Potential of *Acacia angustissima, Leucaena pallida* and *Mimosa scabrella* in Agroforestry Systems on a Rwandan Ferralsol

Marguerite Mukangango
Faculty of Natural Resources and Agricultural Sciences
Department of Soil and Environment
Uppsala

Doctoral thesis
Swedish University of Agricultural Sciences
Uppsala 2019

Acta Universitatis Agriculturae Sueciae
2019:42

Cover: Experimental agroforestry species
(photo: Marguerite Mukangango)

ISSN 1652-6880
ISBN (print version) 978-91-7760-402-0
ISBN (electronic version) 978-91-7760-403-7

Print: SLU Service/Repro, Uppsala 2019

Potential of *Acacia angustissima*, *Leucaena pallida* and *Mimosa scabrella* in agroforestry systems on a Rwandan Ferralsol

Abstract

Agroforestry using coppicing legume trees and shrubs is a way to improve livestock fodder quality and soil fertility in the tropics. However, tree establishment and appropriate management are challenging, hampering their integration into agriculture and livestock systems. This thesis evaluates the biomass production by *Acacia angustissima*, *Leucaena pallida* and *Mimosa scabrella* legume tree species grown on a Ferralsol in Southern Rwanda, determines their effects on fodder quality and assesses the fertiliser quality of the resulting manure and its effect on a maize crop yield and the fertility status of a Rwandan Ferralsol.

In field studies, biomass production and nutritive value of the three agroforestry species when subjected to 0.3 and 1.0 m cutting height were determined and the effects of micro-dosing manure, fertiliser and lime on soil properties and maize yield were examined. Higher biomass production was generally found at lower cutting height. *Acacia angustissima* had the highest biomass production, whereas *M. scabrella* was sensitive to repeated harvests. Crude protein (CP) was not affected by cutting height, but neutral detergent fibre (NDF), acid detergent fibre (ADF) and total polyphenols were higher at grater (1.0 m) cutting height. The highest CP was found in *A. angustissima* and the highest NDF and ADF in *M. scabrella*. Mixing legume leaves with *Chloris gayana* grass improved feed CP content, dietary mineral content and digestibility.

Adding *A. angustissima* into *C. gayana* grass based feed increased the total nitrogen, organic carbon and base cation content in the manure produced. Manure application increased soil pH, soil nutrient content, soil organic carbon, soil cation exchange capacity and water-holding capacity at maize planting stations. Maize agronomic parameters and yield increased with manure micro-dosing method.

Thus *A. angustissima* and *L. pallida* appear to be robust species for use in agroforestry systems with similar biophysical conditions and cutting methods to those tested in this thesis, and can be recommended to improve low-quality forage. Manure micro-dosing is a promising practice for soil fertility replenishment in crop production by smallholder farmers with limited income and access to manure.

Keywords: Ferralsol, biomass production, tree management, nutritive value, digestibility, soil fertility, maize yield, cattle manure, fertilisers, micro-dosing

Author's address: Marguerite Mukangango, SLU, Department of Soil and Environment
P.O. Box 7014, 75007 Uppsala, Sweden

Dedication

To myself and my lovely family:
Elie Makeba Nzeyimana, Amanda Ishema, Arsene Byusa, Lorie Altessa Uganje and Carla Keza Uwanziza.

All is by God's Grace and Mercy.
Romans 3:24

Contents

List of publications

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

I Mukangango M, Nduwamungu J, Naramabuye FX, Nyberg G, Dahlin AS. Biomass production and nutrient content of three agroforestry tree species growing on an acid Anthropic Ferralsol under recurrent harvesting at different cutting heights. (*Submitted manuscript to Agroforestry Systems*)

II Mukangango M, Wredle E, Mutimura M, Dahlin AS (2018). Effect of cutting height on nutritional characteristics of three agroforestry tree legume species and their feed supplement value on *Chloris gayana* Kunth. *African Journal of Agricultural Research* 13:1591-1597

III Mukangango M, Nduwamungu J, Naramabuye FX, Nyberg G, Dahlin AS. Effects of supplementing grass cattle feeds with *Acacia angustissima* on manure quality and soil properties of a Ferralsol in Southern Rwanda. (*Submitted manuscript to Experimental Agriculture/Cambrigde Press*)

IV Dahlin AS, Mukangango M, Nduwamungu J, Naramabuye FX, Nyberg G. Effects of micro-dosed manure from a grass diet and a mixed grass-legume diet on maize production on a Ferralsol in Southern Rwanda. (*Manuscript*)

Paper II is reproduced with the permission of the publisher.

The contribution of Marguerite Mukangango to the papers included in this thesis was as follows:

I Planned the study together with the co-authors. Performed the field work and laboratory work. Wrote the manuscript with contributions from the co-authors.

II Planned the study with the co-authors. Performed the laboratory work. Wrote the manuscript with assistance from the co-authors.

III Planned the study with the co-authors. Performed the field work and laboratory work. Performed data analysis with the assistance of the last co-author. Wrote the manuscript with assistance from the co-authors.

IV Planned the study with the co-authors. Performed the field work and laboratory work. Assisted the main author in data analysis and in writing the manuscript.

1 Introduction

The world's population is expected to increase to 9.7 billion by 2050 and to 11.2 billion by 2100, with more rapid growth projected for the East and North Africa regions (FAO, 2017). In order to meet the food needs of the increasing population, agricultural production in sub-Saharan Africa and Asia needs to more than double by 2050, while in the rest of the world the projected increase needed would be about one-third of the current level (FAO, 2017). Improved strategies are needed to improve resource use efficiency to meet the growing demand for food and reverse environmental degradation (FAO, 2017).

Soil fertility depletion has been reported to be the main cause of the widespread decline in land productivity in sub-Saharan Africa (Sanchez, 2002). High population densities and associated high pressure on land, soil erosion, nutrient leaching, removal of crop residues and continuous cultivation have been identified as some of the factors responsible for soil fertility depletion (Okalebo *et al.*, 2006). The inherent soil properties of common soils such as Ferralsols and Acrisols also contribute to low fertility (FAO, 2006).

Considerable efforts, including fertiliser price subsidies, have been undertaken to make inorganic fertilisers affordable to farmers, but resource-poor farmers still cannot meet crop fertiliser requirements and have difficulties achieving and maintaining the high productivity observed on intensively cropped farms (Partey, 2011). The use of animal manure to improve soil fertility and crop yield assumes particular importance in areas where financial and logistical constraints limit the availability of inorganic fertilisers (Bayu *et al.*, 2004). However, manure production is low for most smallholder farmers. Therefore, a micro-dosing practice, which consists of applying small quantities of fertiliser and/or manure concentrated in small areas or planting holes or planting stations, can be helpful in improving yield and replenishing soil fertility for smallholder farmers (Blessing *et al.*, 2017, Ibrahim *et a*l., 2016, Fairhurst, 2012).

Many smallholder farmers suffer from poor access to fodder, especially high-quality fodder. Legume trees and shrubs can be used to supplement low-quality fodder if their composition meets fodder requirements. Agroforestry practices have shown great promise in improving soil quality (Dollinger and Jose, 2018). Moreover, the integration of trees into farming systems improves food and nutritional security, income and energy security, by providing tree products including fruits, fuel wood, timber, mulch and medical herbs (Sileshi *et al.*, 2007). However, while agroforestry has many positive aspects, it can also reduce crop yields in some instances, due to competition for resources among trees and crops (Kho, 2000). Selection of tree species for agroforestry systems should be based on multiple criteria and accompanied by appropriate tree management for sustainable production in the systems.

2 Objectives

The overall aims of this thesis were to evaluate biomass production by *Acacia angustissima, Leucaena pallida* and *Mimosa scabrella,* legume tree species that are suitable for use in agroforestry, grown on a Ferralsol in Southern Rwanda, and to determine their effects on fodder quality and manure fertiliser quality and its effect on maize crops and soil fertility status.

Specific objectives were to:

1. Assess the effect of different cutting heights at repeated harvests on biomass production by *A. angustissima, L. pallida* and *M. scabrella* on a Ferralsol under a humid tropical climate.
2. Assess the effects of using foliage from these tree species as fodder on feed composition and digestibility.
3. Assess the fertiliser effect of manure produced by animals fed *Chloris gayana* grass supplemented with *A. angustissima* foliage compared with that of manure produced by animals fed *C. gayana* grass only.
4. Assess the effect on soil fertility of manure produced by animals fed a diet supplemented with *A. angustissima* compared with that of manure produced by animals fed C. *gayana* grass only.

In relation to objectives (3) and (4), the hypothesis tested was that manure provides a liming and fertiliser effect comparable to that of combined NPK fertiliser application and liming.

2.1 Overview of papers I-IV

Paper	Reference	Aims
I	Mukangango M, Nduwamungu J, Naramabuye FX, Nyberg G, Dahlin AS. Biomass production and nutrient content of three agroforestry tree species growing on an acid Anthropic Ferralsol under recurrent harvesting at different cutting heights (*Submitted to Agroforestry Systems*)	To assess the effect of different cutting heights and repeated harvests on biomass production and nutrient content of *A. angustissima*, *M. scabrella* and *L. pallida*.
II	Mukangango M, Wredle E, Mutimura M, Dahlin AS (2018) Effect of cutting height on nutritional characteristics of three agroforestry tree legume species and their feed supplement value on *Chloris gayana* Kunth. *African Journal of Agricultural Research* 13, 1591-1597.	To assess the effect of cutting height on leaf fodder quality from *A. angustissima*, *M. scabrella* and *L. pallida* and their nutritional effect when mixed with grass forage in animal feeding.
III	Mukangango M, Nduwamungu J, Naramabuye FX, Nyberg G, Dahlin AS. Effects of supplementing grass cattle feeds with *Acacia angustissima* on manure quality and soil properties of a Ferralsol in Southern Rwanda. *(Submitted to Experimental Agriculture/Cambridg Press)*	To investigate the effect of supplementing the basal grass diet of cattle with a forage legume (*A. angustissima*) on manure properties and the effect of the manures on some soil characteristics.
IV	Dahlin AS, Mukangango M, Nduwamungu J, Naramabuye FX, Nyberg G,. Effects of micro-dosed manure from a grass diet and a mixed grass-legume diet on maize production on a Ferralsol in Southern Rwanda. (*Manuscript*)	To investigate the effect of cattle manure with and without supplementation with *A. angustissima* foliage on maize productivity when micro-dosed.

Paper	Materials and Methods	Main findings
I	Field experiment with three tree species. The trees were subjected to two cutting heights (0.3 and 1.0 m) repeated five times after 3-5 months depending on season. Biomass, height, collar diameter and survival rate were recorded after each harvest. Chemical content was analysed using chemical laboratory methods.	*Mimosa scabrella* established quickly, with the highest shoot production, but did not tolerate repeated harvesting. The survival rate of *A. angustissima* and *L. pallida* was 100% up to the fifth harvest at both cutting heights. *A. angustissima* had the highest overall biomass production and crude protein (CP) content, whereas neutral detergent fibre (NDF) and acid detergent fibre (ADF) were highest in *M. scabrella.*
II	Samples of the leafy fraction of the fifth regrowth were collected (experiment in Paper I). *Chloris gayana* grass samples were collected at flowering stage. Nutrient content was determined by chemical analysis. Feed digestibility was determined using *in vitro* gas production techniques.	Protein level was not affected by cutting height, but higher levels of NDF were found at 1.0 m cutting height in *A. angustissima* and *M. scabrella.* All legumes had high CP content and enhanced diet nutritional value and digestibility when mixed into the grass basal diet.
III	NPK and manure derived from a grass diet and a mixed grass-legume diet, were or were not combined with lime. Manure and lime amendments were micro-dosed in a field trial for four cropping seasons. Non-amended plots were used as reference. Soil sampling and laboratory analysis were performed after each cropping season.	Manure increased soil water holding capacity, soil organic carbon and cation exchange capacity, the soil pH increase was equal to limed treatments. Supplementing the grass basal diet with *A. angustissima* improved manure properties, but did not result in significant differences in soil properties
IV	In the same field experiment as in Paper III, plant growth data and chlorophyll content (determined using a SPAD meter) were recorded at 4, 8 and 12 weeks after planting. Maize yield was determined at maturity. Stover and grain N, P and K content were analysed in the laboratory.	Micro-dosed manure and NPK fertiliser increased maize agronomic parameters, yield and nutrient content. Although manure quality was enhanced by the mixed diet, a significant increase in maize yield when using mixed diet manure was seen only in season four.

3 Background

3.1 General facts about Rwanda

3.1.1 Biophysical aspects

Rwanda is a land-locked country in the Great Lakes region of Eastern and Central Africa. The country lies within latitudes 1° and 3° S and longitudes 29° and 31° E. The topography is dominated by a mountainous plateau that runs from West to East, ranging from 4500 m above sea level at the highest point in the West to around 1000 m in the East (ISAR, 1978). Rwanda has a tropical climate with an average annual temperature of 18 °C. It experiences two rainy seasons: the short rainy season runs from September to December, while the long rains are from February to June. The total surface area of Rwanda is 26,338 km^2, including areas under water. The population is about 12 million people, with an annual growth rate of 2.4%. The national population density has increased from 321 persons per km^2 in 2002 to 445 persons per km^2 in 2015, the highest in Africa (NISR, 2016).

3.1.2 Agriculture in Rwanda

Rwandan agriculture is affected by a bimodal rainfall pattern. Mean annual rainfall varies from 1300 mm to over 2000 mm in the North and North-West and from 750 mm to 1000 mm in the East, a region characterised as semi-arid with distinct dry periods.

Rwanda has very different types of soils, but with Cambisols, Acrisols and Ferralsols representing the most common agricultural soils (Verdoodt and Van Ranst, 2006). These soils are weathered and acidic, with low concentrations of plant-available nutrients for crop and fodder production. Agriculture remains the backbone of Rwanda’s economy. It contributes about 30% of gross domestic product (GDP), generates 60% of foreign currency earnings and employs approximately 70% of the total population (NISR, 2016). However, the average size of landholdings is 0.33 hectares (ha) (MINAGRI, 2016). Therefore, due to land shortages, land is devoted to crop production rather than livestock production.

Actions have been taken by the Government of Rwanda to address the problem of food insecurity: 1) The Crop Intensification Programme (CIP) policy is a strategy aimed at boosting agricultural productivity through improvements in production input use, irrigation coverage and soil quality (MINAGRI, 2009), and 2) A One Cow Per Poor Family programme, popularly known as the “Girinka programme” was initiated in 2006 for the livestock subsector, with the aims of ensuring household food security and providing manure as an efficient and sustainable method for maintaining soil quality and as an alternative for households to generate income (RARDA, 2006). However, the principal challenge facing both programmes is how to achieve sustainable increases in crop and livestock production with limited use of fertilisers and feed supplements.

Agroforestry practices can be used as an option for sustainable production systems for soil fertility improvement and animal fodder quality. Different legume tree species have been promoted in agroforestry systems in Rwanda, *e.g. Calliandra callothyrsus, Leucaena leucocephala* and *Sesbania sesban*, for which a wealth of information is available (Bucagu *et al.*, 2013, Niang *et al.*, 1996, Balasubramanian and Egli, 1986). Other species *e.g. Acacia angustissima*, *Leucaena pallida* and *Mimosa scabrella* are also promoted, although little information is available for contexts resembling Rwanda.

3.2 Dominant soil in Rwanda

Cambisols (Inceptisols), Acrisols (Ultisols), and Ferralsols (Oxisols) (FAO, 2006) or (USDA, 1999) soil taxonomy systems comprise more than 70% of the agricultural soils in Rwanda (Nzeyimana *et al.*, 2014, Verdoodt and Van Ranst, 2006) (Figure 1).

Cambisols are characterised by slight or moderate weathering of parent material and absence of appreciable quantities of clay, organic matter, exchangeable Al and/or Fe. Cambisols occur in all the agroecological zones in Rwanda. They are young soils, good for agriculture, but have low pH and low levels of plant nutrients and are highly eroded (Verdoodt and Van Ranst, 2006).

Acrisols and Ferralsols are restricted to humid and sub-humid climates of the tropics and subtropics, and acidification and leaching are important factors for their development. As Cambisols, they also occur in all the agroecological zones of in Rwanda. According to FAO (2006), Ferralsols and Acrisols differ mostly in their physical properties: Ferralsols have excellent porosity, good permeability, favourable infiltration rates and good water-holding capacity, and are thus less susceptible to erosion. Acrisols have weakly developed soil structure and are highly susceptible to erosion. However, these soils also have properties in common, mostly in chemical properties and managerial requirements for sustainable agriculture production. Both groups are strongly leached, weathered soils dominated by low activity clays. They have low to extremely low soil pH, low concentrations of base cations and low cation exchange capacity (CEC), and generally low levels of plant nutrients. Aluminium toxicity frequently affects crop and fodder production. Both soils are important for Rwandan agriculture when amended and limed. Cambisols, Acrisols and Ferralsols need special attention to maintain soil fertility, *e.g* by liming, organic matter inputs, fallowing and/or agroforestry practices. Preventing surface erosion is essential for sustainable crop and livestock production on these soils.

The mountainous volcanic region of Rwanda is dominated by Andosols which have high potential for agricultural production, and by Regosols, which are highly eroded soils and less used for agriculture. Fluvisols and Vertisols are found under wetlands and used for rice production in Rwanda.

3.3 Managing soil acidity, nutrient deficiency and carbon content

3.3.1 Acid neutralisation and liming materials

Soil acidification in Ferralsols, and in other acidic soils, is a process by which soil pH decreases, base cations are lost and the concentrations of exchangeable aluminium ions (Al^{3+}) and manganese ions (Mn^{2+}) increase over time. Soil acidity is determined by the amount of hydrogen (H^{+}) activity in the soil solution. This is influenced by climate and biological factors and varies with parent rock and the length of time the soil has weathered (McFerland *et al.*, 2001, Schumann, 1999). Acid rain and nitrification of ammonium fertilisers release protons into the soil solution and cause acidification.

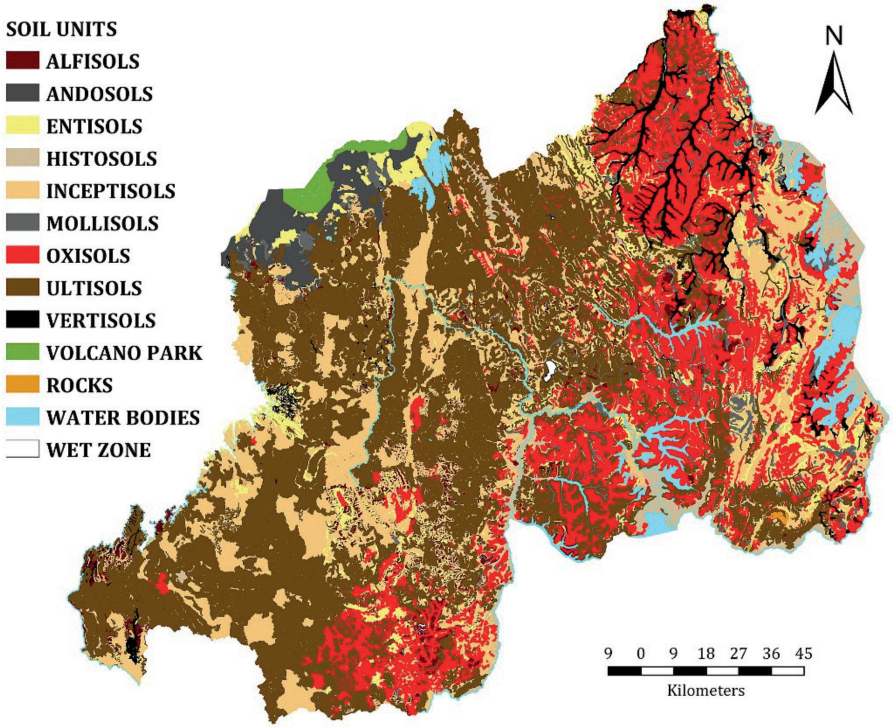

Figure 1. Soil map of Rwanda. Soils are classified using the United States Department of Agriculture soil taxonomy system (USDA). Source: Data collected from Ministry of Agriculture and Animal Resources, using the Rwanda soil database.

Some strongly weathered soils such as Ferralsols and Acrisols are inherently acidic, while others, such as Lixisols, are prone to acidification under inappropriate management practices such as application of ammonium-containing fertiliser without crop residue recycling (Vanlauwe *et al*., 2015). According to McFerland *et al*. (2001), soils are considered slightly acidic between pH 6.5 to 6.1, moderately acidic between 6.0 to 5.5, strongly acidic between 5.0 to 4.4 and extremely acidic below pH 4.4. Aluminium toxicity is one of the major constraints on crop production on acid soils because it reduces the availability of soil nutrients and inhibits plant root growth, thus limiting nutrient uptake. Acidity and aluminium toxicity can be ameliorated by liming and appropriate use of nitrogenous fertilisers, or circumvented by growing plants tolerant to aluminium toxicity (Barber, 1984, Thomas and Hargrove, 1984).

The liming materials most commonly used are calcitic ($CaCO_3$) and dolomitic ($CaMg (CO^3)_2$) limestone, burnt and slaked lime, marl and various organic materials, including crop by-products. According to Haynes and Naidu (1998), the practice of liming acid soils in order to raise pH and precipitate exchangeable aluminium as insoluble hydroxyl-Al is necessary for optimum crop production. However, for both logistical and economic reasons, it is not often possible for resource-poor farmers to apply sufficient rates of lime to their soils (Haynes and Mokolobate, 2001). The use of organic materials (crop residues, household compost, green manure and animal manure) has been proposed as an alternative to lime to reduce aluminium toxicity in acidic soils and increase crop yields (Naramabuye and Haynes, 2006a, Wong *et al.*, 1995, Lungu *et al.*, 1993, Hue *et al.*, 1986).

3.3.2 Supply of nutrients and carbon

Inorganic and organic fertilisers are sources of plant nutrients that can be added to supplement soil fertility. Inorganic macronutrient fertilisers provide the soil with large amounts of nitrogen, phosphorus and potassium, and increase crop productivity, but may be unavailable to poor smallholder farmers due to their cost (Mahmood *et al.*, 2017, Bationo *et al.*, 2007). Therefore an integrated approach, using nutrients from both inorganic and organic sources, is the best strategy for plant nutrient supply and soil fertility management (Oyun *et al.*, 2016).

Animal manures can be an important organic source of nutrients. They provide macronutrients, especially nitrogen, phosphorus and potassium, but also micronutrients (Bayu *et al.*, 2004, Lupwayi *et al.*, 2000). Manure also supplies organic carbon to the soil, thus increasing soil organic matter content, which is key to maintaining soil health and increasing soil microbial activity, decreasing soil bulk density and increasing water-holding capacity (Haynes and Naidu, 1998). Manuring also increases the CEC of soils (Bayu *et a*l., 2004). However, the nutrient content of manures differs because of variations in animal, diets and in the ways in which manure is collected and stored. Feeding animals protein-rich supplements results in higher nitrogen concentrations in the excreta, but this may be lost under inappropriate manure management (Delve *et al.*, 2001).

3.4 Agroforestry in Rwanda

The concept of agroforestry systems in supporting sustainable land use and natural resources management is recognised as an integrated applied science approach that has the potential to address land management and environmental problems found in both developing and industrialised nations (Nair *et al*., 2009). In order to achieve sustainable land use, a number of characteristics should be considered when selecting tree species for agroforestry systems. All cannot be found in a single species, but should be considered in order to achieve sustainable land use. The tree species used in agroforestry should be less competitive, *e.g*. for nutrients, moisture and sunlight, but help build soil fertility by fixing atmospheric nitrogen. Their foliage should have high palatability as fodder and quick decomposition after litterfall. The tree species should also be easy to establish, grow fast, be easy to manage, be adaptable and be able withstand management practices (Nair *et al*., 2009).

Reforestation and tree cultivation have been promoted in Rwanda since the 1930s. Early use of trees in cropping systems and incorporation of agroforestry systems in different Rwandan intensive agricultural systems have been suggested to be solutions to the perpetual shortage of land, food, fodder and tree crops interaction to satisfy the multiple needs of subsistence farmers (Niang *et al*., 1996, Den Biggelaar and Gold, 1996, Yamoah *et al*., 1989, Balasubramanian and Egli, 1986). Different tree species *Sesbania sesban, Leucaena spp., Calliandra callothyrsus* and *Markhamia lutea* have been grown intercropped with beans in the high-altitude and central plateau of Rwanda (Yamoah *et al*., 1989). Use of leafy biomass from agroforestry tree species green as manure can be important in the tropics (Kang *et al*., 1981). Morever, Niang *et al*. (1996) report also the use as fodder in Rwanda of a number of tree species, such as *Acacia koaia, Mimosa scabrella, Acacia koa, Alnus acuminate, Chamaecytisus palmensis, Hagenia abyssinica, Acacia mearnsii* and *Acacia melanoxylon*. Since 1970s, agroforestry has been promoted to smallholder farmers in Rwanda by researchers, government projects and non-government organisations and is still subject of expansion to about 1.5 *million* hectares in Rwanda corresponding to 83% (Mukuralinda *et al*., 2016) of the total agricultural land area in Rwanda (1.8 million hectares) (NISR, 2018).

3.5 Agroforestry tree species studied

While agroforestry expanded well in the past two decades, its adoption by smallholder farmers varies depending on many factors such as the land use system, agroecological conditions and farm management regime (Sileshi *et al*., 2014, Tittonell *et al*., 2005). Agroforestry is suitable for all agricultural land in Rwanda and especially in areas where the population is dense and farm size is small, where there is a need for intensive farming systems that integrate agriculture, livestock and trees/shrub production (Mukuralinda *et al*., 2016).

Establishment and productivity of trees and shrubs are influenced by farm management, farmer's production objectives and resource availability for different agroforestry technologies, which make agroforestry systems diverse in time and space (Bucagu *et al*., 2013). Multipurpose trees such as *Acacia angustissima*, *Leucaena pallida* and *Mimosa scabrella* are potential species that can contribute to agroforestry systems by providing high-protein fodder for *e.g*. dairy cows, enhancing the quality of animal manure and providing erosion control, as well as stakes and fuelwood. However, farmers need to be aware of their appropriate management and their suitability within their respective agricultural systems.

Figure 2. Acacia angustissima (Photo: Marguerite Mukangango SLU).

3.5.1 Acacia angustissima

Acacia angustissima (Figure 2) (Miller) Kuntze (syn. *Acaciella angustissima* (Miller); *Mimosa angustissima* Miller; *M. ptericina* Poir; *Senegalia angustissima* (Miller) Pedley) is a fast growing, small leguminous tree or shrub (2-7 m). It is closely related to, and botanically confused with, *Acacia boliviana* and *Acacia villosa* (Gutteridge, 1998). *Acacia angustissima* is a nitrogen-fixing tropical legume species (Chaer *et al*., 2011). It is native to the America (Arce and Bachman, 2006). It grows well at altitudes up to 2600 m above sea level and at rainfall of between 895 and 2870 mm per annum (McVaugh, 1987). It tolerates a wide range of soils, including free-draining, acidic and infertile soils

(Gutteridge, 1998, Dzowela, 1994, McVaugh, 1987) and shows excellent drought tolerance of up to eight months (Gutteridge, 1998). The leaves of *A. angustissima* have a high nitrogen content, which potentially makes them an ideal supplement to the low-quality crop residues and other grasses that make up the bulk of livestock diets in smallholder farming (Hove *et al.*, 1999). The species grows rapidly and responds well to regular cutting, but information on the response of its biomass and chemical composition to different management practices has not been reported in the literature

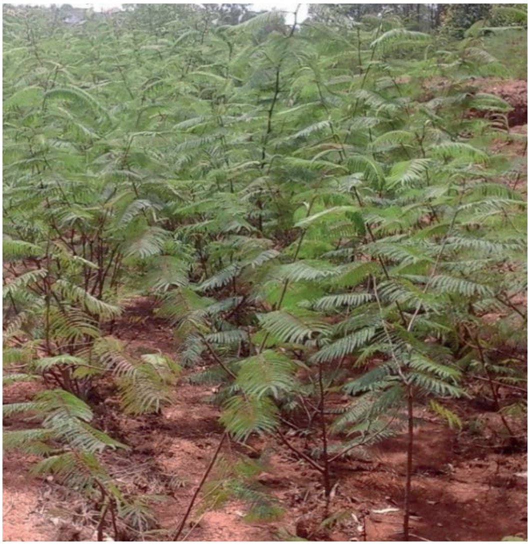

Figure 3. Leucaena pallida (Photo: Marguerite Mukangango SLU).

3.5.2 Leucaena pallida

Leucaena pallida (Figure 3) is a deep-rooted small shrub legume normally 3-7 m tall, with trunk diameter 10-15 cm and an open spreading or narrow crown (Orwa *et al.*, 2009). *Leucaena pallida* is a nitrogen-fixing topical legume (Chaer *et al.*, 2011). It is native to Mexico and has been used in Africa as fodder (Wambugu *et al.*, 2006). *Leucaena pallida* grows well in an altitude range between 1000-2000 m and mean annual temperatures between 16 and 21 °C. It can resist dry seasons lasting up to seven months and grows well with annual rainfall up to 2000 mm, but can withstand annual rainfall as low as 500 mm.

Leucaena pallida does not thrive under soil conditions of low phosphorus and calcium, high Al^{3+} saturation and waterlogging, but tolerates slightly acidic soils with pH>5 (Wambugu *et al.*, 2006). Akyeampong (1998) reported low productivity of *L. pallida* on highland soils in Burundi characterised by aluminium toxicity. In contrast, there have been anecdotal reports that *L. pallida* grows well in the southern parts of Rwanda (Rubona station) with acidic soils (pH 4-5.7). The lack of information on this species in the area calls for further scientific study. *Leucaena pallida* provides high-quality dry season feed, is more resistant to psyllid attack than other *Leucaena* species and is highly productive and tolerant of heavy cutting/coppicing and grazing (Orwa *et al*., 2009). Mutimura *et al*. (2013) identified *L. pallida* as a promising fodder shrub with high dry matter content and high nitrogen content.

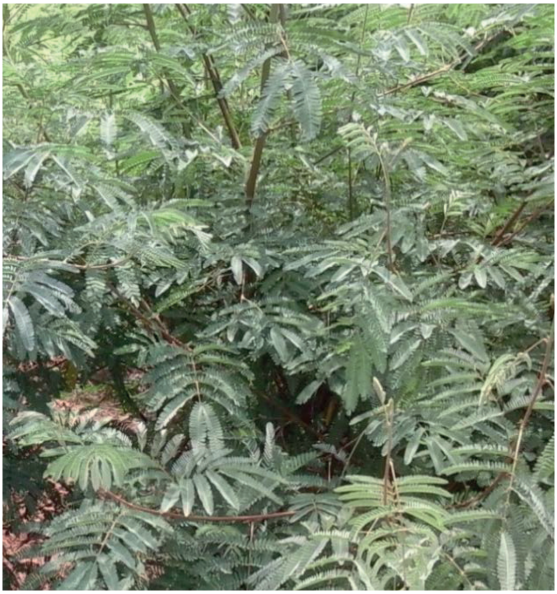

Figure 4. Mimosa scabrella (Photo: Marguerite Mukangango SLU).

3.5.3 Mimosa scabrella

Mimosa scabrella Bentham (Figure 4) is also known as *Mimosa* bracatinga, with the popular name being bracatinga. It is a fast-growing, small to medium tree that grows to 4-12 (max. 20 m) high, with a tall, straight, slender trunk 10-50 cm in diameter. It forms closed stands and is short and branched, with a dense rounded crown of grey foliage, or a large shrub (Gutteridge, 1998). *Mimosa scabrella* is a nitrogen-fixing topical legume (Chaer *et al*., 2011). It is indigenous to south-east Brazil, but is now grown in many other countries (Gutteridge, 1998). It develops very well in regions with an annual rainfall range of 1100 to 3500 mm, annual mean temperature between 16 and 23 °C and altitude between 500 and 1200 m above sea level. It grows on infertile soils with pH values frequently below 4.0 and low soil nutrient availability, and can withstand soils with high Al^{3+} saturation (Somarriba and Kass, 2001). Niang *et al.* (1996) report good adaptation of *M. scabrella* to acidic Oxisol conditions of the rugged Zaire-Nile Crest in Rwanda, with high biomass production and good quality for livestock fodder. However, its ability to tolerate multiple harvesting, which would ensure sustainable production of *M. scabrella* in agroforestry is unclear.

3.6 Nutrient content and digestibility of fodder

Factors contributing to high-quality forage are high concentrations of protein, low levels of cell wall content, suitable mineral content, high palatability and digestibility and low concentrations of anti-nutritional substances (condensed tannins) (Arias *et al.*, 2014, Njidda, 2010, Ndlovu and Nherera, 1997). According to Simbaya (2002), the foliage of fodder trees and shrubs has a high crude protein content, ranging from 14 to 29%, relative to the reported minimum feed crude protein content required for ruminant lactation (12%) and growth (11.3%) (Gusha *et al.*, 2013, Njidda and Ikhimioya, 2010, Francis and Sibanda, 2001). Gusha *et al.* (2013) found crude protein values of 30.5%, 26.5% and 22.7%, and 21.8% respectively, for *A. angustissima*, *Calliandra callothyrsus, Gliricidia sepium* and *L. pallida*. In addition to being a good source of protein, fodder legumes are also an important source of minerals such as sulphur, calcium, copper and iron (Simbaya, 2002, Baloyi *et al.*, 1997).

The neutral detergent fibre (NDF) content in feed reflects the slowly digestible hemicellulose, cellulose and lignin in plant cell walls and affects feed intake and availability of energy in feeds. The acid detergent fibre (ADF) content is a sub-fraction of NDF that consists mainly of cellulose and lignin and affects the digestibility of feeds in the animal's digestive tract (Baloyi *et al.*, 1997). As NDF content in the forage increases, animals consume less forage. This negative correlation, (NDF concentration) is often used in equations designed to predict dry matter intake (Uttam *et al.*, 2010). It has been reported that the maximum dietary NDF concentration that will not hinder intake can be as high as 75% of dry matter (DM) for mature beef cattle (Bray *et al.*, 1997). On the other hand, an NDF content of less than 25% DM can limit feed intake in high-yielding dairy cows (Allen, 2000).

The digestibility of shrubs in ruminants is related not only to the proportion of cell walls, but also to the concentration of secondary compounds such as tannins (Arias *et al.*, 2014). Tannins and hydrolysable phenolics may interfere with the use of high protein and low fibre content as indicators of high nutritional value (Woodward and Reed, 1989). High levels of condensed tannins in temperate legumes have been associated with reductions in forage intake, dry matter digestibility and nitrogen utilisation by ruminants (Barry and Duncan, 1984). The presence of high levels of condensed tannins often found in tropical legumes might thus limit their use as forages.

3.7 Legume tree management and fodder quality

Utilisation of trees and shrubs has long been recognised to be one of the most effective means of improving both the supply and the quality of forage in tropical smallholder livestock systems, especially during the dry season (Gutteridge and Shelton, 1994). The most suitable management of fodder trees for maximum production of edible dry matter depends upon a number of factors, such as time of the initial cut, frequency and intensity of defoliation, cutting pattern prior to the onset of the dry season and stand density of the trees (Sanchez *et al.*, 2006, Petersen *et al.*, 1998).

The reported effects of cutting height and frequency on yield and survival of fodder shrubs do not exhibit a consistent pattern. Some researchers have found that increased cutting height results in higher dry matter yield (Niang *et al.*, 1994, Hairiah *et al.*, 1992). Cutting at 0.2 m above the ground has been reported to be a better management technique for *Moringa oleifera* tree regeneration compared with cutting at 1.0 m, because it gives much higher dry matter yield of leaves (10.4 t ha^{-1} year^{-1} and 3.1 t ha^{-1} year^{-1}, respectively) while not affecting the survival of the shrubs (Isah *et al.*, 2014). Different cutting intervals have no effect on survival of the shrubs, which indicates their high tolerance to cutting or browsing. In contrast, Niang *et al.* (1996) observed that 24% and 48% of *Sesbania sesban* plants died when cut at 6 and 12 months, respectively.

It has been shown that cutting frequency also affects the quality of forage biomass and that there is often an inverse relationship between biomass yield and fodder quality. Habib *et al.* (2007) found that the crude protein content of *Gliricidia sepium* decreased from 291 g kg^{-1} DM to 220 g kg^{-1} DM when the coppicing interval was increased from 1 to 6 months. However, literature information on the effect of different management practices is not available for *A. angustissima, M. scabrella* and *L. pallida*. Given this background, this thesis focused on management of these three tree species, with the aim of improving the life of smallholder farmers in Rwanda by demonstrating the possibilities to improve their cultivation practices using suitable agroforestry species.

4 Materials and Methods

4.1 Experimental site (Papers I, III and IV)

Papers I, III and IV are all based on data collected in field experiments carried out at Tonga research station (2°35’15.122”S; 29°43’43.251”E; 1700 m above sea level), University of Rwanda (Figure 5). Mean annual temperature at the station is 19.1 °C and mean annual rainfall is 1150 mm (Climate-Data.org, 2019). Rainfall is distributed over two cropping seasons: a short rainy season from September to mid-December and a long rainy season from mid-February to mid-June, with precipitation peaks in November and April.

The soil at the site is a former Haplic Ferralsol changed to Anthropic Ferralsol due to radical terracing. It is acidic, with low nutrient concentration and sandy loam texture (Table1). The land was fallowed for more than 10 years prior to the experiments described in Papers I, III and IV, and the dominant vegetation before the start of experiments was *Eucalyptus spp*. and *Eragrostis curvula*. Land preparation was performed by hand hoe and machete. The work in Paper I was conducted for 23 months from 2015 to 2017.The work in Papers III and IV was conducted during four cropping seasons, encompassing the short and long rainy seasons from 2016 to 2018.

Site Characterisation

Field experiment location **Field experiment**

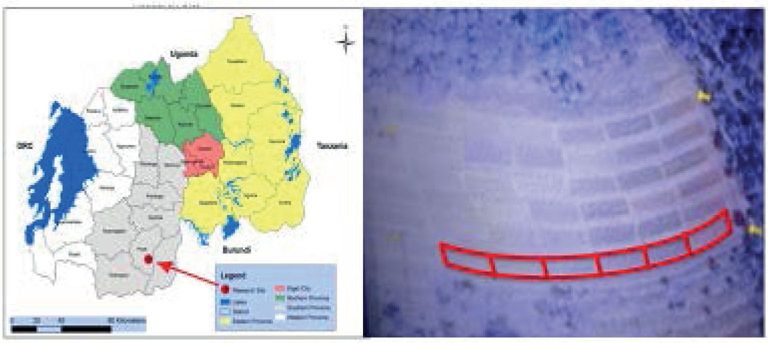

Figure 5. (Left) Map of Rwanda showing the location of the experimental site and (right) satellite image showing the layout of the field plots (plots of one block=terrace marked red).

Table 1.B*aseline characterisation of the Ferralsol soil at the study site in Rwanda*

Soil chemical parameters	Units	Value
pH(H2O)		4.25
Total exchangeable acidity (TEA)	(cmolc kg^{-1})	4.04
Al3+	(cmolc kg^{-1})	2.8
Soil organic carbon (SOC)	%	0.64
Total nitrogen	%	0.06
Available phosphorus	(ppm)	4.9
Cation exchange capacity(CEC)	(cmolc kg^{-1})	5.74
Calcium (Ca^{2+})	(cmolc kg^{-1})	0.48
Magnesium ($Mg^{2+)}$	(cmolc kg^{-1})	0.16
Potassium (K^{+})	(cmolc kg^{-1})	0.31
Soil Physical parameters		
Bulk density		1.23
Sand	%	64
Silt	%	21
Clay	%	15

4.2 Effect of cutting regime on legume tree biomass (Papers I and II)

The experiment in Paper I had a randomised complete block design, in a 3×2 factorial arrangement with six replicates. The factors were the three legume species (*A. angustissima, L. pallida* and *M. scabrella*) and two cutting heights (0.3 m, 1.0 m). Six blocks, each divided into six 10 m×4 m plots, were established on six consecutive bench terraces. Each tree species was grown in monoculture on plots separated by 2-m alleys.

Tree seeds were sown in a nursery bed, in equal parts local soil and composted cattle manure. Seedlings were transferred to and raised in polythene bags in 70:30 soil: compost potting mixture and then transplanted into the field at 0.5 m spacing within rows and 1.0 m between rows, giving a total of 120 trees per plot. When the trees were approximately 1.5 m, all were uniformly cut at 0.2 m above the soil to stimulate shrubby morphology. The first regrowth was then cut at 0.3 or 1.0 m above the ground, according to the experimental treatment. The following five cuts of regrowth for which data were recorded were made again at either 0.3 or 1.0 m above the ground.

The data presented in Paper I were collected on 36 trees in the net plots of 18 m^2 situated in the middle of the 10 m× 4m plots. Information was collected on stump collar diameter, length of new shoots and biomass of the leafy and stem fractions, where the leafy fraction was leaves, twigs and succulent stems (<8 mm diameter) considered suitable as fodder. The dry matter biomass was calculated based on the ratio of dry to fresh weight of representative subsamples dried in the laboratory. Survival status was calculated as:

Number of remaining living trees ÷ Number of planted trees ×100

Harvests were timed to periods with reasonable amounts of regrowth, to reflect farmers' practice. The interval between two successive harvests varied between three and five months, depending on weather conditions.

4.3 Maize trial establishment, management and sampling procedures (Papers III and IV)

A two-factorial randomised complete block design with four replicates was used for testing the effect of micro-dosing agricultural inputs on soil properties and maize yield (Papers III and IV). The blocks, each divided into eight 4 m×3 m plots, were established on four consecutive bench terraces. The factors were: manure/inorganic fertiliser application and liming.

Two types of manures used were collected and composted for each season on a nearby research station of the University of Rwanda. Cattle were stall-fed on 100% *Chloris gayana* grass harvested at flowering stage or 70% *C. gayana* supplemented with 30% *A. angustissma* legume leafy fraction harvested daily on site. Faeces and urine were collected directly after excretion according to feed type, bulked in separate composting pits lined and covered with plastic sheeting to reduce loss of nitrogen by leaching and volatilisation, and composted for 10-12 weeks. The inorganic fertiliser was NPK 17-17-17, where the nitrogen was present as ammonium (NH_4^+). The liming material used was travertine (33.3% calcium and 1.16% magnesium) collected from Mashyuza, Rwanda, and milled to pass through a 2 mm sieve.

The manures were applied at 25% of the recommended rate by the University of Rwanda whereas and lime was used at 25% of the required CaO rate to neutralise the acidity at the site. The NPK treatment served as a positive control where the rate was set to achieve a recommended nitrogen availability of 80 kg N ha^{-1} (Sallah *et al.*, 2009), including the mineral nitrogen available in the soil at the start of the first cropping season. An unamended negative control without amendments was also included. In order to maximise fertiliser effectiveness and use efficiency, all amendments were applied only to the plant-rooting zone at maize planting points or planting stations which made up 25% of the total plot area. Prior to maize planting each season, manure was thus applied at a rate of 5t dry weight ha^{-1}, corresponding to 125 g per planting station and NPK was applied at a rate of 70 kg N ha^{-1}, corresponding to 10 g per planting station. The NPK fertiliser was added as a split application with 20% at planting, 40% at 6 weeks after planting and 40% at 8 weeks after planting. The lime was applied before planting once a year at a rate of 2 t ha^{-1} of travertine corresponding to 50 g per planting station (Paper IV).

The experimental plots were sown with maize, medium season variety PAN 4M-21, at a spacing of 0.5 m × 0.5 m within and between rows. Data collection for the maize in Paper IV was performed only during three cropping seasons because the crop in the first cropping season failed due to drought. During seasons two to four, the following agronomic data were collected on 16 maize plants in each net plot (4 m^2) at 4, 8 and 12 weeks after planting: plant height, number of leaves, collar diameter approximately at 2 cm above ground level and SPAD readings for plant chlorophyll monitoring (SPAD-502 meter, Minolta Japan). At maturity, plants in net plots were harvested and the aboveground biomass was separated into ears (cob + grains) and stover (stem, leaves and husks). The ears were dried at 60 °C to constant weight at approximately 12% moisture content and shelled to obtain grain weight in kilograms for each plot. A subsample of stover was dried for 48 h at 60 °C.

Subsamples of the dried grain and stover were further dried at 105 ^{o}C and the percentage of weight loss during drying was used to calculate total dry weight of the maize yield in tons per hectare. The crop nutrient content in above-ground biomass in (kg ha^{-1}) was calculated as:

((Grain yield (t ha^{-1}) × Nutrient (%) in grain) + (Stover (t ha^{-1}) × Nutrient (%) in stover))/100 × 1000.

The maize stover was left on plots after harvest and the same planting points were retained over all growing seasons. Soil sampling was performed before setting up the experiment. Ten soil samples were taken from the 0-20 cm layer in each plot using an auger and pooled to form a composite sample per plot (Paper III). Soil sampling and analysis was repeated after each cropping season, but samples were then taken only at the planting stations.

4.4 Plants, soil and manure analysis

4.4.1 Analysis of plants composition and *in vitro* digestibility (Papers I, II and IV)

All plant samples for chemical analysis were dried at 60 °C for 72 hours and milled to <1 mm. In Papers I and II, pure samples of the legumes and grass, and of mixed legume-grass in proportions of 30% legumes and 70% grass (Paper II), were chemically analysed. Total ash was determined through ashing by method 942.05 (AOAC, 1990) and crude protein was calculated as 6.25 times the Kjeldahl nitrogen content measured by method 988.05 (AOAC, 1990) (Papers I and II). Calcium, magnesium and phosphorus concentrations were determined by dry ashing (methods 927.08, 964.06). Organic matter (OM) was calculated as the difference between dry matter content and ash content (Paper II). Total polyphenol (TP) content was determined according to Folin-Denis method in Anderson and Ingram (1993). The cell wall constituents (Neutral Detergent Fiber: NDF and Acid Detergent Fiber: ADF) were determined according to Van Soest *et al.* (1991) (Papers I and II).

The *in vitro* organic matter digestibility (IVOMD) of the legumes, grass and legume-grass mixture (Paper II) was determined by the gas production technique following Menke *et al.* (1979), using fermentation medium prepared according to Osuji (1993) and ruminal fluid to provide microbial inoculant. The latter was derived from rumen contents obtained from fistulated steers grazed on *Panicum maximum* and fed *Chloris gayana* in their stalls. Syringes containing samples with fermentation medium or blanks with only fermentation medium were incubated at 39 °C. Gas readings were recorded at time zero, and then at scheduled intervals up to 96 h.

Maize plant and grain samples (Paper IV) were analysed for total nitrogen, available phosphorus and available potassium concentrations. Nitrogen was determined according the micro-Kjeldahl method (Anderson and Ingram, 1993) and phosphorus and potassium were determined in the same digest (Okalebo *et al.*, 2002).

4.4.2 Soil analysis (Paper III)

Soil samples were dried and milled to <2 mm. They were analysed for pH (1:2.5 soil:water ratio) and total exchangeable acidity (TEA, *i.e.* H^+ and Al^{3+}) extracted by 1N potassium chloride (KCl) and measured by titration with sodium hydroxide (NaOH) (Anderson and Ingram, 1993). Total nitrogen content was determined by the micro-Kjeldahl method (Anderson and Ingram, 1993), soil organic carbon (SOC) was determined by the Walkley-Black method (Anderson and Ingram, 1993), and available phosphorus was determined by the Bray-1 test (Bray and Kurtz, 1945). Exchangeable bases cations (Ca^{2+}, Mg^{2+}, K^+) were determined by ammonium acetate extraction and flame photometry (Anderson and Ingram, 1993). The CEC was determined by the acetic acid method as described by Aprile and Lorandi (2012).

Soil water infiltration rates in the field were determined by the double ring method (Anderson and Ingram, 1993). Soil water-holding capacity was determined in the laboratory using sand box apparatus (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) at pF 0, pF 0.4, pF 1, pF 1.5, pF 1.8 and pF 2.0 for undisturbed soil samples and using pressure plate equipment (Soil Moisture Equipment, Santa Barbara CA, USA) at -5 bar and -15 bar for disturbed samples.

4.4.3 Manure analysis

Before application in the field trial, eight subsamples of each manure were taken randomly, pooled and homogenised. The samples were then dried and milled to <2 mm. Total nitrogen was determined using the micro-Kjeldahl method (Anderson and Ingram, 1993) and measured colorimetrically. In the same digest, total phosphorus was measured colorimetrically without pH adjustment (Okalebo *et al.*, 2002), and base cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) were determined by atomic absorption spectrophotometry (VARIAN) (Okalebo *et al.*, 2002). Organic carbon (OC) was determined by the Walkley and Black method (Anderson and Ingram, 1993).

4.5 Statistical analysis

The results in Paper I were analysed as repeated measures data using a mixed model approach, as implemented in the mixed procedure in SAS software 9.4 (SAS, 2012). The relationships between harvest occasions within plots were modelled using an autoregressive covariance structure. The fixed factors in models were species, cutting height, harvest occasions and all interactions between these factors. Blocks were regarded as random variable.

Data on chemical composition, *in vitro* degradation, metabolisable energy (ME) and kinetic parameters were subjected to two-way analysis of variance (ANOVA) using general linear model procedures in SAS software 9.4 (SAS, 2012) (Paper II).

Data on soil properties and maize crop parameters and yields were subjected to two-way ANOVA to evaluate the effect of: a) manure/fertiliser application and liming and their interaction, by cropping season, and b) manure types and liming and their interaction by cropping season, using JMP Pro 14 software (JMP® 14.0.0, SAS Institute Inc., Cary, NC, USA). Block and plot were used as random variables (Papers III and IV). Separation of means was tested in all cases using the Tukey's range test when significant differences were indicated ($P<0.05$).

5 Results and Discussion

5.1 Effect of cutting height and repeated harvests on biomass production in the three legume tree species (Paper I)

Legume trees and shrubs have long been grown by smallholder farmers, with the primary objective of improving both the quality of livestock fodder and soil fertility by using their foliage as green manure (Gutteridge and Shelton, 1994). A major challenge to sustainable productivity of these legume trees is their establishment and management (Partey, 2011).

The results in Paper I showed that *A. angustissima*, *M. scabrella* and *L. pallida* all established well on the weathered Ferralsol soil at the experimental site in Southern Rwanda, but that *L. pallida* established slowly (Figure 6). This corroborates earlier findings of good establishment of *A. angustissima* and *M. scabrella* on acidic and infertile soils (Niang *et al.*, 1994, Dzowela *et al.*, 1997, Somarriba, 1992). It also confirms findings that *L. pallida* does not thrive under soil conditions of low phosphorus and calcium, high Al^{3+} saturation and waterlogging but grows well in soil with pH >5 (Wambugu *et al.*, 2006). Shoot biomass production (stems and leaves) is the primary output for smallholder farmers applying an agroforestry system and depends on tree species and management. There was no consistent effect of cutting regime on shoot biomass accumulation after repeated productivity measurement in Paper I. The overall trend was for somewhat higher shoot biomass production at low (0.3 m) cutting height for *A. angustissima* and *L. pallida*, but lower biomass after repeated cutting *M. scabrella* (Table 1 in Paper I) which may be explained by depletion of carbohydrate reserves (Latt *et al.*, 2000) and loss of plants (Figure 7).

Figure 6. Acacia angustissima, Leucaena pallida and Mimosa scabrella establishment

Figure 7. Mimosa scabrella showed low tolerance to cutting after the third harvest as evidenced by many dead plants (left) compared with *Leucaena pallida* (right)

This is in line with previous reports of varying effects of cutting height for a range of legume tree species. Isah *et al*. (2014) obtained more *Moringa oleifera* biomass at lower cutting (0.2 m) than higher cutting (1.0 m) under drier conditions in Maradi, Niger, while an increase in biomass production with increasing cutting height has been observed for *Gliricidia sepium* and *Leucaena leucocephala* under more humid conditions (Duguma *et al*., 1988). Niang *et al*. (1994) detected an increase in biomass production when moving from low cutting (0.25 m) to high (0.75 m) for some species, including *M. scabrella*, which is corroborated by findings in this thesis. However, Niang *et al*. (1994) found no cutting height effects for other species, while Erdmann *et al.* (1993) found no effect of cutting height on biomass production in *G. sepium*.

The response of legume trees to cutting management may thus be species-dependent and specific to agro-ecological conditions, so each species taken into use for agroforestry needs to be evaluated so that it can be used in the most effective way on farms. *Acacia angustissima* produced more shoot biomass than *L. pallida* and *M. scabrella* throughout the experimental period applied in Paper I. *Mimosa scabrella* established quickly and produced the highest amount of biomass in the first harvest, but did not regrow strongly after the third harvest occasion (Figure 7). In contrast, *L. pallida* initially had the lowest shoot biomass production but it increased from the third harvest, which is explained by the slow establishment reported earlier. *Acacia angustissima* and *L. pallida* showed higher biomass production than previously reported Nyoka *et al.* (2012), (Akyeampong, 1998) respectively whereas leaf production for *M. scabrella* was considerably less than that reported by Niang *et al.* (1994).

The variations in shoot biomass production observed between growing periods for all species in Paper I were most probably caused by variations in weather, especially rainfall, during the experiment (Figure 1 in Paper I). For example, the lower shoot biomass at the second, fourth and fifth harvests is explained by lower rainfall recorded during these growing periods than during the first and third periods (Table 1 in Paper I). Biomass production was closely related to the number of shoots sprouted after harvesting and the tolerance of the tree species to repeated harvests (Figure 8). The number of shoots per tree was not affected by cutting height for *A. angustissima* and *L. pallida* (Figure 8) and they showed 100% survival rate (Figure 9). However, *M. scabrella* cut at 0.3 m showed the highest number of shoots at the first harvest, followed by a sharp decline at later harvests. The decline in *M. scabrella* biomass production and survival rate during the fourth and fifth regrowth periods indicates inability of this species to withstand multiple cuttings. Similarly, Bakke *et al.* (2009) reported non-adaptation of *Mimosa tenuiflora* to annual pruning on soils with a pH range of 5.4-6.0 and a total annual rainfall range of 514-803 mm. Delaying the onset of harvesting, increasing the harvest interval and partial harvesting, and thus avoiding excessive depletion of carbohydrate reserves in trees, could be strategies to increase survival and biomass production.

Legume trees are harvested frequently in cut-and-carry fodder systems to supplement low-quality livestock diets and use as green manure for soil fertility improvement. At different harvesting occasions (Paper I), leaf yield followed the same pattern as biomass yield, but was not affected by cutting height, while stem production decreased at 1.0 m cutting height (Table 1 in Paper I).

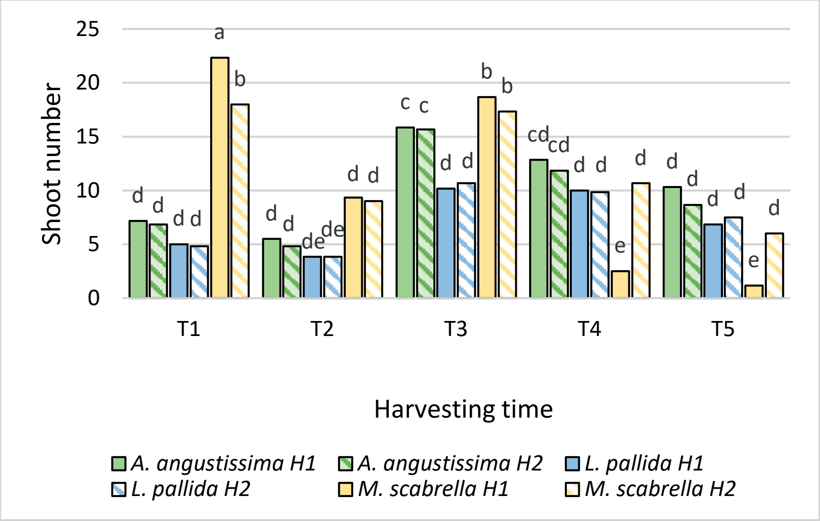

Figure 8. Effect of cutting height and harvest time on number of shoots per tree in *Acacia angustissima, Mimosa scabrella* and *Leucaena pallida* at harvest time T1 to T5. H1: cutting height at 0.3 m; H2: cutting height at 1.0 m. Least square means (bars) with different letters are significantly different at P<0.05.

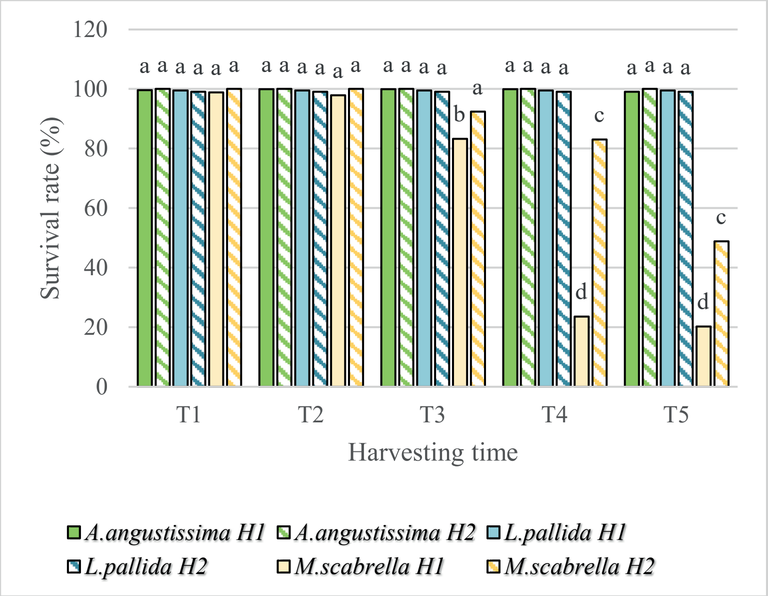

Figure 9. Effect of cutting height and harvest time on survival rates of *Acacia angustissima, Mimosa scabrella* and *Leucaena pallida* at harvest times T1 to T5. H1: cutting height at 0.3 m; H2: cutting height at 1.0 m. Least square means (bars) with different letters are significantly different at P<0.05.

This led to consistently higher average leaf: stem ratio at 1.0 m than 0.3 m cutting height for the harvested biomass. For forage plants, it is important that the leaf:stem ratio is greater than 1 (Calado *et al*., 2016). This ratio exerts a great influence with regard to animal nutrition, since the nutrient content and digestibility are generally higher in leaves than in stems (Casanova-Lugo *et al*., 2014). For the three species tested in Paper I, leaf: stem ratio was >1 at both cutting heights in all the cases except that *L. pallida* had a leaf: stem ratio <1 at 0.3 m cutting height.

Overall, *A. angustissima* and *L. pallida* performed well at both cutting heights and repeated harvest times, with the highest total biomass and leaf production in *A. angustissima*. On the other hand, the poor performance of *M. scabrella* at later harvests suggests that this species is not useful for fodder production under these agro-ecological conditions. This species could possibly be more useful for supplying other tree products, such as fuelwood, building poles and stakes for climbing crops.

5.2 Quality and digestibility of pure species and feed mixtures (Papers I and II)

The nutritive value of animal feed is a function of the chemical composition, mainly crude protein (CP) and fibre, feed digestibility and voluntary intake, and these depend on the plant species and management practice. The CP content was high in all species analysed in this thesis and was not affected by cutting height. However, when measured across all species and harvests, the highest values of NDF, ADF and total polyphenols were observed at 1.0 m cutting height, although differences in general were not significant for individual harvests or species (Table 2 paper I).

The CP content in *A. angustissima* and *L. pallida* was higher than that reported by Abdulrazak *et al*. (2000) for different *Acacia spp*. And that reported by Mutimura *et al*. (2013) for *L. pallida*. This difference in CP may explained by climate at the time of sampling (Lee, 2018). The range of CP content observed for *M. scabrella* (Table 2 Paper II) was not far from that reported by Niang *et al*. (1996). In all cases, the CP content of the leafy fraction of *A. angustissima*, *L. pallida* and *M. scabrella* at both cutting heights was greater than 19%, a threshold value used to classify prime fodder (Kamanzi and Mapiye, 2012).

Mixing *A. angustissima*, *L. pallida* and *M. scabrella* with the basal grass diet (*Chloris gayana*) increased the dietary CP content from an initial 8.4% in the grass to 19.8%, 18.1% and 16.1%, respectively (Figure 10).

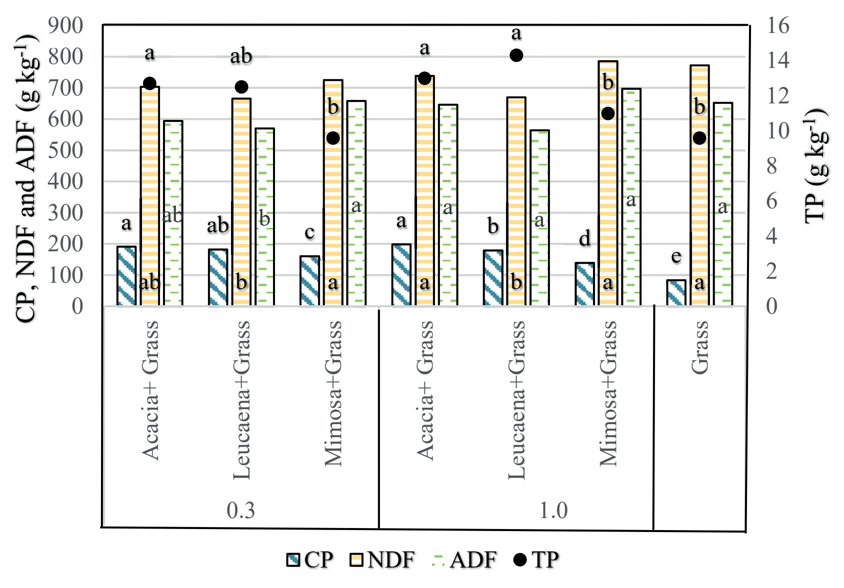

Figure 10. Effect of *Acacia angustissima* , *Mimosa scabrella* and *Leucaena pallida* cut at 0.3 m and 1.0 m height on crude protein (CP), neutral detergent fibre (NDF), acid detergent fibre (ADF) and total polyphenol (TP) content in a mixed legume-grass (*Chloris gayana*) feed. Least square means (bars) with different letters are significantly different at $P<0.05$.

The fibre content (NDF and ADF) in all three species was higher than in the grass (Figure 10) and higher than most literature values (Mutimura *et al*., 2013, Rubanza *et al*., 2005, Hove *et al*., 2001), but lower than that reported by Diriba *et al*. (2013). Higher NDF and ADF could be due partly to the presence of petioles in the leafy samples. Topps (1992) attributed higher values of cell wall fractions in forage to inclusion of woody twigs during the analysis. Total polyphenol content was much lower than reported by Rubanza *et al*. (2005) for *A. angustissima* grown in Tanzania and by Mutimura *et al*. (2013) for *L. pallida* grown in Rwanda. However, the values were similar to those found by others (Mokoboki, 2011, Rubanza *et al*., 2006) for Acacia spp. and browse tree species (Salem *et al*., 2013) classified as good supplements for low-crude protein forage. Furthermore, due to the total polyphenol content being below the 5% threshold suggested by Haile and Tesfamaraiam (2013) for green manure for crops, the tree legumes analysed in this thesis can also be valuable as green manures, thus providing another potential use on farms. However, *A. angustissima* and *L. pallida* increased the NDF and ADF content in the mixed diet compared with grass alone.

The *in vitro* organic matter digestibility (IVOMD) of the mixed diet was found to be intermediate between that of pure legumes and grass. Mauricio

(1996) suggests that the main chemical components involved in fermentation are proteins, carbohydrates and cellulose. All the feed mixtures in Paper I, irrespective of cutting height, had CP >130 g/kg DM, which exceeds the level required to allow growth of rumen microorganisms responsible for feed fermentation (Dal Pizzol *et al.*, 2017). However, the higher NDF and ADF content in the feed mixtures could limit their potential as a supplement to low-quality feeds, by limiting feed intake through physical fill effects (McDonald *et al.*, 2011). This effect would be more pronounced for *A. angustissima* and *M. scabrella* cut at 1.0 m, since they had the highest NDF content. Nevertheless, the species could be used as supplements to low-quality grass diets.

5.3 Effect of supplementing cattle feed on manure quality (Paper III)

The composition of manure depends largely on the animal diet, animal species, and the ways in which the manure is collected, stored and applied (Bayu *et al.*, 2004). Supplementing *Chloris gayana* grass with *A. angustissima* leaves improved the quality of the manure produced by cattle, by increasing the concentration of nitrogen, carbon, calcium, magnesium and potassium (Table 2). Increased nutrient concentrations in the manure derived from mixed feed of *C. gayana* and *A. angustissima* were the result of the enhanced nutrient concentrations found in the mixed feed (Paper II).

The findings in this thesis are thus in line with Lekasi *et al.* (2002), who reported a linear relationship between nitrogen intake and nitrogen excretion in faeces and urine. The findings in this thesis and those reported by Lekasi et al. (2002) and Muinga *et al.* (2007) also suggest that diets with higher protein concentrations can result in manures with higher concentrations of nitrogen. For this to be achieved, however, the additional nitrogen (and other nutrients) must be retained during manure handling and storage, and as much urine as possible must be collected with the faeces. According to Mafongoya *et al.* (2006), up to 60% of nitrogen and 10% of phosphorus in manure are lost due to poor management in smallholder farming. Storing manure in heaps has been shown to maintain the nitrogen concentration at a higher level than in unheaped stored manure (Mafongoya *et al.*, 2006). Manure storage in plastic-covered heaps, as in this thesis, proved to be sufficiently efficient in retaining losses, allowing differences caused by diet supplementation to be revealed. Storage in plastic may be affordable for many smallholder farmers.

Table 2. *Chemical composition (per unit mass after drying at 70ºC) of different manures obtained from cattle fed on grass only diet or a mixed grass+legume*

		Manure properties			Application rates of manure	
	Unit	Grass	Grass+legume	Unit	Grass	Grass+legume
pH_{H2O}		6.9	7.0			
C	%	17 ^{b}	20 ^{a}	t ha^{-1}	0.85	1.0
N	%	1.2 ^{b}	1.5 ^{a}	kg ha^{-1}	60	75
C/N		14.1	13.2			
P	g kg^{-1}	6.2	6.2	kg ha^{-1}	31	31
Ca	g kg^{-1}	6.4 ^{b}	9.3 ^{a}	kg ha^{-1}	32	46
Mg	g kg^{-1}	2.9 ^{b}	3.7 ^{a}	kg ha^{-1}	14.5	18.5
K	g kg^{-1}	3.1 ^{b}	6.5 ^{a}	kg ha^{-1}	15.5	32.5
Na	g kg^{-1}	0.9^{b}	1.4^{a}	kg ha^{-1}	4.5	7.0

Grass: manure from *Chloris gayana* grass only; Grass+legume: Manure from *C. gayana* supplemented with *A. angustissima*. Data presented are Least Square Means for the four seasons, where values followed by the same letters are not significantly different ($P < 0.05$).

5.4 Effect of manure, NPK fertiliser and liming on soil properties (Paper III)

Soil analysis before the start of the experiments showed that the soil at the study site was very acidic (pH = 4.3), with low soil organic carbon, nitrogen, phosphorus, potassium, calcium and magnesium concentrations and low CEC (Table 1). Thus, the soil status would be expected to restrict crop growth (Hazelton and Murphy, 2007). However, soil parameters improved gradually after manure, NPK and lime (travertine) application at the maize planting stations.

5.4.1 Effect on soil water-holding capacity and infiltration rate

Soil infiltration rate and water-holding capacity (WHC) increased with the manure treatment compared with NPK fertilisation and the control treatment (Figure 1 in Paper III). Changes in soil physical properties with organic manure treatment have also been reported by other researchers (Li *et al.*, 2015, Bayu *et al.*, 2004, Haynes and Naidu, 1998). In Paper III, the changes agreed with SOC concentration in the manure treatments. Soil organic carbon increases the stability of aggregates, the frequency of macro-pores and soil porosity (Li *et al.*, 2015), thus increasing the soil infiltration rate. Soil water storage can be expected to increase with SOC content, which generally increases the WHC and especially the plant available-water through improving the pore distribution (Gilley *et al.*, 2002, Franzluebbers, 2002). Increased infiltration rate can reduce water losses by runoff and, together with increased soil WHC, can increase the amount of water available to plants, increase nutrient solubility and availability, and enhance soil microbial activity. The increased water stock can sustain the crop through dry spells during the growing season, which are otherwise a challenge in rain-fed agriculture.

5.4.2 Effect on soil acidity

Manure and lime application increased soil pH and decreased total exchangeable acidity (TEA) and exchangeable Al^{3+} compared with the baseline (prior to treatment) and non-fertilised treatments (Figure 11). These findings are in line with previous reports of an increase in pH after manure application (Naramabuye and Haynes, 2006b, Whalen *et al.*, 2000, Eghball, 1999). The increase in soil pH and decrease in TEA and exchangeable Al^{3+} resulting from manure application was similar to that of liming using travertine, supporting the starting hypothesis that manure provides a liming and fertiliser effect comparable to that of combined NPK fertiliser and lime application for soil improvement. The application of travertine resulted in an increase in soil pH of 0.19 pH units after the first cropping season. This was similar to that detected by Nduwumuremyi *et al.* (2013) 16 weeks after application of 1.4 t travertine ha^{-1} (0.17 pH units). Although the manure and lime at the applied rates increased the soil pH from extremely acidic (pH <4.4) to strongly acidic (pH between 5.1 to 5.5) (McFerland *et al.*, 2001) over the two years, the pH did not reach the value at which aluminium toxicity is substantially alleviated (pH>5.5) (Hazelton and Murphy, 2007). Nevertheless, in the longer term the practice of micro-dosing manure would be progressively beneficial for soil fertility and crop production for farmers with limited capacity to purchase lime and obtain cattle manure.

The soil pH in the non-limed NPK treatment was similar to that in the control and the baseline soil prior to treatment. Ammonium-based NPK fertilisers are known to be potentially acidifying. Such acidification seemed to be insignificant at the study site used in this thesis work, probably due to the low pH limiting the nitrification process. According to Sahrawat (2008) stated that substantial nitrification takes place in soil at pH ranging between 5.5 and 10.0, with the optimum around 8.5, and that nitrification is severely curtailed at soil pH less than 5.0. The low original pH at the experimental site may thus have precluded further acidification through nitrification, an otherwise common challenge in the region, where urea and ammonium-based fertilisers dominate the market.

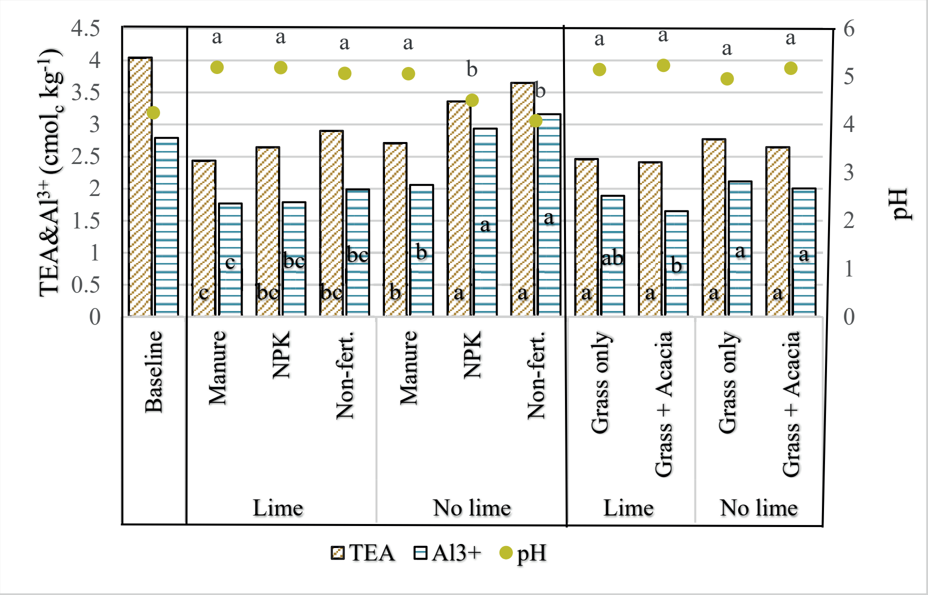

Figure 11. Effect of manure, NPK fertiliser and lime on soil total exchangeable acidity, aluminium and pH. Data shown are least square means for the fourth cropping season. Means with boxes with the same letter are not significantly different at (P<0.05).

5.4.3 Effect on soil organic carbon and cation exchange capacity

The manure and NPK treatments increased SOC and CEC compared with the control treatments (Figure 12). This increase in SOC and CEC corroborates findings in general of (Haynes and Naidu, 1998) and those of Adams *et al.* (2016) with reduced fertiliser in particular. The high values in the manure treatment were mainly associated with the organic carbon in the manure itself, but also with increased above- and below- ground biomass production. The slight increase in SOC with NPK fertiliser is likely due to the increased biomass production. As CEC is closely related to SOC content, it can be expected to change with SOC content, and this was corroborated in this thesis. Soil organic matter acts as a source and sink for plant nutrients. Maintenance of SOC levels through manure application, leaving crop residues in the field and enhancing crop biomass production through good crop management results in retention and storage of nutrients. It also increases aggregate stability and thereby improves soil macrostructure, infiltration and water-holding capacity (Bayu *et a*l., 2004), as discussed above.

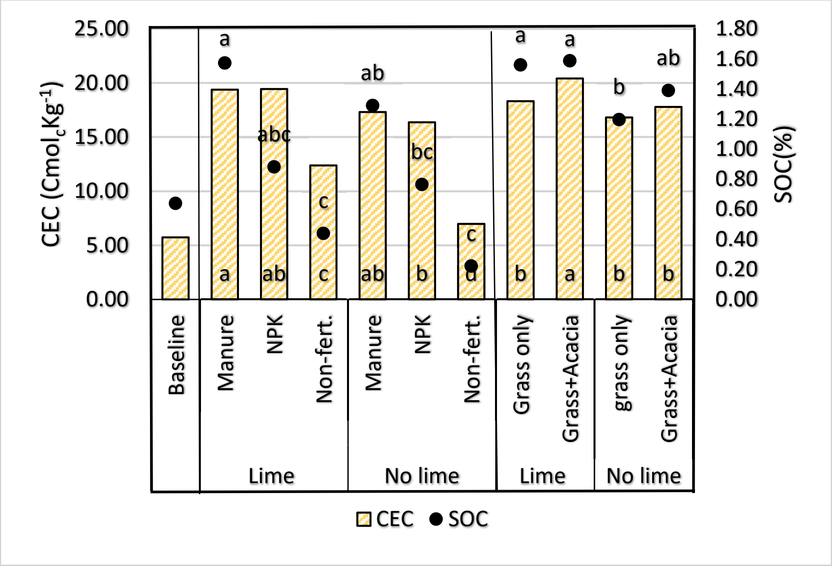

Figure 12. Effect of manure, NPK fertiliser and lime on soil organic carbon (SOC) and cation exchange capacity (CEC). Data shown are least square means for the fourth cropping season. Means with boxes with the same letter are not significantly different at (P<0.05).

5.4.4 Effect on soil nutrients

Cattle manure and NPK fertiliser increased the level of most nutrients compared with the baseline and the control treatments. Total nitrogen and available phosphorus content increased in manure and NPK treatments compared with baseline and the unfertilised control (Figure 13). However, there was no difference between the manure and NPK fertiliser treatments as regards total nitrogen. The increase in soil total nitrogen and available phosphorus provides support for the hypothesis that manure can improve soil fertility as efficiently as NPK fertiliser and also provides a liming effect. An increase in total nitrogen and available phosphorus in soil with manure application has also been reported by Whalen *et al.* (2000). In addition to the increase in nitrogen, phosphorus and potassium, manure application increased exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations at the maize planting stations , indicating that manure played a substantial role in provision of Ca^{2+} and Mg^{2+}, either directly and/or by influencing their availability through provision of exchange sites on soil organic matter (Mulia *et al.*, 2019). Overall, the results show that micro-dosing animal manure improved the general soil fertility parameters at the planting stations. However, the enhanced manure quality derived from fodder supplementation did not carry through to detectable differences in soil quality during the course of the experiment.

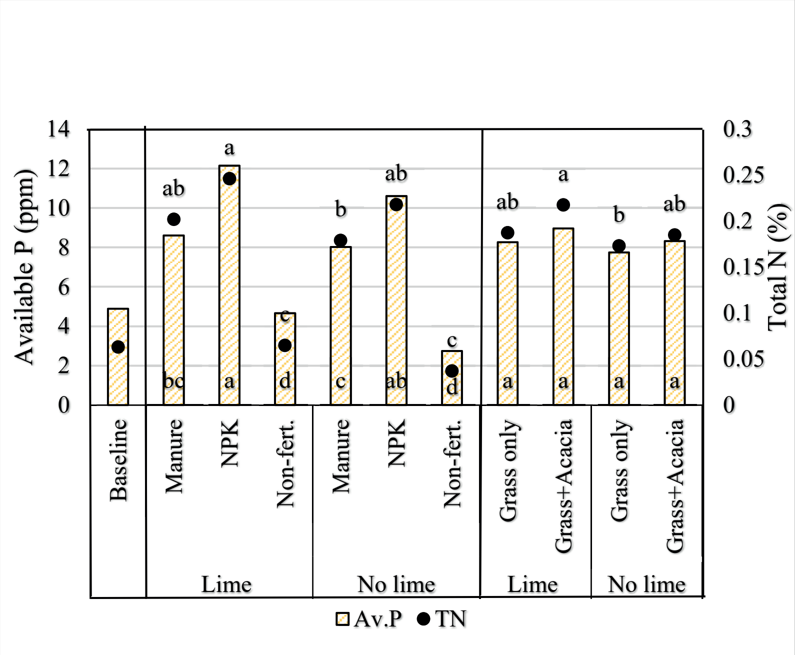

Figure 13. Effect of manure, NPK fertiliser and lime on total nitrogen and available phosphorus. Data shown are least square means for the fourth cropping season. Means within boxes followed by the same letter are not significantly different at (P<0.05).

5.5 Effect of manure, NPK fertiliser and liming on maize yield

The results presented in this thesis are for three cropping seasons out of four studied, because the first maize crop failed due to drought. During the subsequent three growing seasons, manure and NPK fertiliser treatments increased number of maize leaves, plant height, SPAD values and maize yield compared with the control treatment (Figure 1A in Paper IV). With NPK fertiliser (supplying 70 kg N ha^{-1}), there was a maize grain and stover yield increase from the second season compared to manure and unfertilised control (Figure 14a); the increase in maize grain was 3- to 4-fold (to 7 t ha^{-1}) and that of stover approximately 3-fold in season 4, compared with the unfertilised control (Figure 2A in Paper IV). This increase in maize yield compared with the unfertilised control treatment upon NPK fertilisation shows that the soil at the experimental site is responsive to fertiliser application. It also suggests that other nutrients in the soil were present in sufficient amounts for crop demand, at least during the three cropping seasons studied.

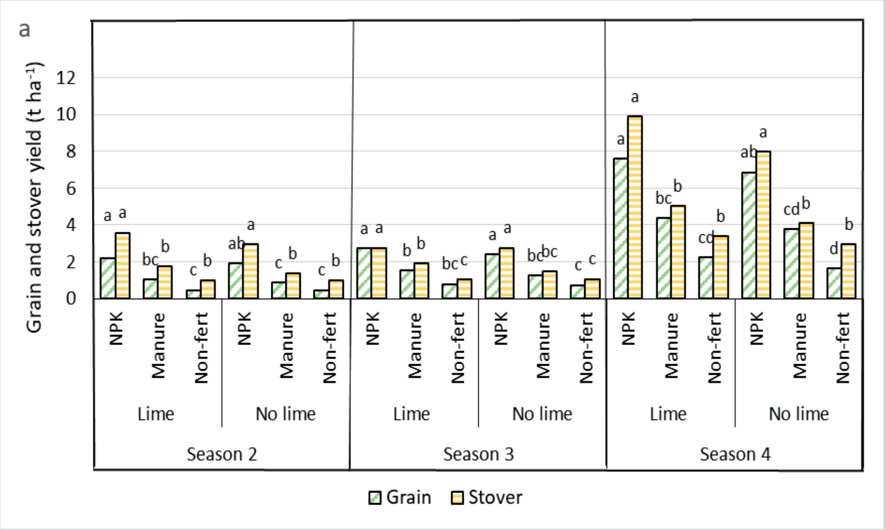

Figure 14a. Effect of manure, NPK fertiliser and lime on maize grain and stover yield. Data shown are least square means for three cropping season. Means within boxes followed by the same letter are not significantly different at (P<0.05).

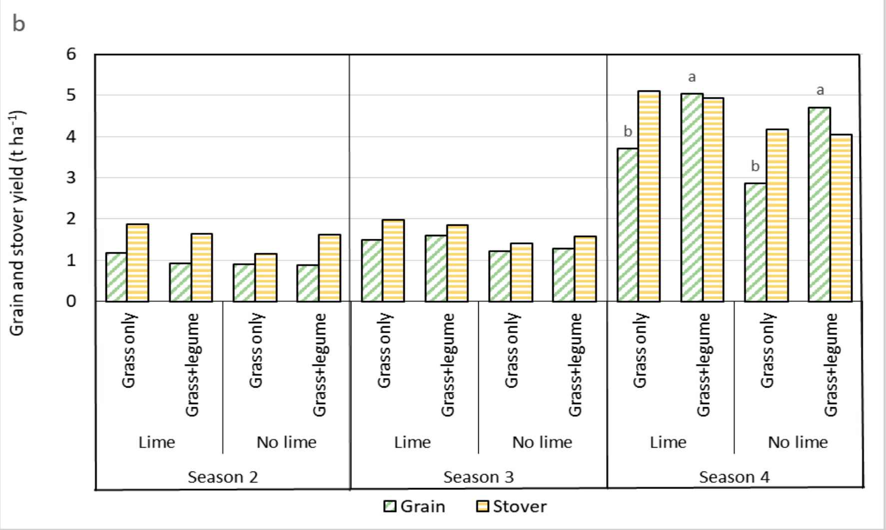

Figure 14b. Effect of grass only, grass + legume manure and lime on maize grain and stover yield. Data shown are least square means for three cropping season. Means within boxes followed by the same letter are not significantly different at (P<0.05

Cattle manure on smallholder farms in sub-Saharan Africa is frequently characterised by low nutrient concentrations (Mugwira and Mukurumbira, 1985, Lekasi *et al.*, 2002) and slow nutrient release. Therefore cattle manure may need to be applied for several growing seasons before yields increase significantly (Nyamangara *et al.*, 2005). Due to the loss of the maize crop in the first growing season, the effect of manure application in that season was not evaluated in this thesis. However, the yield increased significantly from the second season, suggesting a relatively rapid nutrient supply from the manure. The highest nitrogen supply, SPAD readings and yield were found in the NPK treatment. However, considering that some nitrogen and phosphorus were held in the organic fraction of the manure and that the manure dose was only 5 t dry weight ha^{-1} (25% of recommended dose), the maize yield increase in the manure treatment was considerable. Where insufficient manure availability precludes sufficient application rates to achieve this on a wider scale, micro-dosing manure (or other organic soil amendments) may be a way to enhance the rooting environment and survival of the young crop plants and retain higher crop density on fields.

Manure quality, in terms of nitrogen and base cation concentrations, was enhanced by the inclusion of *A. angustissima* in the mixed diet for cattle. This did not significantly increase yield during the first two seasons, but it did so during the fourth season (Figure 14b), suggesting a benefit from the improved manure quality in the longer term. An enhanced fertiliser effect of the manure produced by animals fed improved feed may be a positive side-effect of the increased production level, provided that the increased nutrient (particularly nitrogen) concentrations in faeces and urine can be retained in the manure during handling and storage.

Maize is generally considered to suffer at soil pH below 5.5 (Lidon and Barreiro, 2002), and liming of soils may be needed at pH_{H2O} <4.5 (Fairhurst, 2012). The small difference in yield observed between limed and non-limed treatments suggests that soil pH was nevertheless not a major limiting factor for the maize variety used in Paper IV, and the capacity of the manure to affect maize performance and yield via raised pH was not truly tested.

Many studies have shown increased cereal crop yields following micro-dosing of inorganic fertiliser (*e.g.* (Hayashi *et al.*, 2008, Twomlow *et al.*, 2010, Aune and Ousman, 2011, Bagayoko *et al.*, 2011)). Manure micro-dosing has been less well studied. Since manure is a valuable and limited resource, application by micro-dosing could be the most efficient way to make use of this resource. Differences in application technology were not tested in Paper IV, but the increase observed in maize growth and yield in response to manure micro-dosing confirms findings by Mugwira *et al.* (2002) that small amounts of micro-dosed manure are efficient in raising yields. Ibrahim *et al.* (2016) also reported a positive effect of manure micro-dosing when it was combined with inorganic fertiliser micro-dosing.

In the experiment in Paper III, manure management was improved compared with common farming practice in the study region, but was still not very advanced. The practice of collecting faeces and urine frequently and covering the manure with plastic sheeting is achievable for many smallholder farmers. Furthermore, the amount of manure applied by micro-dosing in this study, 25% of the recommended manure application dose, *i.e.* 5 t dry weight ha^{-1}, is within reach of many smallholder farmers. This is especially the case in a densely populated country like Rwanda, where most farms are considerably smaller than 1 ha, also aligns with, and is achievable within, the One Cow Per Poor Family programme in Rwanda.

6 Conclusions and recommendations

This thesis provides new insights regarding legume tree management in agroforestry systems for sustainable biomass production on acid soil and use of low manure rates to improve soil properties and crop production.

Major conclusions of this work are:

- As *Acacia angustissima* and *Leucaena pallida* performed well on acidic soils, showed good tolerance to repeated harvests and produced more biomass at low cutting height than high cutting height they are recommended for use as fodder and green manure. In contrast, *Mimosa scabrella* showed rapid establishment but did not survive repeated harvests, especially at low cutting height.

- Low cutting is recommended as an ideal management practice to farmers aiming for high leaf production by *A. angustissima* and *L. pallida* for higher quality fodder and shoot production.

- As the leafy fraction of *A. angustissima* and *L. pallida* have high protein content and minerals, they are recommended for use for supplementing a grass-based diet in order to improve the nutritional quality and digestibility of the diet.

- *Acacia angustissima* and *L. pallida* are suitable agroforestry species to integrate on small and depleted parcels for smallholder farmers as long as their cutting management is driven by the farmer's objectives, *e.g.* use as fodder, green manure, boundary demarcation, fuelwood, reforestation etc.

- Supplementing low-quality grass-based animal feed with high protein content foliage such as *A. angustissima* is recommended to improve the manure quality.

- Manure application is recommended to improve soil properties and crop production for smallholder farmers with limited purchasing power of inorganic and liming materials.

- Micro-dosing practices to replenish soil fertility and increase crop production would be a feasible practice for farmers lacking the resources to produce sufficient manure for conventional banding or broadcasting.

7 Implications and future perspectives

Food security embraces food production, stability and supply. Rwanda is one of the most densely populated countries in Africa, with more than 445 inhabitants per km^2. Two major programmes have been introduced to overcome the food insecurity in the country, namely the Girinka (or One Cow Per Poor Family) programme and the Crop Intensification Programme (CIP). However, their success requires an integrative concept of soil fertility maintenance, animal production and crop production. For the Girinka programme to succeed, farmers need sufficient quality feeds for the improved breed cows distributed to them in the programme, but land and resource limitations are challenging. Agroforestry is one practice to overcome resource limitations, but it would be better to have more species that can establish well on depleted acid soils and that are adapted to multiple harvests at various cutting heights.

The results presented here suggest that *Acacia angustissima* and *Leucaena pallida* can be grown on weathered acidic soils for long-term biomass production. Use of foliage from these agroforestry species as a supplement to low-quality grass and crop residues for animal feeding can help to reduce the dependency on off-farm resources and provide a balanced diet for the animals. This would increase milk and meat production and improve manure quality.

Factors determining success in the CIP initiative are increasing use of agricultural production inputs (fertiliser and manure) and sustainable management of natural resources. Agroforestry using legume species can play a considerable role in improving soil fertility also on non-animal farms by increasing the nitrogen content in soil through biological nitrogen fixation, while also increasing inputs of carbon and plant nutrients to the root-zone of arable crops by decomposition of litter fall and green manure, and by reducing soil erosion. The results presented here suggest that the species such as *A. angustissima* and *L. pallida* can provide these benefits also on very strongly acidic soils. However, further studies are needed on the green manure decomposition rates of these species in order to determine their fertiliser value.

The increasing need for agricultural inputs for crop production is a major challenge for low-income Rwandan farmers. In this thesis, the use of fertiliser and manure micro-dosed concentrated at maize planting stations resulted in an improvement in soil fertility and an increase in crop yield. Micro-dosing could therefore be a viable solution in crop production towards meeting the food security problem in Rwanda, but more research is needed on micro-dosing of manure alone and in combination with *e.g.* mineral fertiliser.

References

Abdulrazak, S. A., Orden, E. A., Ichinohe, T. & Fujihara, T. 2000. Chemical composition, phenolic concentration and in vitro gas production characteristics of selected acacia fruits and leaves. *Asian-Australasian Journal of Animal Sciences*, 13, 935-940.

Adams, A. M., Gillespie, A. W., Kar, G., Koala, S., Ouattara, B., Kimaro, A. A., Bationo, A., Akponikpe, P. B. I., Schoenau, J. J. & Peak, D. 2016. Long term effects of reduced fertilizer rates on millet yields and soil properties in the West-African Sahel. *Nutrient Cycling in Agroecosystems*, 106, 17-29.

Akyeampong, E. 1998. Comparative performance of Leucaena pallida and Calliandra calothyrsus on an acid soil in a Sub-Humid environment in Burundi. *International Tree Crops Journal*, 9, 227-232.

Allen, M. S. 2000. Effects of diet on short-term regulation of feed intake by lactating dairy cattle. *Journal of Dairy Science*, 83, 1598-1624.

Anderson, J. M. & Ingram, J. S. I. 1993. Tropical soil biology and fertility: a handbook of methods, Wallingford, UK.

AOAC 1990. Association of official Analytical chemists. Official methods of analysis 15th edition. A.O.A.C. Arlington Virginia, USA.

Aprile, F. & Lorandi, R. 2012. Evaluation of cation exchange capacity (CEC) in tropical soils using four different analytical methods. *Journal of Agricultural Science* (Toronto), 4, 278-289.

Arce, M. L. R. & Bachman, S. A taxonomic revision of" Acaciella"(Leguminosae, Mimosoidae). Anales del Jardín Botánico de Madrid, 2006. *Real Jardín Botánico*, 189-244.

Arias, L., Soriano, R., Sánchez, E. & González, C. 2014. Chemical composition and in vitro digestibility of fodder trees and shrubs consumed by goats in the Low Mixteca region of Oaxaca, Mexico. *Research Journal of Biological Sciences*, 9, 92-97.

Aune, J. B. & Ousman, A. 2011. Effect of seed priming and micro-dosing of fertilizer on sorghum and pearl millet in western sudan. *Experimental Agriculture*, 47, 419-430.

Bagayoko, M., Maman, N., Pale, S., Sirifi, S., Taonda, S. J. B., Traore, S. & Mason, S. C. 2011. Microdose and N and P fertilizer application rates for pearl millet in West Africa. *African Journal of Agricultural Research*, 6, 1141-1150.

Bakke, I. A., Bakke, O. A., Salcedo, I. H. & Andrade, A. P. 2009. In situ fodder production of Mimosa tenuiflora under pruning in native caatinga tropical dry forest in Brazil. *Tropical Grasslands*, 43, 178-187.

Balasubramanian, V. & Egli, A. 1986. The role of agroforestry in the farming systems in Rwanda with special reference to the Bugesera-Gisaka-Migongo (BGM) region. *Agroforestry systems*, 4, 271-289.

Baloyi, J. J., Ngongoni, N. T., Topps, J. H. & Ndlovu, P. 1997. Chemical composition and degradability of Brachystegia spiciformis (musasa) leaves and stems harvested over 4 months from three sites in Zimbabwe. *Animal Feed Science and Technology*, 69, 179-186.

Barber, S. A. 1984. Liming materials and practices. Soil acidity and liming, 171-209.

Barry, T. N. & Duncan, S. J. 1984. The role of condensed tannins in the nutritional value of Lotus pedunculatus for Sheep 1 Voluntary intake British Journal of Nutrition, 51, 485-491.

Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B. & Kimetu, J. 2007. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. *Agricultural Systems*, 94, 13-25.

Bayu, W., Rethman, N. F. G. & Hammes, P. S. 2004. The role of animal manure in sustainable soil fertility management in sub-Saharan Africa: A review. *Journal of Sustainable Agriculture*, 25, 113-136.

Blessing, O. C., Ibrahim, A., Safo, E. Y., Yeboah, E., Abaidoo, R. C., Logah, V. & Monica, U. I. 2017. Fertilizer micro-dosing in West African low-input cereals cropping: benefits, challenges and improvement strategies. *African Journal of Agricultural Research*, 12, 1169-1176.

Bray, R. A., Palmer, B. & Ibrahim, T. M. 1997. Performance of shrub legumes at four sites in Indonesia and Australia. *Tropical Grasslands*, 31, 31-39.

Bray, R. H. & Kurtz, L. T. 1945. Determination of total organic and available forms of phosphorus in soils Soil Science, 59, 39-45.

Bucagu, C., Vanlauwe, B., Van Wijk, M. T. & Giller, K. E. 2013. Assessing farmers' interest in agroforestry in two contrasting agro-ecological zones of Rwanda. *Agroforestry Systems*, 87, 141-158.

Calado, T. B., Da Cunha, M. V., Teixeira, V. I., Dos Santos, M. V. F., Cavalcanti, H. S. & Lira, C. C. 2016. Morphology and productivity of "Jureminha" genotypes (Desmanthus spp.) Under different cutting intesities. *Revista Caatinga*, 29, 742-752.

Chaer, G. M., Resende, A. S., Campello, E. F. C., De Faria, S. M. & Boddey, R. M. 2011. Nitrogen-fixing legume tree species for the reclamation of severely degraded lands in Brazil. *Tree Physiology*, 31, 139-149.

Dal Pizzol, J. G., Ribeiro, H. M. N., Quereuil, A., Le Morvan, A. & Niderkorn, V. 2017. Complementarities between grasses and forage legumes from temperate and subtropical areas on in vitro rumen fermentation characteristics. Animal Feed Science and Technology, 228, 178-185.

Delve, R., Cadisch, G., Tanner, J., Thorpe, W., Thorne, P. & Giller, K. 2001. Implications of livestock feeding management on soil fertility in the smallholder farming systems of sub-Saharan Africa. Agriculture, ecosystems & environment, 84, 227-243.

Den Biggelaar, C. & Gold, M. A. 1996. Development of utility and location indices for classifying agroforestry species: The case of Rwanda. *Agroforestry Systems*, 34, 229-246.

Diriba, G., Mekonnen, H., Ashenafi, M. & Agdugna, T. 2013. Nutritive Value of selected browse and herbeceous forage legumes adapted to medium altitude subhumid areas of Western Oromia,Ethiopia. *Global Veterinaria* 11 (6), 809-816.

Dollinger, J. & Jose, S. 2018. Agroforestry for soil health. Agroforestry Systems, 92, 213-219.

Duguma, B., Kang, B. T. & Okali, D. U. U. 1988. Effect of pruning intensities of tree woody leguminous species grown in alley cropping with maize and cowpea on an Alfisol *Agroforestry Systems*, 6, 19-35.

Dzowela, B. H. 1994. *Acacia angustissima*: a Central American tree that's going places. 6, 13-14.

Dzowela, B. H., Hove, L., Mafongoya, P. L. & Maasdorp, B. V. 1997. Performance of legume shrubs at four sites in Indonesia and Australia. *Trop. Grass lands* 31, 31-39.

Eghball, B. 1999. Liming effects of beef cattle feedlot manure or compost. Communications in Soil Science and Plant Analysis, 30, 2563-2570.

Erdmann, T. K., Nair, P. K. R. & Kang, B. T. 1993. Effects of cutting frequency and cutting height on reserve carbohydrates in Gliricidia Sepium (Jacq) Walp. *Forest Ecology and Management*, 57, 45-60.

Fairhurst, T. 2012. Africa Soil Health Consortium: Handbook for integrated soil fertility management.

FAO (ed.) 2006. Guidlines for soil description Viale delle Terme di Caracalla, 00100 Rome, Italy: Publishing Management Service Information Division FAO.

FAO 2017. The future of Food and Agriculture -Trends and Challenges. Rome.

Francis, J. & Sibanda, S. 2001. Participatory action research experiences in smallholder dairy farming in Zimbabwe. *Livestock Research for Rural Development*, 13, 1-12.

Franzluebbers, A. 2002. Soil organic matter stratification ratio as an indicator of soil quality. *Soil and Tillage Research*, 66, 95-106.

Gilley, J. E., Risse, L. M. & Eghball, B. 2002. Managing runoff following manure application. Journal of Soil and Water Conservation, 57, 530-533.

Gusha, J., Ngongoni, N. T. & E. Halimani, T. 2013. Nutritional composition and effective degradability of four forage trees grown for protein supplementation. *Online Journal of Animal and Feed Research* (OJAFR), 3, 170-175.

Gutteridge, R. C. 1998. The potential of nitrogen fixing trees in livestock production systems.

Gutteridge, R. C. & Shelton, H. M. 1994. Animal production potential of agroforestry systems.

Habib, G., Akmal, M., Luqman, Z. & Ahmad, N. 2007. Biomass production and feed quality of three summer fodder species planted under two nitrogen levels. *Sarhad Journal of Agriculture*, 23, 1145-1149.

Haile, W. & Tesfamaraiam, A. 2013. Potential of local plants as a source of N P K on small hollder fields in Southern Ethiopia.

Hairiah, K., Noordwijk, M. V., Santoso, B. & Syekhfani, M. S. 1992. Biomass production and root distribution of eight trees and their potential for hedgerow intercropping on an ultisol in southern Sumatra. *Agrivita*, 15, 54-68.

Hayashi, K., Abdoulaye, T., Gerard, B. & Bationo, A. 2008. Evaluation of application timing in fertilizer micro-dosing technology on millet production in Niger, West Africa. *Nutrient Cycling in Agroecosystems*, 80, 257-265.

Haynes, R. J. & Mokolobate, M. S. 2001. Amelioration of Al toxicity and P deficiency in acid soils by additions of organic residues: a critical review of the phenomenon and the mechanisms involved. *Nutrient Cycling in Agroecosystems*, 59, 47-63.

Haynes, R. J. & Naidu, R. 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. *Nutrient Cycling in Agroecosystems*, 51, 123-137.

Hazelton, P. & Murphy, B. 2007. Interpreting soil test results: what do all the numbers mean?

Hove, L., Chakoma, C. & Nyathi, P. 1999. The potential of tree legume leaves as supplements in diets for ruminants in Zimbabwe. In: HOLNESS, D. (ed.) Proceedings of a joint ZSAP/FAO workshop. Harare, Zimbabwe.

Hove, L., Topps, J. H., Sibanda, S. & Ndlovu, L. R. 2001. Nutrient intake and utilisation by goats fed dried leaves of the shrub legumes Acacia angustissima, Calliandra calothyrsus and Leucaena leucocephala as supplements to native pasture hay. *Animal Feed Science and Technology*, 91, 95-106.

Hue, N. V., Craddock, G. R. & Adams, F. 1986. Effect of organic -acids on Aluminium toxicity in Subsoils Soil Science. *Society of America Journal*, 50, 28-34.

Ibrahim, A., Abaidoo, R. C., Fatondji, D. & Opoku, A. 2016. Fertilizer micro-dosing increases crop yield in the Sahelian low-input cropping system: A success with a shadow. *Soil Science and Plant Nutrition*, 62, 277-288.

ISAH, A. D., AND, B. A. G. & S.A., Z. 2014. Effects of cutting heights and interval of cutting on the yield of Moringa Oleifera (horse radish). International *Journal of Development and Sustainability*, 3, 1147-1151.

ISAR 1978. Rapport Annuel. Butare-Rwanda.

Kamanzi, M. & Mapiye, C. 2012. Feed inventory and smallholder farmers' perceived causes of feed shortage for dairy cattle in Gisagara District, Rwanda. *Tropical Animal Health and Production*, 44, 1459-1468.

Kang, B., Wilson, G. & Sipkens, L. 1981. Alley cropping maize (Zea mays L.) and leucaena (Leucaena leucocephala Lam) in southern Nigeria. *Plant and soil*, 63, 165-179.

Kho, R. M. 2000. On crop production and the balance of available resources. *Agriculture, ecosystems & environment*, 80, 71-85.

Latt, C. R., Nair, P. K. R. & Kang, B. T. 2000. Interactions among cutting frequency, reserve carbohydrates, and post-cutting biomass production in *Gliricidia sepium* and *Leucaena leucocephala*. *Agroforestry Systems*, 50, 27-46.

Lee, M. A. 2018. A global comparison of the nutritive values of forage plants grown in contrasting environments. *Journal of plant research*, 131, 641-654.

Lekasi, J. K., Tanner, J. C., Kimani, S. K. & Harris, P. J. C. 2002. Manure management methods to enhance nutrient quantity and quality on smallholdings in the Central Kenya Highlands. *Biological Agriculture & Horticulture*, 19, 315-332.

Li, J., Chang, D. & Yang, X. 2015. Impact and simulation of soil organic carbon on soil water infiltration process. *African Journal of Agricultural Research*, 10, 1434-1441.

Lidon, F. C. & Barreiro, M. 2002. An overview into aluminum toxicity in maize. *Bulg. J. Plant Physiol*, 28, 96-112.

Lungu, O. I., Temba, J., Chirwa, B. & Lungu, C. 1993. Effects of Lime and Farmyard manure on soil acidity and maize growth on an acid Alfisol from Zambia. *Tropical Agriculture*, 70, 309-314.

Lupwayi, N. Z., Girma, M. & Haque, I. 2000. Plant nutrient contents of cattle manures from small-scale farms and experimental stations in the Ethiopian highlands. *Agriculture Ecosystems & Environment*, 78, 57-63.

Mafongoya, P. L., Bationo, A., Kihara, J. & Waswa, B. S. 2006. Appropriate technologies to replenish soil fertility in southern Africa. *Nutrient Cycling in Agroecosystems*, 76, 137-151.

Mahmood, F., Khan, I., Ashraf, U., Shahzad, T., Hussain, S., Shahid, M., Abid, M. & Ullah, S. 2017. Effects of organic and inorganic manures on maize and their residual impact on soil physico-chemical properties. *Journal of Soil Science and Plant Nutrition*, 17, 22-32.

Mauricio, R. M. 1996. *In vitro* assessmeent of the nutritive value of mixtures of leaves from tropical fodder trees. University of Oxford.

McDonald, P., Edwards, R. A., Greenhal .J.F., Morgan, C. A., Sinclair, L. A. A. & Wilkinson, R. G. 2011. Animal Nutrition. Seventh Edition, Edenburg Gate, Harlow, Assex CM 2JE, England, Pearson Education Limited.

McFerland, M. L., Haby, V.A., Redmond,L. A., & BADE, D. H. 2001. Managing Soil Acidity. Texas cooperative Extension. Texas.

Menke, K. H., Raab, L., Salewski, A., Steingass, H., Fritz, D. & Schneider, W. 1979. The estimation of the digestibility and metabolizable energy content of ruminant feedingstuffs from the gas-production when they are incubated with rumen liquor *in vitro*. *Journal of Agricultural Science*, 93, 217-222.

MINAGRI 2009. Strategic Plan for the Transformation of Agriculture in Rwanda-Phase II (PSTA II). Final report. Kigali: Ministry of Agriculture and Animal Resources.

MINAGRI 2016. Rwanda Dairy Development Project. Kigali-Rwanda.

Mokoboki, H. K. 2011. Effect of species within season on techniques used to measure nutritive value and anti-nutritional factors in browse tree leaves. *Life science journal*, 8, 112-1119.

Mugwira, L. & Mukurumbira, L. 1985. Nutrient supplying power of different groups of manure from the communal and commercial feedlots. Zimbabwe Agricultural Journal (Zimbabwe).

Mugwira, L. M., Nyamangara, J. & Hikwa, D. 2002. Effects of manure and fertilizer on maize at a research station and in a smallholder (peasant) area of Zimbabwe. *Communications in Soil Science and Plant Analysis*, 33, 379-402.

Muinga, R. W., Mureithi, J. G., Juma, H. & Saha, H. M. 2007. The effect of supplementing Napier grass or maize stover basal diet with either Gliricidia, Clitoria or Mucuna on manure quantity and quality in Jersey cows. *Tropical and Subtropical Agroecosystems*, 7, 157-163.

Mukuralinda, A., Ndayambaje, J., Iiyama, M., Ndoli, A., Musana, B., Garrity, D. & Ling, S. 2016. Taking to scale tree-based systems in Rwanda to enhance food security, restore degraded land, improve resilience to climate change and sequester carbon. Washington, DC: PROFOR.

Mulia, S., McMahon, P. J., Purwantara, A., Bin Purung, H., Djufry, F., Lambert, S., Keane, P. J. & GUEST, D. I. 2019. Effect of organic and inorganic amendments on productivity of Cocoa on a marginal soil in Salawesi. *Indonesia Experimental Agriculture*, 55, 1-20.

Mutimura, M., Myambi, C. B., Gahunga, P., Mgheni, D. M., Laswai, G. H., Mtenga, L. A., Gahakwa, D., Kimambo, A. E. & Ebong, C. 2013. Rumen liquor from slaughtered cattle as a source of inoculum for in vitro gas production technique in forage evaluation. *Agricultural Journal*, 8, 173-180.

Nair, P. K. R., Kumar, B. M. & Nair, V. D. 2009. Agroforestry as a strategy for carbon sequestration. *Journal of Plant Nutrition and Soil Science*-Zeitschrift Fur Pflanzenernahrung Und Bodenkunde, 172, 10-23.

Naramabuye, F. X. & Haynes, R. J. 2006a. Effect of organic amendments on soil pH and AI solubility and use of laboratory indices to predict their liming effect. *Soil Science*, 171, 754-763.

Naramabuye, F. X. & Haynes, R. J. 2006b. Short-term effects of three animal manures on soil pH and Al solubility. *Australian Journal of Soil Research*, 44, 515-521.

Ndlovu, L. R. & Nherera, F. V. 1997. Chemical composition and relationship to in vitro gas production of Zimbabwean browsable indigenous tree species. *Animal Feed Science and Technology*, 69, 121-129.

Nduwumuremyi, A., Mugwe, J. N., Ruganzu, V., Rusanganwa, K. C. & Nyirinkwaya, B. 2013. Effects of Travertine in Improving Selected Soil Properties and Yield of Irish Potato (Solumun tuberosum L.) in Acidic Soils. *Journal of Agricultural Science and Technology,* 3, 175-182.

Niang, A., Styger, E., Gahamanyi, A. & Ugeziwe, J. 1994. Comparative growth performance of some fifteen exotic species and provenances of high elevation acidic soils of Rwanda. Taller International Sobre Arboles Fijadres de Nitrogeno para Suelos Acidos' at Turrialba, Costa Rica, 3-8.

Niang, A., Ugiziwe, J., Styger, E. & Gahamanyi, A. 1996. Forage potential of eight woody species: Intake and growth rates of local young goats in the highland region of Rwanda. *Agroforestry Systems*, 34, 171-178.

NISR 2016. Agricultural statistics survey. Kigali-Rwanda.

NISR 2018. Seasonal Agricultural survey 2018 annual report. Kigali: National Institute of Statistics of Rwanda.

Njidda, A. A. 2010. Chemical composition, fibre fraction and anti-nutritional substances of semi-arid browse forages of North-eastern Nigeria. *Nigerian Journal of Basic and Applied Sciences*, 18, 181-188.

Njidda, A. A. & Ikhimioya, I. 2010. Correlation between chemical composition and in vitro dry matter digestibility of leaves of semi-arid browses of North-eastern Nigeria. *American-Eurasian Journal of Agricultural and Environmental Science,* 9, 169-175.

Nyamangara, J., Mudhara, M. & Giller, K. 2005. Effectiveness of cattle manure and nitrogen fertilizer application on the agronomic and economic performance of maize. South African *Journal of Plant and Soil*, 22, 59-63.

Nyoka, B. I., Sileshi, G., Akinnifes, F. K., Matarirano, L., Mng'omba, S., Mavhankeni, B. O. & Bhebhe, E. 2012. Productivity of Acacia angustissima accessions at two sites in the subtropics. *African Journal of Biotechnology*, 11(91), 15763-15770.

Nzeyimana, I., Hartemink, A. E. & Geissen, V. 2014. GIS-based multi-criteria analysis for Arabica coffee expansion in Rwanda. *PloS one*, 9, e107449.

Okalebo, J. R., Gathua, K. W. & Woomer, P. L. 2002. Laboratory methods of soil and plant analysis: A working Manual Nairobi, Kenya, TSBF-CIAT and SACRED Africa, Nairobi, Kenya.

Okalebo, J. R., Othieno, C. O., Woomer, P. L., Karanja, N. K., Semoka, J. R. M., Bekunda, M. A., Mugendi, D. N., Muasya, R. M., Bationo, A. & Mukhwana, E. J. 2006. Available technologies to replenish soil fertility in East Africa. *Nutrient Cycling in Agroecosystems*, 76, 153-170.

Orwa, C., Mutua, A., Kindt, R., R., J. & Simons, A. 2009. Agroforestry database: a tree reference and selection guide version 4.0 [Online]. Nairobi,Kenya: ICRAF. [Accessed].

Osuji, P. O., Nsahlai, I.V. & Khalili, H 1993. Feed Evaluation. ILCA Manual 5. ILCA (International Livestock Centre for Africa), Addis Ababa, Ethiopia.

Oyun, M., Fasinmirin, J., Olufolaji, O. & Ogunrinde, O. 2016. Growth of Maize (Zea mays. L) In Response to Varying Organic and Inorganic Fertilizer Treatment.

Partey, S. T. 2011. Effect of pruning frequency and pruning height on the biomass production of Tithonia diversifolia (Hemsl) A. Gray. *Agroforestry Systems*, 83, 181-187.

Petersen, S. O., Lind, A. M. & Sommer, S. G. 1998. Nitrogen and organic matter losses during storage of cattle and pig manure. *Journal of Agricultural Science*, 130, 69-79.

RARDA 2006. Rwanda Animal Resources Development Authority, Annual Report. KIgali, Rwanda.

Rubanza, C. D. K., Shem, M. N., Ichinohe, T. & Fujihara, T. 2006. Polyphenolics and minerals composition of selected browse tree species leaves native to north-western Tanzania traditional fodder banks. *Journal of Food, Agriculture & Environment*, 4, 328-332.

Rubanza, C. D. K., Shem, M. N., Otsyina, R., Bakengesa, S. S., Ichinohe, T. & Fujihara, T. 2005. Polyphenolics and tannins effect on in vitro digestibility of selected Acacia species leaves. *Animal Feed Science and Technology*, 119, 129-142.

Sahrawat, K. L. 2008. Factors affecting nitrification in soils. *Communications in Soil Science and Plant Analysis*, 39, 1436-1446.

Salem, A. Z. M., Zhou, C.-S., Tan, Z.-L., Mellado, M., Cipriano Salazar, M., ELGHANDOPUR, M. M. M. Y. & Odongo, N. E. 2013. In vitro Ruminal Gas Production Kinetics of Four Fodder Trees Ensiled With or Without Molasses and Urea. *Journal of Integrative Agriculture*, 12, 1234-1242.

Sallah, P. Y. K., Mukakalisa, S., Nyombayire, A. & Mutanyagwa, P. 2009. Response of two maize varieties to density and nitrogen fertilizer in the highland zone of Rwanda. *Journal of Applied Biosciences*, 20, 1194-1202.

Sanchez, P. A. 2002. Ecology - Soil fertility and hunger in Africa. Science, 295, 2019-2020.

Sanchez, R. N., Ledin, S. & Ledin, I. 2006. Biomass production and chemical composition of Moringa oleifera under different management regimes in Nicaragua. *Agroforestry Systems*, 66, 231-242.

SAS 2012. Statistics. Version 9.4 ed. USA: SAS Institute, Inc., Cary, NCC.

Schumann, B. 1999. The cause of soil acidity. New South Wales.

Sileshi, G., Akinnifesi, F. K., Ajayi, O. C., Chakeredza, S., Kaonga, M. & Matakala, P. 2007. Contributions of agroforestry to ecosystem services in the Miombo eco-region of eastern and southern Africa. *African journal of environmental science and technology*, 1, 68-80.

Sileshi, G. W., Mafongoya, P., Akinnifesi, F., Phiri, E., Chirwa, P., Beedy, T., Makumba, W., Nyamadzawo, G., Njoloma, J. & Wuta, M. 2014. Agroforestry: fertilizer trees. Encyclopedia of agriculture and food systems, 1, 222-234.

Simbaya, J. 2002. Potential of fodder tree/shrub legumes as a feed resource for dry season supplementation of smallholder ruminant animals. International Atomic Energy Agency Technical Documents (IAEA-TECDOCs), 69-76.

Somarriba, E. 1992. Revisiting the past: an essay on agroforestry definition. *Agroforestry systems*, 19, 233-240.

Somarriba, E. & Kass, D. 2001. Estimates of above-ground biomass and nutrient accumulation in Mimosa scabrella fallows in southern Brazil. *Agroforestry Systems*, 57, 77–84.

Thomas, G. W. & Hargrove, W. L. 1984. The chemistry of soil acidity. Soil acidity and liming, 3-56.

Tittonell, P., Vanlauwe, B., Leffelaar, P. A., Rowe, E. C. & Giller, K. E. 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya - I. Heterogeneity at region and farm scale. *Agriculture Ecosystems & Environment*, 110, 149-165.

Topps, J. H. 1992. Potential, composition and use of legume shrubs and trees as fodder for livestock in the Tropics. *Journal of Agricultural Science*, 118, 1-8.

Twomlow, S., Rohrbach, D., Dimes, J., Rusike, J., Mupangwa, W., Ncube, B., Hove, L., MOYO, M., Mashingaidze, N. & Mahposa, P. 2010. Micro-dosing as a pathway to Africa's Green Revolution: evidence from broad-scale on-farm trials. *Nutrient Cycling in Agroecosystems*, 88, 3-15.

USDA 1999. Soil Taxonomy. A Basic System of Soil Classification for Making and Interpreting Soil Surveys, Washington, DC 20402.

Uttam, S., Leticia, S., Dennis, H., Nicholas, H., Lawton, S., Gary, H. A. & David, E. K. 2010. Common terms used in animal feeding and nutrition. In: GEORGIA, T. U. O. (ed.) College of Agriculture and Environmental Sciences. Virginia, USA.

Wambugu, C., Franzel, S., Cordero, J. & Stewart, J. 2006. Fodder shrubs for dairy farmers in East Africa: making extension decisions and putting them into practice, World Agoforestry Centre.

Van Soest, P. J., Robertson, J. B. & Lewis, B. A. 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysacharides in relation to animal nutrition. *Journal of Dairy Science*, 74, 3583-3597.

Vanlauwe, B., Descheemaeker, K., Giller, K., Huising, J., Merckx, R., Nziguheba, G., Wendt, J. & Zingore, S. 2015. Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. *Soil,* 1, 491-508.

Verdoodt, A. & Van Ranst, E. 2006. Environmental assessment tools for multi-scale land resources information systems: A case study of Rwanda. *Agriculture, Ecosystems & Environment*, 114, 170-184.

Whalen, J. K., Chang, C., Clayton, G. W. & Carefoot, J. P. 2000. Cattle manure amendments can increase the pH of acid soils. *Soil Science Society of America Journal*, 64, 962-966.

Wong, M. T. F., Akyeampong, E., Nortcliff, S., Rao, M. R. & Swift, R. S. 1995. Initial response of maize and beans to decreased concentration of monomeric inorganic Aluminium with application of manure or tree prunings to an Oxisols in Burundi. *Plant and Soil*, 171, 275-282.

Woodward, A. & Reed, J. D. 1989. The influence of polyphenolics on the nutritive value of browse: a summary of research conducted at ILCA. ILCA Bulletin, 2-11.

Yamoah, C., G, R. & Nizeyimana, E. 1989. Early growth of alley shrubs in the Highland region of Rwanda. *Agroforestry Systems*, 9, 171-184.

Popular science summary

Agriculture contributes to more than one-third of the gross domestic product in Rwanda. It also meets 90 percent of national food needs with 70 percent of total employment. The rapidly increasing population pressure on the available land has led to land degradation and to loss of productivity of arable lands and increased food insecurity. Achieving food security while preventing further expansion of agricultural land is a major issue for the country's policy makers. Thus farm production need to be increased with improved agricultural practices.

Soil acidity is also a constraint to agricultural production in Rwanda. Two thirds of the cultivated soils are acidic with half of these soils having a pH less than 5.5. Limes have been advocated for a long time as a means of alleviating soil acidity and improve soil quality and crop production, but their application at rates recommended by agricultural research is constrained by high costs for smallholder farmers. Organic amendments, particularly cattle manure, can be a replacement or supplementary material to both mineral fertilisers and lime in reversing degradation of soils. Manure application is an efficient and sustainable method for maintaining soil quality and water retention. However, animal manure is often only available in limited quantities and low quality. Innovative low-input practices such micro-dose have been presented as a major step along the agriculture intensification, but so far mostly used for mineral fertilisers.

Livestock is important in low income countries as contribution to food security, but also for socio-economic and cultural reasons. To increase the productivity of livestock, improved nutrition through sufficient quality feeds is needed. However, tropical grasses mature rapidly, causing the feed quality to decrease, which leads to protein deficiency in the animal. Supplementing low quality basal fodder with protein-rich concentrates is a challenge for smallholder farmers with low income, though, but leguminous trees and shrubs have been shown as potentially valuable sources of proteins and mineral supplements for smallholder famers´ ruminant animals.

Agroforestry, i.e. combining trees with food crops and/or livestock on the same land, is one of the options to alleviate the effects of deforestation, lack of livestock fodder quality and soil fertility degradation. Tree and shrub species that can provide high protein animal fodder, green manure, as well as production of stakes and fuelwood are recommended to be intercropped with annual crops in the fields or grown at terrace risers.

The aim of this thesis was to evaluate the biomass production of the legume trees *Acacia angustissima, Leucaena pallida* and *Mimosa scabrella* grown on an acidic soil with low nutrient content in Southern Rwanda and to determine their effects on feed quality, the manure´s fertiliser quality and effect on a maize crop, and the fertility status of the soil.

The legumes were grown with the objective of assessing their growth, biomass production and nutrient concentration under different cutting managements. The three species were subjected to repeated harvests at low cutting (0.3m above ground) and high cutting (1.0m above ground). *Leucaena pallida* had slow growth at the start of the experiment but *A. angustissima* and *M. scabrella* grew quickly. The regrowth biomass production after repeated cutting was in the order *A. angustissima* > *L. pallida* > *M. scabrella*. The biomass production of the regrowth was higher for *A. angustissima* and *L. pallida* at lower cutting height (0.3m), but lower for *M. scabrella* at this cutting height after the third harvest. All *A. angustissima* and *L. pallida* plants survived throughout the trial but *M. scabrella* did not cope with repeated cuttings; 80% of the *M. scabrella* plants cut at 0.3m had died by the fifth harvest.

Cutting height did not affect the nutrient content of the leaves. When used to supplement a basal grass diet, all the species improved the nutritive quality by increasing the diet´s nitrogen content. This was especially clear at the low cutting height. All the species, irrespectively of the cutting height, are suitable protein supplement to low-quality basal diets.

In conclusion, tree management is species dependent. Selection of appropriate tree species and biomass harvest methods depends on a number of factors, including the purpose of the agroforestry practices, the tree component prioritised, arrangement of the trees relative to food crops and the resources available, especially labour. However, *A. angustissima* and *L. pallida* appear to be robust species for use in agroforestry systems with biophysical conditions and cutting methods similar to those in this study. *Acacia angustissima* also showed advantages over the other species tested in terms of quick establishment, tolerance to repeated cuttings at different height, rapid recovery and contributing most to high biomass production and nutritional composition. *Mimosa scabrella* established rapidly, but did not survive repeated cutting and hence produced biomass for a shorter period. However lower cutting height (0.3m) should be recommended to farmers aiming for high quality fodder and shoot biomass production.

A field experiment was conducted to test the hypotheses that manure provides a liming and fertiliser effect comparable to that of combined NPK fertiliser application and liming for soil properties and yield improvement. The effects of supplementing the animals′ basal grass diet with a forage legume (*A. angustissima*) on soil properties and maize crop when the resulting manure is applied to soil were also tested. The manures and lime were applied only to the planting stations (i.e. in close proximity to each maize plant) and at a reduced rate (25% of the recommended rate) considered affordable to smallholder farmers.

Supplementing low quality grass feeds with *A. angustissima* increased C, total N and base cation concentrations in the manure compared to grass feeds only. After four maize cropping seasons, manure increased the soil water retention capacity and infiltration rate compared to NPK application but there was no difference between the two types of manures. Manure and lime application increased soil pH and reduced the total exchangeable acidity and aluminium toxicity compared to the control treatment but there was no difference between the effects of the two manure types. Soil organic carbon and cation exchange capacity increased after manure application compared to an unfertilised control treatment. Manure and NPK treatments did not differ in soil total N and available P. Manure, lime and NPK treatments increased the soil exchangeable Ca^{2+} and Mg^{2+} compared to baseline. Manure treatment also increased Mg^{2+} compared to NPK. Liming also increased Ca^{2+} and Mg^{2+} concentrations in the unfertilised treatment.

Manure treatment (at 25% recommended of rate) and NPK fertiliser increased the maize growth and yield compared to the control treatment with the highest values in the fourth season. The NPK treatment had the highest maize plant growth and yield. The increased biomass yields upon NPK fertilisation is also associated with increased uptake of nutrients and thus increases nutrient export via farm produce and this is important to replenish through appropriate fertilisation. Animal manure is characterised by slow release of nutrients. However the increase in maize growth and yield in manure observed from the second season suggest a relatively rapid nutrient supply from manure.

Many studies have shown increased cereal crop yields when practicing micro-dosing of inorganic fertiliser but only few studies have investigated micro-dosing of manure. Since manure is a valuable and limited resources, its application in micro-dose could be the most efficient way to make use of it. In this study the manure management was improved compared with common practice but not very advanced. The practice of collecting faeces and urine frequently and covering the manure with a plastic sheet is achievable for many smallholder farmers. Furthermore, the amount of manure applied by micro-dosing in this study, i.e. 5 t dw ha^{-1}, is within reach of many smallholder farmers. This is especially the case in a densely populated country like Rwanda where most farms are considerably smaller than 1 ha. It also aligns with and is achievable within the “One cow to every poor family” policy of Rwanda.

Populärvetenskaplig sammanfattning

Jordbruket bidrar till mer än en tredjedel av bruttonationalprodukten i Rwanda. Det står också för 90% av det nationella livsmedelsbehovet och för 70% av den totala sysselsättningen. Det snabbt ökande befolkningstrycket har dock lett till en förlust av bördighet hos jordbruksmarken och en minskad livsmedelssäkerhet. Att uppnå livsmedelssäkerhet utan ytterligare expansion av jordbruket till ny mark är ett prioriterat område för landets beslutsfattare. Därför måste jordbrukets produktivitet ökas genom förbättrade jordbruksmetoder.

Lågt pH hos jordbruksmarken är också ett hinder för jordbruksproduktionen i Rwanda. Två tredjedelar av de odlade markerna är sura och hälften av dessa jordar har ett pH lägre än 5,5. Kalkning har länge förespråkats som ett medel för att höja markens pH och förbättra bördigheten och växtproduktionen. Småbönder har dock svårt att tillföra de kalkmängder som krävs p.g.a. den höga kostnaden. Organiska markförbättringsmedel, särskilt nötkreatursgödsel, kan potentiellt ersätta eller komplettera både mineralgödsel och kalk för att höja bördigheten. Tillförsel av kreatursgödsel kan vara en effektiv och hållbar metod för att upprätthålla bördigheten och markens förmåga att lagra växttillgängligt vatten. Tillgången till kreatursgödsel är dock begränsad och gödseln håller ofta låg kvalitet. Innovativa brukningsmetoder såsom mikrodosering av gödselmedel är en metod som underlättar för småbönder att intensifiera sin produktion, men metoden har hittills främst testats för mineralgödselmedel.

Boskap är viktig i låginkomstländer och bidrar till livsmedelssäkerheten, men är även viktig av socioekonomiska och kulturella skäl. För att öka produktiviteten hos boskapen behövs höjd foderkvalitet. Tropiska gräs utvecklas snabbt och förlorar i fodervärde, vilket leder till proteinbrist hos djuren. Det är en utmaning för småbönder med låg inkomst att komplettera basfoder med proteinrika tillskott, men unga skott från baljväxtträd och -buskar har visat sig vara potentiellt värdefulla proteinfoder som även bidrar med extra mineraler.

Agroforestry, d.v.s. att integrera träd med livsmedelsgrödor och/eller fodergrödor på samma yta, är en möjlighet att lindra bristen på kvalitetsfoder och utarmningen av marken samt effekterna av avskogning. Olika arter av träd och buskar som kan ge proteinfoder, gröngödsel, samt produktion av störar och bränsle kan odlas tillsammans med ettåriga grödor på åkrarna, eller odlas längs terrasskanter och stabilisera dessa.

Syftet i denna avhandling är att utvärdera biomassproduktionen av baljväxtträden A*cacia angustissima*, *Mimosa scabrella* och *Leucaena pallida* när dessa odlas på en sur och näringsfattig jord i södra Rwanda, och att utvärdera deras effekt på foderkvaliteten, kreatursgödselns kvalitet samt effekten på en majsgröda och jordens bördighet då gödseln används.

Träden odlades som buskar för att bedöma deras biomassaproduktion och näringsinnehåll under olika skördesystem. De tre arterna skördades upprepade gånger, antingen lågt (0,3 m över marken) eller högt (1,0 m över marken). Leucaena pallida hade långsam tillväxt i början men *A. angustissima* och *M. scabrella* växte snabbt. Skottåterväxten efter upprepad skörd var i ordningen *A. angustissima* > *L. pallida* > *M. scabrella*. Återväxten var större för *A. angustissima* och *L. pallida* vid låg klipphöjd (0,3 m), men lägre för *M. scabrella* efter den tredje skörden. Alla buskar av *A. angustissima* och *L. pallida* överlevde under hela försöket men *M. scabrella* klarade inte upprepade skördar; 80% av *M. scabrella*-buskarna klippta vid 0,3 m hade dött vid den femte skörden.

Klipphöjden påverkade inte de unga skottens proteininnehåll. När de användes för att komplettera en gräsdiet förbättrade alla arter fodervärdet genom att höja proteinhalten. Detta var särskilt tydligt vid låg klipphöjd. Alla arter, oberoende av klipphöjden, är lämpliga proteintillskott till lågkvalitativt foder.

Sammanfattningsvis bestäms vad som är lämplig skötsel av vilken art det är. Val av trädslag och skördemetod beror av ett antal faktorer, inklusive vilket syfte bonden har och därmed vilka trädprodukter som prioriteras, hur träden ska placeras i förhållande till eventuella livsmedelsgrödor och vilka tillgängliga resurser som finns, särskilt arbetskraft. *Acacia angustissima* och *L. pallida* tycks dock vara robusta arter för användning i agroforestrysystem under mark- och klimatförhållanden och skördemetoder som liknar dem i denna studie. *Acacia angustissima* visade också fördelar jämfört med de andra arterna som testades i och med snabb etablering, tolerans för upprepade skördar på olika höjd, snabb återhämtning, hög biomassaproduktion och högt näringsinnehåll. *Mimosa scabrella* etablerades snabbt, men överlevde inte upprepad skörd på låg höjd och producerade därmed biomassa under en kortare period. Låg skördehöjd (0,3 m) bör ändå rekommenderas till bönder som syftar till högkvalitativt foder.

Ett annat fältförsök genomfördes för att testa hypotesen att kreatursgödsel ger en kalknings- och gödslingseffekt på majsgrödan och marken jämförbar med den för kombinerad NPK-gödsling och kalkning. I samma fältförsök testades även effekten av att komplettera nötkreaturs gräsdiet med foder från *A.*

angustissima (blanddiet) på grödan och marken när djurens gödsel används. Gödseln och kalken tillfördes endast ”planteringspunkterna” (d.v.s. ca 30 cm vida fläckar där varje majsplanta skulle sås i mitten) med en mängd motsvarande 25% av rekommenderad giva. Den lägre givan valdes för att den är mer överkomlig för småbönder i landet. Blanddieten (gräs + *A. angustissima*-skott) ökade gödselns halt av kväve och mineraler jämfört med den rena gräsdieten. Efter fyra odlingssäsonger hade gödseln ökat markens vattenhållande förmåga och infiltrationshastighet i förhållande till NPK-gödslingen, men det var ingen skillnad mellan de två typerna av kreatursgödsel. Användning av kreatursgödsel och kalk ökade markens pH och därmed aluminiumtoxiciteten jämfört med en ogödslad kontrollbehandling, men det var återigen ingen skillnad mellan effekterna av de två typerna av kreatursgödsel. Halten organiskt material och jordens förmåga att hålla kvar näring ökade vid användning av kreatursgödsel jämfört med kontrollbehandlingen. Jordens innehåll av kväve och tillgänglig fosfor skilde sig inte åt mellan kreatursgödsel- och NPK-behandlingarna. Alla gödslings- och kalkningsbehandlingarna ökade halten växttillgängligt kalcium och magnesium i marken, och kreatursgödseln ökade magnesiumtillgängligheten ytterligare jämfört med NPK.

Kreatursgödseln (vid 25% av rekommenderad giva) och NPK ökade majsskörden jämfört med den ogödslade kontrollbehandlingen, och NPK-gödslingen gav allra högst skörd. Den ökade biomasstillväxten vid NPK-gödsling är kopplad till ett stort upptag av näringsämnen vilket ökar bortförseln av näring med skörd. Det är då viktigt att ersätta dessa näringsmängder genom tillräcklig gödsling. Komposterad kreatursgödsel kännetecknas generellt av långsam frisättning av näringsämnen. Den ökning i majsskörd som observerades redan från andra växtsäsongen tyder dock på en relativt snabb näringsförsörjning från denna kreatursgödsel.

Många studier har visat ökade spannmålsskördar vid mikrodosering av mineralgödselmedel men endast få studier har gjorts på effekter av mikrodosering av kreatursgödsel. Eftersom kreatursgödsel är en värdefull och begränsad resurs, kan dess användning i mikrodos vara det mest effektiva sättet att utnyttja den. I denna studie insamlades och lagrades gödsel på ett mer näringshushållande sätt än hos en genomsnittsbonde. Metoden var dock inte avancerad; metoden av att samla träck och urin ofta och täcka gödseln med plastfilm kan användas av många småbönder. Dessutom är den mängd gödsel som användes i denna studie möjlig att uppnå för många småbönder. Detta är speciellt fallet i ett tätbefolkat land som Rwanda där de flesta gårdar är betydligt mindre än 1 hektar, och passar även till och kan uppnås inom Rwandas politik "En ko till alla fattiga familjer".

Acknowledgements

The accomplishment of this work would not have been possible without the support and guidance received from many people. I thank you all who in one way or another contributed to this doctoral long journey.

The studies presented in this thesis were carried out at the Faculty of Natural Resources and Agricultural Sciences, Department of Soil and Environment at Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden and the University of Rwanda (UR) with UR-SIDA bilateral program sponsorship. I am grateful for all the support from all these institutions. I would like to extend my sincere appreciation to the professors, administration staffs, graduate students and postdoctoral researchers at Department of Soil and Environment, Swedish University of Agricultural Sciences Uppsala, Sweden for providing me all rounded working environment and necessary facilities throughout the study period.

A special thank you goes to my PhD supervisory group Professor Sigrun Dahlin and deputy supervisors, Professor Ewa Wredle, Professor Gert Nyberg, Professor Francois Xavier Naramabuye and Professor Jean Nduwamungu for their guidance, assistance, and constructive comments throughout my PhD studies.

To main supervisor Professor Sigrun Dahlin, I say thank YOU for all your hard work. This would not been possible without your dedication. I am very grateful to your exceptional supervision that led me to this step. Thank you for supporting and coaching me throughout the complete process and sharing your wide knowledge in soil sciences with me. Thank you for always being willing to have scientific discussion and constantly being positive and encouraging throughout the years. Many thanks for the fruitful and critical discussion, orientation and advices. Thanks for your valuable administrative support, patience and leadership. Thank you for your care and sharing nice social moments especially in depressive winter Christmas seasons when I was away from my family. Thank you for being there for me.

Thank you Sigrun and Mary McAfee for good inputs on my writing and English and Anna, Magnus and Mats for helpful suggestions to improve the thesis summary.

To my co-author Mupenzi Mutimura, thank you for good cooperation.

I also want to thank my colleagues from Rwanda/Uppsala: Florence, Olive, Jean Baptiste, Alphonsine, Léon and Marius, Dr Aimable and Dr Maximilian from SLU, Naomi, Tom and Innocent from Uppsala University and all Master's students in SI programme from Rwanda at SLU and Uppsala University, my stay in Uppsala was smooth with you all around me.

I am indebted to Rwanda embassy and all members of the Rwandan community in Sweden and particularly in Uppsala, thank you for your concern and care throughout my stay in Uppsala.

To the new friends both on PhD and Masters at SLU from different countries; Alice, Winnie, Sussy, Mario and Emilio. It was great sharing experience with you. I want also to thank the people of the Redeemed Christian Church of God, Uppsala. God Bless you all.

A very special gratitude to Linnea Hanson for your smile and availability in answering all of my questions. Sabina Jordan and your family, I will always remember your devotion in teaching me to bike. My officemates Sabina Braun and Hugo, thank you for a calm working environment.

My heartfelt gratitude to the University of Rwanda, for enormous support. In particular, I want to say thanks to Dr. Simon Rukera Tabaro, Karara Alex, Charles Gakomeye, Raymond Ndikumana, Claudine M., Oreste, Dr. Sylvie Mucyo, Dr. Laetitia Nyinawamwiza. Without your support I wouldn't be here now.

Many thanks to Cassien Biregeya and all the member of team you worked together from the starting of the experiment to the end of data collection. Thank you for your commitment, companionship and support during the field work. You have been my eye during my absence. Mwarakoze cyane.

To the laboratory staff and internees of CAVM at Huye. Emmanuel Ndikumana, your introduction to laboratory work have been helpful before you start your PhD studies in Germany. Solange, Providence and Eustache, I say thank you for all your support in lab.

To Vestine and Seraphina, ntabwo nabona amagambo nkoresha mbashimira. Mwambereye abana mu rugo, mwangaragarije ubwitange no kwihangana muri iki gihe cyose nari mu masomo. Imana yonyine izabampembere.

I would like to thank my family members for supporting me in this PhD project: Mama Vestine for your immeasurable education, Mama Concessa, I know I am always in your thoughts and prayers, Papa Leonidas (RIP), Papa Joseph (RIP).

To Bizimana Joseph, thank you for your availability and weekend phone calls. It helped me to release my stress.

I am grateful to my brothers, sisters and my in-laws for your moral support.

To Samantha, Florence, Aunt Rose (Mama Samantha), I acknowledge here your moral and physical support to my kids. You have been there for them during my absence.

My deepest thanks to Rucyahana and Murigande families for your countless support and encouragement, you mean a lot in my life. May God bless you.

Last but not least, I would like to express my deepest thanks and love to my husband Elie Makeba for your love, spiritual and emotional support all along this PhD journey. You were constantly at my side to cherish and strengthen me. Special gratitude to my lovely children: Amanda, Arsene, Lorie Altessa and Carla. Sorry we have missed each other and I understand how tough the years apart have been but thank you very much for your love, support, understanding and sharing happiness. I love you.

Thanks for all your encouragement
Marguerite Mukangango
Uppsala, June 2019