the low, medium and high altitude regions and across the three regions

Variables	Altitude regions Low	Medium	High	Across regions
Amount of farm fuelwood use	-		-	-
Gender of head of the households				-
Location of the households in LAR				+
Location of the households in MAR				+
Monthly expenditure on firewood			+	
Monthly expenses	-			
Monthly frequency of firewood collection			+	
Number of adults members in the household	+			
Number of household members in informal employment				+
Number of meals per day				+
Presence of woodlot	+			
Season in which much fuelwood is used			+	
Selling of tree products	+			+

"+" denotes significant positive effects ($p < 0.05$); "-" denotes significant negative effects ($p < 0.05$); blank means the variable is irrelevant

In addition, some factors that influenced the choice of keeping trees at regional level such as the number of adult persons in the households and the household monthly expenses on fuelwood were irrelevant for the household's decision to keep farm trees on national basis. However, location of the household, number of household members in informal employment, selling of tree products on markets and number of meals per day were positively correlated with the presence of trees on farms.

The results indicated that the amount of farm fuelwood use had a significant and consistently negative influence on the likelihood of presence of trees on farms in all the three altitude regions. This implies that collection of farm fuelwood for domestic consumption reduces tree stock on farms if replanting is not done or sufficient fuelwood production on farms is secured. Considering the multiple benefits of farm trees to farmers, tree planting is done also on small farms where agricultural crops are produced. Fuelwood trees may be present at lower density compared to other tree species such as those enhancing soil fertility and soil conservation, suggesting that the potential for fuelwood production is constrained by the need to produce food crops. The extent at which this amount of fuelwood can meet fuelwood demand depends upon other household demographic and socio-economic characteristics including number of adult persons in household, and ownership of a woodlot.

The effect of gender of the head of the household is interesting because it reflects the gender role in tree planting. Female heads of households are likely to plant trees on farms more than men, reflecting the increasing role of women in tree planting for fuel and food production, contrary to the customary belief that women plant fewer trees than men. In male-headed households, women are active in agricultural production and contribute 40-80 % of agricultural farm labour (Randolph and Sanders 1992). Thus, women are responsible for planting and managing trees more than their husbands.. The diversity of tree species on small farms, characterised by the presence of trees for food and income among the dominant tree species (Chapter 6) arise from the preferences of women since they are customary responsible for food production (Den Biggelaar 1996; Mekonnen 1999). In many circumstances, the production of fruit is the main motive behind tree planting on farms by women. Hence, female-headed households are likely to plant trees producing food and generating income more than their male counterparts.

Consistent with expectation, a rise in household monthly expenditure is correlated negatively with the likelihood of maintaining trees on farms particularly in the low altitude region. The ability of the household to purchase goods from markets depends on its income; the levels of expenses determine opportunities of the households for spending on market fuelwood. The relationship between the levels of monthly expenses and the propensity to keep trees on farms points out that market fuelwood is expensive since only higher income category of households are able to purchase fuelwood instead of keeping trees for fuelwood production. The low altitude region has a low forest cover and a low farm tree cover (Chapter 6), implying different strategies in the household supply of wood products. It is recognised that even when fuelwood is in short supply, farmers rarely grow trees for fuel (Dewees 1995), except perhaps where there are markets for it (Dewees and Saxena 1995). Since the levels of household expenses rise with decreased likelihood of maintaining trees on farm in the lowland region, a large proportion of the lowland farmers collect fuelwood from forests. With increasing fuelwood shortage, rural households may reach a point at which the labour cost of collecting fuelwood outweighs the monetary cost of purchasing it. In this way, as argued by Benjaminsen (1996) and Vermeulen et al. (2000), the proportion of rural households using purchased fuelwood may increase. Concomitantly, fuelwood producer households are likely to increase since the fuelwood market makes a contribution to rural livelihoods. The planting of trees on farms may therefore be enhanced by a well organised fuelwood market.

Determinants of the household choice to own farm woodlots

The decision of rural households to maintain woodlots on their farms is apparently a simple one, at least in terms of economic benefits from trees. *Eucalyptus spp.* and *Grevillea robusta* were the most common tree species grown in woodlots in order to produce mainly fuelwood and building poles, and to a lesser extent generate income and produce timber (Chapter 5, Table 4). Many studies (e.g. Erickson et al. 2002; Wiersum et al. 2005) suggest that ecological and environmental benefits are becoming increasingly important motives for growing woodlots. These purposes are relevant when and where the household needs in economic benefits from trees are met and alternatives to fuelwood are widely available. This study indicated that environmental protection was of little concern to many households in Rwanda (Chap 5, Table 4). Trees on farms are private goods with positive externalities for the environment, for which farmers are not compensated. This is likely to be so in developing countries such as Burkina Faso, Ethiopia and India where fuelwood shortage prevails, and trees on farms are important for fuelwood supply.

The household choice to keep farm woodlots was influenced by the interacting household socio-economic characteristics and attitudes toward fuelwood supply. These factors varied in their effects on the presence of woodlots in the three altitude regions. This suggested that these factors were region-specific and could not be generalised to explain the presence of woodlots in all regions. The specific models developed depend on the altitude region where the data were collected, and therefore should not be applied to areas outside the range of data. However, the modelling approach is of general applicability and can be used to predict the presence of woodlots in other areas as well.

In general, the presence of farm woodlots was predictable among the households with large farms, located in regions with medium forest cover, where the household heads were older, where many household members were employed, and where the households were located away from the fuelwood sources. Households that depended on purchased wood for fuel, in location with low tree cover, and that were keeping livestock, were unlikely to take the decision to keep woodlots. This situation is expected to prevail, except if there is a change that involves for instance rotational woodlot and silvopastoral technologies in the agricultural production systems. So far growing woodlots is done as an alternative crop for degraded parts of the farms, instead of being part of a land use intensification strategy. For example, silvopastoral practices could be an option for wood production and livestock grazing in well managed woodlots. Also, the growing of woodlots on farms in rotation with crops could be attractive when the woodlots have shorter production cycles and when farmers have interest in income from the selling of fuelwood. The planting of woodlots on farms, therefore, requires careful trade-offs between food and wood production. Woodlots can be planted on farmlands, when and where the profitability of wood production is higher than the production of crops. However, profitable woodlots require large area planting ranging from 0.25 to 2.0 ha (GTZ and MARGE 2008). Considering that average farm size in Rwanda is 0.76 ha, farms with average or above the national average size could be profitable and sustainable in fuelwood production. Households with such small size woodlots can maximise their income by selling wood on local markets. The income derived from the selling of wood products (including fuelwood) may be used to buy a variety of food for household consumption. The results of the thesis showed that about 70 % of the households had trees on their farms and 40 % of the households planted woodlots (Chapter 3). With the exception of woodlot farming, farm size had no effect on the presence of trees on farms, suggesting that trees were available on all farm size categories. As a result, scattered trees were more common than woodlots among the rural households. This result complies with the finding by Bertomeu (2012) that widely spaced trees on farms are more profitable and feasible to smallholders than woodlots. To further enhance the profitability and feasibility from the association of trees with crops, the competition between trees and crops on small farms has to be managed in a win-win oriented incentive strategy through the planting of optimum number of trees of selected trees species, improved crop varieties, fertilization, and improved tree management practices.

7.5 The relevance of trees and woodlots on farms to fuelwood production

Scattered trees on farms are an integral part of the agricultural production system, providing mainly products such as firewood, fruit and timber. At farm level and across the three altitude regions, scattered trees were present in low densities (20 - 167 trees ha^{-1}), included trees of a wide range of sizes distributed among many tree genera (29 - 40 per altitude region, 56 in total), and were dominated by a subset of common species that were important timber, fruit or fuelwood species (Chapter 6, Table 7). In general, according to the inventory of 457farms on which trees were present, the average standing aboveground tree biomass averaged 6 t ha^{-1} of which 4 t ha^{-1} was the present usable amount as fuelwood. At the landscape level, these estimates reduced steadily because of the presence of many landscape elements including houses, roads, lakes and bare lands that result in fewer trees per hectare. The number of scattered trees in the three landscapes ranged from 6 to 9 trees ha^{-1} and produced 1 to 3 t ha^{-1} of aboveground woody biomass.

Woodlots are also an important feature of the fabric of the agricultural landscape. The dominant woodlot species was *Eucalyptus* and occurred as a single species in 91 % of the woodlots surveyed. Indeed in the farming systems of Rwanda, Eucalyptus planting is preferred as an alternative crop for low productivity land on which eucalyptus are the most adapted and profitable crop (Burren 1995; Clement et al. 1995). Many Eucalyptus species have a high coppicing ability, which increases the stock density and profitability per unit area (Bagchi and Mittal 1996; Babitha et al. 2000; Turnbull 2000; Little and Gardner 2003). This evidence is supported by this thesis. The size of the farm woodlot was very small (0.32 ha) but the tree density was high, ranging from about 1700 to more than 2000 trees ha^{-1}. The high stocking density was caused by the management of *Eucalyptus spp.* into coppices by the woodlot owners. Many rural households in Rwanda depend on eucalyptus planting for the production of fuelwood and construction poles. Among many benefits to farmers, eucalyptus woodlots are sources of additional income from the selling of poles, fuelwood and charcoal. Being planted on infertile parts of the farms (Chapter 3), Eucalyptus species are tolerant to low soil fertility where they produce abundant stems per unit area (Chapter 6) because of their high coppicing ability. These comparative advantages of the species over many existing exotic species such as *Grevillea robusta* and many indigenous species (e.g. *Markhamia platycalyx, Podocarpus falcatus, Maesopsis eminii*) made it the dominant species of all Rwandan landscapes and part of the rural livelihood. However, eucalyptus woodlots have come under criticism by policy makers and environmentalists due to the assumption that eucalyptus consume a lot of water and deplete soil nutrients compared to other tree species in the country. There are many research results however (e.g. Nshubemuki 1988; Davidson 1995; El-Amin et al. 2001; Nduwamungu et al. 2007), which reveal that eucalyptus species are efficient water and nutrient users. Evidently, as fast growing species, it seems logical that eucalyptus species consume more water and nutrients from the soil, which translates into higher biomass production (Davidson 1989) compared to other tree species such as *Grevillea robusta* and *Pinus spp.*. What matters is the economic return against the biomass produced per unit of water consumed and the management practices put in place to replenish the nutrient balance of the soil. As an example, the soil nutrient levels under eucalyptus woodlots may be improved by adjusting spacing and introducing leguminous planting. Where water is scarce, water use by eucalyptus might be reduced by planting fewer trees per unit area or by thinning.

Since eucalyptus woodlots in Rwanda are growing under different ecological conditions and management practices by owner households, their biomass production is highly variable among sites. For instance, the estimated standing wood volume in woodlot ranged from 210 ± 76 m^3 ha^{-1} in the low altitude region to about 460 ± 80 m^3 ha^{-1} in the high altitude region. The standing wood volume is very high partly due the presence of many stems in small coppice stands of 0.32 ha on average, resulting in sometimes rather dense stands, possibly leading to overestimation due to border effects. High stocking densities enhance competition for moisture and nutrients between individual trees, which result in slow growth rates, long rotations and small diameter trees. A thinning programme may be effective, to remove the less vigorous and deformed stems in order to minimise competition and concentrate growth on better stems selected for timber production.

The aboveground woody biomass varied in the same order as the standing wood volume in woodlots, from about 100 t ha^{-1} in lowland woodlots to more than twice this value in midland and highland woodlots. The present fuelwood availability in farm woodlots was higher than that of scattered trees: 65 - 85% of the present total standing biomass could be used for fuelwood in each altitude region. Across the three landscapes, wooded lands represented 23 % of the total land area, of which the share of forests (> 0.5 ha) and small woodlots (<0.5 ha) were 21 % and 2 %, respectively.

This thesis showed that the total aboveground biomass was higher in woodlots (8×10^6 t dry weight) than in scattered trees (1×10^6 t dry weight). Based on the recent forest inventory data in Rwanda, the total standing woody biomass on agricultural land was about twice that in forest plantations (> 0.5 ha). Converted to units of carbon (carbon = 0.5 x biomass dry weight), carbon accumulation in aboveground woody biomass on agricultural land averages 0.9 t C ha^{-1} in scattered trees and 92 t C ha^{-1} in farm woodlots (<0.5 ha). Biomass density in forests is reported to be on average 75 t C ha^{-1} (Saatchi et al. 2011), which is somewhat lower than our value found for farm woodlots.

Nevertheless, the values for carbon density reported here for trees and woodlots on agricultural land are probably underestimates since belowground carbon accumulation is not accounted for. They are based only on aboveground woody biomass, and trees and woodlots on agricultural land are likely to accumulate additional carbon in belowground parts. Since farm woodlots compete for land with agricultural crops, strategies that consider the complementarities between wood production and crop production might be more successful in determining the accumulation of carbon than biomass ha^{-1} alone. The additional food production, wood products and income from trees on small farms may result in farmer choice to increase carbon stock on farms by adopting some forms of agroforestry such as boundary planting and planting of dispersed trees on farmland.

The woody biomass on farms for fuelwood was generally important and accounted for about 50 % of the estimated amount of fuelwood consumed in Rwanda. However, there were regional variations in biomass production, suggesting that wood deficit might not be felt equally across the country. From a landscape perspective this is important for increasing tree and woodlot cover. The higher standing woody biomass in some regions reflects higher potential for fuelwood and carbon accumulation in the aboveground components of trees and woodlots.

It is worth mentioning that, at farm level, scattered trees were present in low densities, with many tree species being represented by less than 10 % of the total number of individual trees present (Chapter 6, Table 7). Consequently, harvesting a few of these trees for fuelwood is expected to reduce farm tree stock and diversity. In addition, in all of the three altitude regions, there were indigenous trees which are likely to disappear over the next few years following continued exploitation for fuelwood use. Whereas many exotic tree species may be propagated on farms, some of the indigenous tree species such as *Markhamia spp., Ficus spp.*, and *Vernonia amygdalina* are likely to be lost since they are already reported to be rare (Gapusi and Mugunga 1998). The conservation of indigenous trees and the diversification of exotic trees on farms are likely to have economic benefits to farm owners and to provide ecological benefits on landscape level such as the contribution to biodiversity conservation and climate change mitigation. This opens up possibilities for linking incentives including carbon credits to conservation and sustainable use of trees and woodlots on agricultural land.

In the long run, the failure to increase the agroforestry cover may have significant negative impacts both on farm productivity, farm biodiversity and environmental protection. For example, the reduction in tree density and overall tree cover could reduce the availability of fuelwood, building poles and timber for farmer use, and also reduce the service functions of the trees for reducing soil erosion particularly in the high altitude region where soil losses and landslides occur (MINIFOM 2010). In the low altitude region, the decline in agroforestry cover could lead to increased pressure on the remaining savannah woodlands and gallery forests which are already threatened.

We found that the abundance and biomass of scattered trees and woodlots on farms differed significantly between the three regions (Chapter 6). This implied that the extent of farmer involvement in tree planting varied both in terms of the number of farms with trees, the area planted, the number of trees per farm, and sizes of trees. Trees and woodlots on farms, if at sufficient density and high productivity rates, can provide products and services to farmers while enhancing connectivity in agriculture landscapes (Schroth et al. 2004; León and Harvey 2006; Jose 2009). Without recognition of the value of scattered trees and woodlots on farms, and the risks associated with unsustainable exploitation for fuelwood, the ability of the agricultural landscapes to conserve biodiversity and provide ecosystem services in the long term could be reduced.

7.6 Scenarios and projections of farm fuelwood supply and consumption

On the basis of the data on woody biomass and biomass for fuelwood on farms (Chapter 6), it is now possible to make fuelwood supply scenarios and projections under different sets of assumptions. It can be expected that woody biomass increases with increased tree planting, which results in increased production of fuelwood and a smaller gap between fuelwood demand and supply. Increasing the proportions of land under trees and woodlots cover may result in increased woody biomass production given different productivity rates of trees and woodlots on farms. Unfortunately, accurate productivity data of farm trees and woodlots in Rwanda are not available. Since trees on farms are not cultivated for the sole purpose of providing wood, but are supplying fodder, green manure, and small woody materials for staking climbing beans (Chapters 3&4), productivity may be lower.

In order to relate on-farm woody biomass to national fuelwood use, the following detailed assumptions were made:

(i) Land under agroforestry is expanded from the current 36 % to 85 % of the agricultural lands to match the government policy target in its vision 2020. Each year, the area under trees is increased by about 4 %;

(ii) Tree productivity per unit of land under agroforestry is set to increase from 1.5 m^3 ha^{-1} $year^{-1}$ (Samyn 1993) to 9.5 m^3 ha^{-1} $year^{-1}$, identical to forest plantation productivity (Drigo and Nzabanita (2011). This productivity is assumed to increase by 0.7 m^3 ha^{-1} $year^{-1}$;

(iii) The productivity of woodlots is raised from the mean annual increments of 7.8 - 14 m^3 ha^{-1} $year^{-1}$(Drigo and Nzabanita 2011) to 15 m^3 ha^{-1} $year^{-1}$; the later should be easily achievable if trees are of high genetic quality, properly site matched and well managed. In addition, woodlot cover is assumed to increase from the present 2.5 % to 5 % of total agricultural land;

(iv) The proportions of biomass for fuelwood to the total on-farm woody biomass in trees and woodlots on farms as found by the research reported in this thesis (Chapter 6) remain unchanged over the projected period from 2008 to 2020;

(v) Fuelwood consumption is derived from the population projections (NISR 2009) and assuming that the annual fuelwood consumption per capita is 484 kg (Hategeka 1997a), corresponding to 0.67 m^3 per capita (Chapter 2). Considering that biomass energy is expected to decrease from 90 % to about 50 % following the use of alternative sources of energy and improved cooking devices (GTZ and MARGE 2009b), a 2 % reduction of fuelwood consumption was applied to the annual theoretical consumption of fuelwood.

Given the assumptions above, between 2008 and 2020, total standing wood volume in woodlots remain higher than in scattered trees even though the land area under agroforestry is expanded from 0.7 million ha to 1.5 million ha at national level(Fig. 7-1). This results mainly from higher volume production per unit area of woodlot. Planting of trees on agricultural land planting is possible over a large area, but only part of this can be planted due to the presence of permanent crops other than trees such as coffee and tea. In addition, trees scattered on agricultural land in wide spacing reduces competition between trees and crops. Under these conditions, it is likely that maintaining a high level of wood production on farms may interfere with crop production. Nevertheless, producing more woody biomass on agricultural land is achievable if high quality silvicultural and management practices are practiced to achieve high timber yields on a small area. Considering this, the data in Fig. 7.1 should be interpreted with caution.

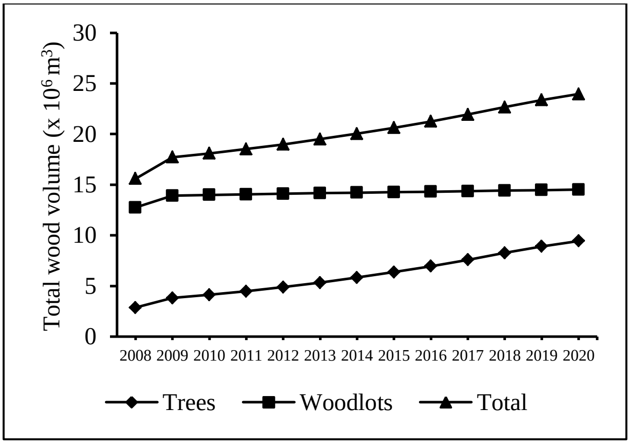


Fig. 7-1 Forecast of standing wood volume for fuelwood in trees and woodlots on agricultural land of Rwanda between 2008 and 2020

From Figure 7-2, where the projections of fuelwood production, fuelwood consumption, and fuelwood balancee are given for the base year 2008 to 2020, the supply of fuelwood from agricultural land increases, which results in reducing the gap between supply and consumption of fuelwood toward achieving a balance toward 2016 and to producing a surplus thereafter. Under the present assumptions, there are fuelwood shortage that are probably met by fuelwood collections from forests, other wooded lands and the use of crop residues. The policy target of expanding agroforestry to 85 % of the agricultural land by 2020 is likely to contribute more to reducing the gap between the supply and consumption of fuelwood and reducing the dependence of farmers to forests. In order to achieve this, however, it could be necessary to reduce consumption of fuelwood by promoting use of improved cooking devices and increase the productivity of trees and woodlots in agroforestry systems. By so doing, no fuelwood shortage could be predicted and a large part of the fuelwood consumption could come from woodlots and trees on the farms.

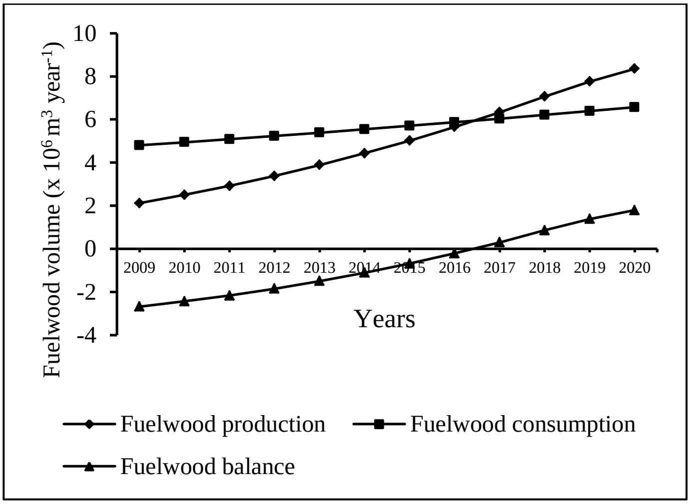


Fig.7-2 Forecast of fuelwood demand and fuelwood supply from agricultural land of Rwanda between 2009 and 2020. Fuelwood supply from agricultural land includes both fuelwood from trees and woodlots. It is achieved by increasing the productivity of trees up to 10 m^{3}ha^{-1}year and that of woodlots up to 15 m^3 ha^{-1}year^{-1}, by expanding woodlot area from 44,800 ha to 92,500 ha and by increasing the area under agroforestry from 0.7 million ha to 1.5 million ha. Fuelwood consumption is calculated based on population size, per capita fuelwood consumption and assuming 2% reduction of fuelwood consumption following use of alternative sources of energy for cooking and use of improved cooking stoves. Fuelwood balance is the difference between fuelwood consumption and fuelwood production on agricultural land.

Since this thesis showed regional variations in fuelwood collection choices by rural households (Chapter 3), the imbalance between fuelwood supply from farms and consumption by farmers will differ between regions. To obtain a balance between consumption and production, it is important to consider the prospects for growing more trees and woodlots as well as improving their productivity rates. Nevertheless, there are factors that weigh against this strategy, viewed from the perspective of fuelwood and crop production. Even though farmers may realise that planting trees present a possible remedy to their fuelwood problems, they may consider that the time taken for trees to yield woody biomass is too long, and they may consider the competition with the agricultural crops, for land area and water and nutrient resources. In such a case they may look for a substitute fuel or, if their problems are not pressing, then they may defer taking any action until it is more necessary.

It is uncertain whether the creation of new woodlots and the expansion of tree planting in the agricultural lands are economically viable and sustainable, considering the competition between crop and wood production, especially on small farms. Farms in Rwanda are small, few farmers are as large as 1 ha, and in many areas farm sizes are considerably smaller. Woodlots require land, and since farms are so small, it is important to estimate how much land is required for households to satisfy their own fuelwood requirements. The minimum area required for fuelwood self-sufficiency depend on fuelwood demands, productivity (or mean annual increments) of the trees and tree spacing. Evidently, land area required for fuelwood self-sufficiency by means of woodlots will be relatively large, within the range of 0.06 to 5.20 ha (GTZ and MARGE 2008). For many farmers in Rwanda, even 0.06 ha would constitute a large proportion of land to be taken out of arable land for crop production. Since in some regions, areas of public land exist which are unsuitable for cropping (e.g. degraded areas, rocky hill sides, etc.) and if these were owned by individual farmers, then possibly woodlots of a sufficient size for self-sufficiency could be planted. Whilst such a strategy may assist a number of farmers, it is unlikely that it will have an impact for the majority of farmers in the most densely populated areas of the country, such as in the Northern Province where the density is 528 persons km^{-2} (NISR 2012b). Thus, the problem of small farm size for fuelwood supply can only be overcome if types of agroforestry, other than woodlots, are adopted. About seven different types of agroforestry including scattered trees on farms, woodlots, and alley cropping are potentially fit for wood production and, possibly, also increased yield of crops (Chapter 2). There are, therefore, a number of alternatives to woodlots and if these can be successfully developed then the small size of farms may not be as serious an obstacle as it first appears. However, farmers need to produce both fuelwood and crops; hence they need to enhance the performance of the system by exploiting the interactions between the trees and crops. Tree management practices such coppicing, pollarding, and pruning (roots, branches) could enhance the potential of the trees in terms of wood yields and may provide beneficial effects on crops as well. In addition, farmers need to plant improved tree species which, under improved silvicultural and management techniques, could give higher woody biomass yields and improve overall agricultural production at the same time.

7.7 Implications for management, research and policy

In the light of the fuelwood shortages and impact of fuelwood consumption on forests, there is an increasing awareness that tree-crop based production systems, such as agroforestry, have the potential to provide fuelwood on sustainable basis and to ease the pressure on forests (e.g. Vermeulen et al. 2011; Githiomi et al. 2012). Considering the low potential for expanding afforestation and the need for fuelwood, the planting of trees and woodlots on farms in the context of agroforestry, holds promise in reducing the gap between fuelwood demand and supply. However, it is uncertain whether available farm area is sufficient for planting trees and woodlots. In order to meet the fuelwood demands from farms, productivity must be improved. It is very important to get more specific data on productivity of trees and woodlots from the different agroecological areas, and more research in this field is necessary so as to confirm the initial indications presented in this thesis.

Addressing the fuelwood issues on a national basis requires the creation of a policy environment allowing for this. Fuelwood issues should also be recognized and addressed by the agricultural sector, since the majority of fuelwood originates from agricultural land, but no policies or planning for its production exist at present. As fuelwood is the major energy supplier, the energy sector needs to incorporate it and its sources into energy policies and planning. Since fuelwood demand and supply issues require the involvement of both the agricultural, energy and forestry sectors, these should engage in much closer cooperation regarding fuelwood production to ensure a balanced demand and supply situation. At present, the forestry sector is responsible for fuelwood production in forest plantations and agroforestry (farm forestry). However, the potential of farm forestry is constrained by lack of supportive regulatory framework and poor coordination of the practices prompted by lack of stand-alone agroforestry policy. Since, many agricultural and natural resources related policies and legal instruments are concerned with issues related to agroforestry, it is essential that these policies are harmonized along with carrying out lobbying and advocacy towards the formulation of agroforestry policy.

In the absence of alternative sources of energy for cooking, wood remains the only fuel used by the majority of the households in Rwanda. A number of factors influence what type of fuelwood is used by which household. In general, households with higher socio-economic status are disposed to acquire fuelwood from farms and markets over alternatives. This correlation can be manifested both in rural and urban areas of the developing countries where energy sources are not diversified and accessible.

Not all rural households, however, have enough land to ensure fuelwood supply from farms, but because of household socioeconomic status and agroecological location, farm fuelwood may not be available to all households. Policy makers and planners should be aware that small farm owners and income-poor households are the most affected by fuelwood shortage, hence must be supported in meeting their fuelwood demands through raising their income. Diversification of income sources in rural areas is one of the ways to raise the capacity of smallholders to adapt to fuelwood shortage. It can also lead to higher income and livelihood improvements, thus enhancing the ability of the smallholders to buy fuelwood from markets or to adopt modern sources of energy.

This thesis showed that markets provide important incentives to tree planting. A strengthening of fuelwood production and trade would serve to bring fuelwood into the household economy thereby increasing production and access to fuelwood. So an active fuelwood market may act as a valuable tool for any attempts to propagate sustainable agroforestry systems. The development of a well-structured fuelwood market therefore needs to be a major consideration in the planning of energy system.

Efforts to address the energy situation, must take into account substitution of fuels. This must be done along with the formulation of effective energy policies, and with the public awareness of the existing problems such as the cost of alternative fuels and the impact of the continued reliance on wood for energy on land use and environment. In addition, the extension services should be aware of the different factors affecting the choice of fuelwood sources by the households given their different socio-economic conditions and locations. Their interventions must target specific regions and different groups in the rural communities in order to identify when and where support in energy supply is required.

The prevailing land scarcity and rapidly expanding population make land a sensitive issue alongside national policies which encourage reforestation and agroforestry. The planting of trees and woodlots on farms may not be a direct result of these policies, but a result of a combination of the household socio-economic status alongside local factors. These characteristics must be explored to gain proper understanding of the determinants of household choice to plant trees and woodlots on farms. Government actions must always take place at the location where the problem of fuelwood shortage is felt most. During the process, socio-economic based planning strategies besides measures to reduce the fuelwood shortage must be implemented.

From the results presented in this thesis, it is clear that trees and woodlots are grown by farmers mostly for economic benefits. But trees and woodlots are increasingly also valued for their environmental values by national and global communities (Goldstein et al. 2012; O'Rourke and Kramm 2012). It is unlikely that rural households will plant trees and woodlots for purposes other than those of direct benefits, such as fuelwood, timber, and food. However, additional financial provisions may motivate farmers' choice of planting of trees as part of agricultural systems. Payments for environmental services by the government, including carbon finance, may possibly provide an incentive for smallholder farmers to consider environmental issues when deciding to plant trees on farms. Such payments could cover labour, inputs (seeds, fertilisers) and costs of planting and management of the trees well before longer-term benefits such fuelwood, fruits, and timber occur. Therefore, if environmental services from trees and woodlots on farms are to be enhanced, targeted policies on the part of policy makers, and education and awareness raising on the part of the extension services are necessary in order to change the current agricultural practices toward more sustainable productive and ecologically-sound systems with a stable tree component.

Different forms of agroforestry, rather than woodlots, will be easier to promote among farmers, since they may contribute to increased production of food and fuelwood while protecting the resource base. In contrast, woodlots exploited over longer rotations may be difficult to promote among the smallholder farmers, because of the long-term occupation of agricultural land. Farm woodlots, however, managed on shorter rotations (3-4 years) together with food crops, may be productive and profitable, particularly if the markets for wood products (including fuelwood) are attractive. Extension programmes should consider issues related to farm size by focusing not only on subsistence and household uses but also on options for market-oriented activities because markets of wood products and fruits are available both in rural and urban areas.

Since rural households are barred from collecting fuelwood from forests, the only alternative left to them is to intensify the planting of trees on their farms. By promoting either integration of trees with crops or woodlots on marginal areas, fuelwood supply may be enhanced. However, given the constraint of small farm size, and the competition between crops and trees, additional fuelwood supply may still be collected from the forests, albeit illegally. The findings that many rural households collect fuelwood from forests supports the needs to strengthen the enforcement of forest regulations and restrictions on forests and to promote alternative sources of energy in rural areas such as provided by agroforestry systems.

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Summary

Trees and woodlots on farms are increasingly managed in the context of agroforestry systems. They are valued for their role in meeting the people's basic needs for fuelwood, timber, fodder and other wood products. They also contribute to increased crop yields, conserve biodiversity and reduce pressure on forests through the acquisition of wood products and other resources from farms; at the same time, they compete for land and resources and may invoke loss of crop productivity. For a country like Rwanda where forest resources are small and dependence on fuelwood for cooking high, the importance of trees and woodlots on farms is large, especially for small farm households with little opportunity to buy fuelwood or charcoal from markets. Nevertheless, the current country statistics do not include woody biomass on agricultural land in the assessment of energy supplies, obscuring the fuelwood demand and supply balance and rendering it inaccurate and partly unreliable. Evidence suggests that a substantial part of the rural household demand for fuelwood is met from trees and woodlots on farms. However, the amount of fuelwood from them and the factors underlying rural household decision to own trees and woodlots on farms are largely unknown.

In this thesis, I set out to identify and analyse the factors that affect the rural household choice of fuelwood collection sources and the conditions that may enhance the decision to maintain trees and woodlots on farms. In addition, I surveyed smallholder farmers in order to provide basic data on the characteristics, quantity and existing stocks of woody biomass and biomass for fuelwood on agricultural land. The following issues were addressed: (1) What is the situation of fuelwood in Rwanda and what is the potential of forests and agroforestry systems combined, to provide fuelwood? (2) What

are the socio-economic factors and attitudes that influence the choice of fuelwood sources by smallholder farmers in the low, medium and high altitude regions of Rwanda? (3) What are the motivations and main purposes that drive smallholder farmers to keep trees and woodlots on farms in the three altitude regions? (4) What is the current status of woody biomass on farms and its potential to provide fuelwood?

In order to answer question 1, a review of fuelwood demand and supply in Rwanda was carried out by analysing the role of forests and agroforestry systems to provide fuelwood on sustainable basis. Questions 2 and 3 were investigated by analysing data obtained from socio-economic surveys of rural households in various study areas representing the low, medium and high altitude regions of Rwanda. Question 4 was addressed through survey of woody biomass at farm and landscape level in the three altitude regions. For these investigations, stratified random sampling techniques based on agroecological areas and administrative units in Rwanda were used in order to collect the primary data from 480 farms and farm owners, representing the rural households in three altitudes regions.

Rwanda is one of the developing countries where fuelwood is the main source of energy for about 90 % of the population. In Chapter 2 the demand and supply of fuelwood are reviewed. Existing studies show a continuously rising demand of fuelwood from forests, which may contribute to deforestation in Rwanda. The review indicated that forest plantations and agroforestry systems are structural sources of fuelwood. For rural household use, however, various agroforestry systems including woodlots and scattered trees play an important role in the supply of fuelwood because of the

availability of many multifunctional trees and shrubs having fuelwood characteristics such as rapid growth, coppicing ability, high productivity rates and increased efficiency of fertiliser use. The review concluded that failure to include farm woody biomass in the energy supplies has led to an overestimation of the perceived mismatch between fuelwood supply and consumption because current estimates are based on forest stock only. There is also a major uncertainty in the alleged impact of fuelwood consumption on deforestation since many other factors such as land clearing for agriculture, settlements and livestock farming contributed to the high deforestation rate reported for Rwanda. Because of small forest area and low potential for afforestation, the review concluded that fuelwood was expected to be produced on agricultural lands through use of suitable tree species and proper management to minimise competition for space, water, nutrient, and light with agricultural crops.

Given the preceding analysis, the main fuelwood collection sources available for rural households are mainly farms and forests. Another source of fuelwood identified through the household and farm surveys is markets. Different factors influence what type of fuelwood is used by different households given their own socio-economic status and biophysical environment. The main factors that distinguished the choice between fuelwood collection sources were monthly income, source of income, household size, gender of head of household and the agroecological location of the households. These factors implied the highest probability to collect fuelwood from farms since fuelwood choice model predicted about 75 % of households that obtain fuelwood from farms. In general, the households with higher socio-economic status obtain fuelwood from their farms and markets over collecting from forests.

Many studies indicate that fuelwood is a secondary product from agroforestry. Thus, the household choice to keep trees and woodlots on farms is driven by multiple objectives and the decision to maintain trees and woodlots is influenced by their socio-economic factors. Chapter 4 and 5 compared the three altitude regions in terms of the purposes and determinants of having trees and woodlots on farms and used pooled household-level data to identify the factors that generalise the implication of the results for policy and national extension programme. These results indicated that the households were commonly motivated to maintain trees and woodlots on farms for economic benefits and to a much lesser extent for environmental purpose. Scattered trees were kept mainly to meet needs in food, firewood and income. Woodlots on farms were primarily owned to produce fuelwood (48 % of woodlot owners) and building materials (43 % of woodlot owners).

The household choice to keep trees and woodlots on farms or not was influenced by different combinations of household characteristics. The statistically significant factors influencing this choice were region-specific, indicating the need to avoid generalisation at national scale. This was reflected in the pooled models having significant variables that were irrelevant for the regional models and vice versa.

At national level, the presence of trees on farms was positively correlated with the number of household members in informal employment, the number of meals per day, the selling of tree products and the household being in the low and medium altitude regions. The amount of farm fuelwood use reduced the propensity to keep trees on farms, supporting the notion that fuelwood is not the main incentive for growing trees on farms. These factors implied that policies that promote the planting of trees on farms may be more effective if implemented with actions supporting food security, off-farm income and commercialisation of tree products. Moreover, because of differences in socio-economic and ecological conditions, interventions by development projects should be site (region) specific, to account for boundary socio-economic realities and biophysical conditions that entail farmers keep different tree species on their farms.

The presence of farm woodlots, considered as a special form of agroforestry that compete for space with crops, was enhanced by the age of the householder, the number of household member in formal employment, farm size, distance to fuelwood sources and the household being in the medium altitude region. In contrast, the households that depended on purchased fuelwood, located where forest cover is low, and keeping livestock were unlikely to grow woodlots. The inverse relationship between livestock farming and the growing of woodlots underscores the competition for space, where livestock farming is attractive to farm households. Chapter 3 indicates that, as for scattered trees, the promotion of woodlots must be region specific and accounting for specific socio-economic circumstances of its inhabitants. In particular, the finding of the study led to the conclusion that policies addressing energy problems in rural areas were likely to make impact if sustainable land use practices are promoted, income improved through the creation of jobs, and woodlots incorporated as an integral component of the production systems of crops and livestock.

The results of the study showed that 60% of the survey farms had scattered trees, 21% had woodlots and 19% had both scattered trees and woodlots. Different tree species distributed into 56 tree genera occurred on farms but a few tree species dominated, with the ten most common species accounting for over 70% of all trees on farms in the three altitude regions. The survey of woody biomass in scattered trees on farms averaged 6 t ha^{-1} of which 4 t ha^{-1} was biomass for fuelwood. Farm woodlots consisted of eucalyptus coppices for 90% of the cases. The estimated standing biomass in woodlots (< 0.5 ha) was about 96 t ha^{-1} in the lowland woodlots, 221 t ha^{-1} in the midland woodlots and 205 t ha^{-1} in the highland woodlots. Although scattered trees occurred over large areas of agricultural land, they produced less woody biomass than woodlots. Consequently, woodlots contributed a large share of woody biomass for meeting the household demands or fuelwood. Compared to forest plantations, the total woody biomass dry weight on agricultural land doubled that in forest plantations for the entire country, suggesting that the consumption of fuelwood from trees and woodlots on agricultural land could significantly reduce pressure on existing forests. In fact, this study estimated that potential fuelwood supply from agricultural land was about 1.5 times the estimated 5 million m^3 of fuelwood consumed annually in Rwanda. However, there were important variations in biomass production between regions, suggesting that wood deficit is not felt equally across the entire country.

Population figures and growing stocks are commonly used to determine the balance between fuelwood consumption and supply. This study indicated that, under a set of assumptions notably the expansion of tree and woodlot cover, improvement of management practices, and measures to reduce consumption of wood for fuel, the projected gap between supply and consumption could be reduced progressively by woody biomass from agricultural land toward achieving a balance and producing surplus in the future. In order to achieve these while contributing to food security and environmental conservation, smallholder farmers must be supported and provided with incentives to grow more woodlots and to adopt sustainable agroforestry systems. Currently, agroforestry is receiving increasing attention from policy makers. The challenge is, however, the integration of food production with fuelwood production under conditions of low income, food insecurity and small farms. Results in chapter 4 and 5 indicated that rural households were motivated to keep trees and woodlots for economic benefits. Consequently, the planting of trees and short rotation woodlots for economic benefits are easier to promote among farmers. Sustainable production of fuelwood on farms requires, however, enabling socio-economic, extension and policy environments. The extension services must be aware of the socioeconomic factors that enhance or limit the presence of trees and woodlots on farms in order to decide on types of interventions, intervention zones and target households. The current land scarcity and rapidly expanding population make land use a sensitive issue in national policies for agriculture, forestry, energy and environment. Efforts to address the energy situation must take into account not only biomass from forests, agroforestry, and crop residues, but also substitution of fuel. This must be done along with the formulation of relevant policies, effective collaboration between stakeholders, and stimulation of public awareness of the existing energy problems and their implication for land use, biodiversity and environmental conservation.

Samenvatting

Bomen en houtpercelen op landbouwgrond worden steeds meer beheerd als onderdeel van land-bosbouw systemen (agroforestry). Ze worden gewaardeerd omdat ze voorzien in de basisbehoefte voor brandhout, timmerhout, veevoer en andere bosproducten. Ze dragen tevens bij aan een toename van de gewasopbrengst, behoud van biodiversiteit en ze zorgen voor een verminderde druk op overige bossen omdat hout en niet-houtige producten van de landbouwbedrijven komen. Tegelijk concurreren ze om land en andere productiemiddelen, hetgeen tot verlies van gewasproductie kan leiden. Voor Rwanda, met weinig bos, maar met een grote afhankelijk van brandhout voor koken, is het belang van bomen en houtpercelen op landbouwgrond groot, met name voor kleine landeigenaren met weinig mogelijkheden om brandhout of houtskool op de markt te kopen. Echter, in de statistieken voor de beschikbare energievoorraden wordt de houtige biomassa in het agrarische gebied niet meegenomen, waardoor de balans van vraag en aanbod van brandhout incompleet is, en daardoor deels onjuist en onbetrouwbaar. De beschikbare resultaten geven aan dat bomen en houtpercelen voor een belangrijk deel voorzien in de vraag naar brandhout voor rurale huishoudens. Echter, de totale hoeveelheid brandhout uit de landbouw en de factoren die bepalen waarom boeren beslissen om bomen en houtpercelen te beheren op hun grond, zijn grotendeels onbekend.

In dit proefschrift analyseer ik welke factoren een rol spelen bij de keuze van boeren voor verschillende soorten van brandhout, en onder welke omstandigheden boeren besluiten om meer bomen en houtpercelen te handhaven op hun landbouwgrond. Daarnaast heb ik data verzameld bij kleine landeigenaren over de karakteristieken en hoeveelheden van houtige biomassa en biomassa voor brandhout in de landbouw. De volgende vragen zijn onderzocht: (1) Wat is de huidige situatie voor brandhout in Rwanda en wat is de potentie van bossen en agroforestry samen voor de brandhoutvoorziening? (2) Wat zijn de sociaaleconomische factoren en wat is de houding van kleine landeigenaren in de lagere, middelhoge en hoog gelegen gebieden in Rwanda bij de keuze voor verschillende soorten brandhout? (3) Wat zijn de belangrijkste beweegredenen en doelen die kleine landeigenaren er toe bewegen om bomen en houtpercelen te planten en te beheren in de drie verschillende hoogtezones? (4) Wat is de huidige status van de houtige biomassa in de landbouw en wat is de potentie daarvan voor de brandhoutvoorziening?

Voor het beantwoorden van vraag 1 is onderzoek gedaan naar vraag en aanbod van brandhout in Rwanda, door analyse van de rol van bossen en agroforestry systemen in de duurzame voorziening van brandhout. Vraag 2 en 3 zijn onderzocht door analyse van sociaaleconomische data verkregen van rurale huishoudens in verschillende gebieden in de lagere, middelhoge en hoge gebieden van Rwanda. Vraag 4 is geanalyseerd door onderzoek naar houtige biomassa op bedrijfs- en landschapsniveau in de drie hoogtezones. Voor dit onderzoek is gebruik gemaakt van een gestratificeerde steekproef op basis van de verschillende agro-ecologische gebieden en administratieve regio’s in Rwanda, waarbij data zijn verzameld van 480 kleine boerenbedrijven en landeigenaren, die de verschillende rurale huishoudens vertegenwoordigen in de drie hoogtezones.

Rwanda is één van de ontwikkelingslanden waar brandhout de belangrijkste energiebron is voor zo’n 90% van de bevolking. In hoofdstuk 2 worden vraag en aanbod van brandhout nader bekeken. Bestaande studies laten een continue stijging zien in de vraag naar brandhout, hetgeen mogelijk belangrijk bijdraagt aan de ontbossing in Rwanda. Op basis van bestaande gegevens wordt geconstateerd dat plantagebossen en agroforestry systemen structurele bronnen zijn voor brandhout. Voor rurale huishoudens zijn de agroforestry systemen, inclusief houtpercelen en de verspreid-staande bomen op de akkers, een belangrijke bron van brandhout door de combinatie van nuttige eigenschappen bij verschillende multifunctionele snelgroeiende boom en struiksoorten zoals brandhoutproductie, mogelijk gebruik als hakhout, en efficiënt gebruik van meststoffen. Op basis van literatuuronderzoek wordt geconcludeerd dat het niet meetellen van de houtige biomassa uit het landbouwgebied in de totale energieverzorging leidt tot een overschatting van het verondersteld verschil tussen brandhoutaanbod en -consumptie, omdat de huidige schatting alleen is gebaseerd op de houtvoorraad in het bos buiten het landbouwgebied. Het is daardoor onzeker wat het feitelijke effect is van het brandhoutgebruik op ontbossing, daar vele andere factoren, zoals uitbreiding van landbouwgrond, nederzettingen, en veehouderij eveneens hebben bijgedragen aan de sterke ontbossing van Rwanda. Door het kleine bosareaal en de geringe mogelijkheid voor herbebossing, is de conclusie dat veel brandhout uit het landbouwgebied kan komen, door gebruikmaking van de juiste boomsoorten en door goed beheer om competitie met landbouwgewassen voor ruimte, water, nutriënten en licht te beperken.

De voorgaande analyse toont aan dat de belangrijkste bronnen voor brandhout voor rurale huishoudens de landbouwgronden en de bossen zijn. Een andere bron die uit het onderzoek onder de rurale huishoudens naar voren kwam is de markt. Verschillende factoren beïnvloeden welk type brandhout wordt gebruikt door de verschillende huishoudens, in relatie tot hun sociaaleconomische situatie en de biofysische omgeving. De belangrijkste factoren bij de keuze voor een bepaalde bron van brandhout waren maandinkomen, inkomstenbron, omvang van het huishouden, geslacht van hoofd van de huishouding en de agro-ecologische locatie. Deze factoren geven aan dat de kans om brandhout uit het landbouwgebied te verzamelen het grootste is aangezien het brandhout keuzemodel aangeeft dat 75% van de huishoudens daar hun brandhout vandaan haalt. In het algemeen halen huishoudens met een hogere sociaaleconomische status hun brandhout meer van hun eigen land en uit de markt dan uit het bos.

Veel studies geven aan dat brandhout een bijproduct is van agroforestry. Dit betekent dat de keuze van boeren om bomen en houtpercelen op hun land te hebben wordt bepaald door meerdere doelen, en de beslissing voor het hebben van bomen en houtpercelen wordt tevens beïnvloed door sociaaleconomische factoren. Hoofdstuk 4 en 5 vergelijken de drie hoogtezones met betrekking tot beweegredenen voor het houden van bomen en houtpercelen op het land, en met gebruik van geaggregeerde gegevens zijn factoren geïdentificeerd om de resultaten te kunnen generaliseren ten behoeve van beleid en voor nationale ontwikkelingsprogramma's. De resultaten geven aan dat huishoudens vooral gemotiveerd waren om bomen en houtpercelen op hun land te hebben voor economisch voordeel en in veel mindere mate voor milieudoelstellingen. Verspreid staande bomen werden vooral beheerd om te voorzien in voedsel, brandhout en inkomsten. Houtpercelen werden vooral beheerd voor brandhout (48% van de eigenaren) en constructiemateriaal (43% van de eigenaren).

De keuze van huishoudens om wel of geen bomen en houtpercelen te hebben werd bepaald door verschillende combinaties van factoren. Significante factoren die deze keuze beïnvloeden waren regio specifiek, wat aangeeft dat generalisatie op landelijk niveau niet goed mogelijk is en vermeden moet worden. Dit kwam ook uit de geaggregeerde modellen waar de significante variabelen niet relevant bleken voor de regionale modellen en andersom.

Op landelijk niveau vertoonde de aanwezigheid van bomen en houtpercelen een positieve correlatie met aantal leden van het huishouden met informeel werk, met het aantal maaltijden per dag, met de verkoop van boomproducten, en met het voorkomen in de lagere en middelhoge hoogtezones. De hoeveelheid brandhoutgebruik van landbouwgrond verminderde de bereidheid om bomen te houden, hetgeen de veronderstelling ondersteunt dat brandhout niet de belangrijkste stimulans om bomen op landbouwgrond te planten. Deze factoren geven aan dat beleid dat aanplant van bomen op landbouwgrond stimuleert mogelijk meer efficiënt is tezamen met acties die voedselzekerheid, extra inkomen en commercialisering van boom producten ondersteunen. Bovenal zouden ontwikkelingsprojecten, door de verschillende sociaaleconomische en ecologische situaties, regio specifiek moeten zijn en zo rekening houden met de sociaaleconomische verschillen en biofysische condities waardoor landeigenaren verschillende boomsoorten aanplanten op hun land.

De aanwezigheid van houtpercelen, in dit verband feitelijk een aparte vorm van agroforestry die direct concurreert met de gewassen voor ruimte, nam toe met de leeftijd van het gezinshoofd, het aantal leden van het huishouden met officieel werk, met de grootte van de boerderij, met afstand tot brandhoutbronnen en indien het huishouden zich in de middelhoge hoogtezone bevond. Daar tegenover staat dat huishoudens die afhankelijk zijn van gekocht brandhout, in gebieden met lage bosbedekking en met vee, meestal geen houtpercelen hadden. De negatieve relatie tussen veehouderij en aanwezigheid van houtpercelen onderstreept de competitie voor ruimte, daar waar veehouderij aantrekkelijk is voor landeigenaren. Hoofdstuk 3 geeft weer dat, evenals voor verspreid staande bomen, promotie van houtpercelen regio specifiek moet zijn en rekening moet houden met de sociaaleconomische omstandigheden van de boeren. De studie laat vooral zien dat beleid gericht op energieproblemen in landelijke gebieden kans van slagen heeft als duurzaam landgebruik wordt gestimuleerd, het inkomen kan worden vergroot door creatie van banen, en wanneer houtpercelen een integraal onderdeel zijn van het productiesysteem, samen met gewas en vee.

De resultaten van de studie laten zien dan 60% van de onderzochte bedrijven verspreid staande bomen had, 21% houtpercelen en 19% beide. Verschillende boomsoorten kwamen voor, verdeeld over 56 geslachten, maar enkele soorten domineerden, waarvan de tien meest voorkomende soorten 70% omvatten van het totaal aantal bomen op het land, in alle drie de hoogtezones. De hoeveelheid houtige biomassa van verspreid staande bomen op het land was gemiddeld 6 t ha^{-1}, waarvan 4 t ha^{-1} biomassa potentieel geschikt voor brandhout. Houtpercelen bestonden voor 90% uit eucalyptus hakhout. Geschatte staande biomassa in houtpercelen (<0.5 ha) was ongeveer 96 t ha^{-1} in het laagland, 221 t ha^{-1} in het middelhoge gebied en 205 t ha^{-1} in het hoogland. Ondanks dat verspreid staande bomen over een groot areaal landbouwgebied voorkomen, is de productie van houtige biomassa minder dan in de houtpercelen. De houtpercelen leveren dus een belangrijke bijdrage aan de brandhoutvoorziening. In vergelijking met plantagebossen is de totale houtige biomassa in agrarische gebieden in het hele land, dubbel zo groot dan in de plantagebossen, hetgeen aangeeft dat de brandhoutconsumptie op basis van bomen en houtpercelen op landbouwgrond tot een belangrijke afname van de druk op de bestaande bossen leidt. De resultaten van deze studie geven ook aan dat potentieel oogstbaar brandhout van agrarisch land ongeveer 1,5 keer groter was dan de geschatte 5 miljoen m^3 brandhout die jaarlijks wordt gebruikt in Rwanda. Echter, er zijn grote regionale verschillen in biomassaproductie, waardoor houttekorten niet overal in het land gelijk zijn.

Bevolkingsaantallen en de staande houtvoorraad worden vaak gebruikt ter bepaling van de balans van vraag en aanbod van brandhout. Deze studie geeft aan dat, met inachtneming van een paar aannames, de uitbreiding van bomen en houtpercelen op landbouwgrond, verbetering van het beheer, en maatregelen ten behoeve van de reductie van het gebruik van hout als brandstof, het verwachte tekort tussen aanbod en vraag flink zou kunnen verminderen door het gebruik van houtige biomassa op agrarisch land, ten behoeve van evenwicht tussen productie en consumptie, met mogelijk een productieoverschot van brandhout in de toekomst. Om dit te bereiken en tevens bij te dragen aan voedselzekerheid en milieubehoud, moeten kleine landeigenaren worden ondersteund en voorzien van stimuli om meer bomen en houtpercelen te planten, en duurzame agroforestry systemen te implementeren. Op dit moment staat agroforestry steeds meer in de aandacht van beleidsmakers. De uitdaging is echter om voedselproductie en brandhoutproductie te combineren, in een situatie met lage inkomens, voedselonzekerheid, en kleine boerenbedrijven. Resultaten in hoofdstuk 4 en 5 laten zien dat rurale huishoudens gemotiveerd zijn om bomen en houtpercelen te houden voor economisch profijt. Aanplant van bomen en korte-rotatie houtpercelen voor economisch profijt zijn dus makkelijker te promoten onder boeren. Duurzame productie van brandhout op landbouwgrond vraagt echter om geschikte sociaaleconomische, voorlichtings- en politieke randvoorwaarden. Voorlichtingsorganisaties dienen zich bewust te zijn van de sociaaleconomische factoren die de aanwezigheid van bomen en houtpercelen op landbouwgrond stimuleren of juist beperken, om op basis daarvan de juiste maatregelen te kiezen, rekening houdend met gebied specifieke omstandigheden en de doelhuishoudens. Het huidige gebrek aan landbouwgrond en snelle populatietoename maken landgebruik een gevoelig onderwerp in het nationale beleid op het gebied van landbouw, bosbouw, energievoorziening en milieu. Inspanningen om het energievraagstuk aan te pakken moeten niet alleen rekening houden met de biomassa uit bossen, agroforestry systemen en uit gewasresten, maar ook met de vervanging van brandstof. Dit moet gebeuren naast de formulering van relevant beleid, effectieve samenwerking met belanghebbenden, en stimulering van maatschappelijke bewustwording aangaande de bestaande energieproblemen en de gevolgen voor landgebruik, biodiversiteit en milieubeheer.

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Short biography

Jean Damascene Ndayambaje was born on the 3rd of April 1965 at Butare, Rwanda. He completed his secondary school in 1987, with Mathematics and Physics as major subjects at Groupe Scolaire Saint André, Kigali. He joined Sokoine University of Agriculture in January 1988 and got Bachelors degree in Forestry Sciences in 1991. Thereafter, he worked as research assistant in forestry and agroforestry programmes at Rwanda Agriculture Research Institute (ISAR) since August 1992. While working at ISAR, he participated in many trainings in agroforestry organised by the International Centre for Research in Agroforestry (ICRAF - The World Agroforestry Centre) and served as a Rwanda focal person of the African Forestry Research Network (AFORNET) and Trees on- Farms Network (TOFNET) of the Association for Strenghening Agricultural Reseach in East and Central Africa (ASARECA). In 2000, He obtained a fellowship from the Rwanda Government for participating in the MSc. Programme of Stellenbosch University, South Africa. For his thesis, he looked at the potential for joint management and multiple use of Nyungwe Forest, South West Rwanda. He obtained his MSc degree in Community Forestry in 2002. After graduation, he rejoined ISAR where he worked as a researcher and head of the agroforestry programme. In March 2006, he was admitted to the Sandwish Fellowship programme of Wageningen University, the Netherlands and joined the Forest Ecology and Forest Management Group for a PhD study in Agroforestry that led to this dissertation. During his doctoral programme, he participated in different research activities in agroforestry and forestry at ISAR, then at Rwanda Agriculture Board (RAB) after the merging of ISAR with Rwanda Animal Resources Development Authority (RARDA) and Rwanda Agriculture Development Authority (RADA). He is a senior research fellow and coordinates research and extension work at RAB. Jean Damascene Ndayambaje is married to Assumpta Muhayisa and they have four boys.

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PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (6 ECTS)

- Fuelwood demand and supply in Rwanda and the role of agroforestry

Writing of project proposal (4.5 ECTS)

- Trees and woodlots on farms in Rwanda and their role in fuelwood supply

Post-graduate courses (6.6 ECTS)

- Tropical forest ecology and management; PE&RC (2006)
- The art of modelling; PE&RC, SENSE (2006)
- Linear models; PE&RC (2010)
- Generalised linear models; PE&RC (2010)
- Mixed linear models; PE&RC (2010)

Laboratory training and working visits (3.3 ECTS)

- Forest mapping, analysis and interpretation of aerial photographs; National University of Rwanda (2011)
- Methods for biomass estimation and forest cover mapping in the tropics: from carbon policy to technical training; Rwanda Ministry of Natural Resources (2011)

Deficiency, refresh, brush-up courses (3 ECTS)

- Remote sensing and GIS (2007)

Competence strengthening / skills courses (3 ECTS)

- PhD Competence assessment; WGS (2006)
- Scientific writing; National University of Rwanda, African Crop Science Society and Wageningen University/NPT Project (2007)
- Information literacy including Endnote introduction; Wageningen UR Library (2011)

PE&RC Annual meetings, seminars and the PE&RC weekend (1 ECTS)

- PE&RC Weekend (2006)
- The last stretch of the PhD programme (2011)

Discussion groups / local seminars / other scientific meetings (5.1 ECTS)

- Monthly seminars of the Centre for Ecosystems Studies (2006/2007/2011/2012)
- Eucalyptus dilemma in Rwanda (2010)
- Annual meeting of the Regional Network of Conservation (2010/2011)

International symposia, workshops and conferences (5.4 ECTS)

- Agroforestry and soil management (2008)
- The role of agroforestry in agricultural production and wood production increase (2011)

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