

**SEQUENTIAL AGROFORESTRY SYSTEMS FOR IMPROVING FUELWOOD  
SUPPLY AND CROP YIELD IN SEMI-ARID TANZANIA**

by

Anthony Anderson Kimaro

A thesis submitted in conformity with the requirements  
for the degree of Doctor of Philosophy

Graduate Department of Forestry  
University of Toronto

© Copyright by Anthony Anderson Kimaro 2009

# **Sequential agroforestry systems for improving fuelwood supply and crop yield in semi-arid Tanzania**

Anthony Anderson Kimaro

Doctor of Philosophy

Graduate Department of Forestry  
University of Toronto

2009

## **ABSTRACT**

Promotion of agroforestry practices in sub-Saharan Africa may help sustain subsistent food and wood production by integrating trees and crops on farmlands to replenish soil fertility and improve crop yield. Using rotational woodlot and pigeonpea intercropping systems in semi-arid Tanzania as case studies, my research screened suitable tree species to increase fuelwood supply and examined mechanisms for reducing tree-crop competition. By adopting nutrient use efficiency (the ratio of biomass yield to nutrient uptake) as a criterion, I found that selecting tree species of low wood nutrient concentrations would minimize nutrient exports by 42 – 60 %, thus reducing soil nutrient depletion while concurrently sustaining local fuelwood supply harvested from rotational woodlots. Currently smallholder farmers cannot afford to replenish soil fertility because of high fertilizer costs. However, 5-year tree fallowing raised soil N and P levels for maize culture as high as those from recommended fertilizer applications. Post-fallow maize yield was also increased significantly over natural fallow practices. Apparently there is a trade-off between yields of maize and fuelwood under rotational woodlot culture providing farmers the choice to proportion tree and crop composition based on priority demands. An alternative practice of intercropping pigeonpea with maize may also rapidly replenish soil fertility as well as enhance maize yield when competitive interactions between trees and crops are controlled. Vector analysis revealed that such interactions suppressed biomass yields of maize and pigeonpea by 30 % and 60 %, respectively, due to limited soil nutrients and/or moisture. Optimizing yields of both crops would require prescribed fertilizer addition when intercropped, but dose rates can be lowered by half under the

improved fallow system due to alleviating interspecific competition. My findings form the basis of a plea for greater use of rotational woodlot and pigeonpea intercropping systems in semi-arid areas. I conclude that smallholder farm management of rotational agroforestry systems can be significantly improved by refining tree selection criteria and mitigating nutrient competition between trees and crops to maintain food and fuelwood production.

## ACKNOWLEDGEMENTS

I would like to acknowledge the immense support of my thesis advisor, Dr. Vic Timmer; your guidance and enthusiasm enabled me to complete this thesis. Special thanks for your advice during the difficulty moment for our family at the start of my study program. My sincere gratitude also goes to other supervisory committee members: Drs. Sharon Cowling, Andy Kenney, and John Caspersen for their guidance and valuable inputs that improved my research and thesis. I acknowledged valuable suggestions from former members of my supervisory committee: Drs. Terry Blake and Tony Davis that laid the foundation of this work as well as constructive and insightful comments from my thesis examiners Drs. Andrew Gordon and Nathan Basiliko. Technical and logistic supports from Dr. Yuanxin Teng, Dr. Francis Salifu, Ian Kennedy, and John McCarron are highly appreciated. I am thankful for the friendship and contributions from my fellow graduate students: Marney Isaac, Martin Kijazi, Willis Atie, Olivia Wilkins, Adam Martin, Shaik Hossain, Kathleen Ryan, and Abdul Awal.

In Tanzania, I am very grateful to Drs. Chamshama, S.A.O, Ngaga, Y.N and the late Dr. Mugasha, A.G. for their valuable inputs and guidance throughout my studies, and to the Sokoine University of Agriculture for granting me the study leave. I extend my appreciation to other people (Msalilwa, J., Kafui, E., Mohamed, H., Edward, E., Naomi, M., Mbilinyi, G., Sogomba, T., Gonza, S., Mwendu, P., and Said, M.) for their technical and field assistance. I am also grateful to Matilda Mgeni and the Ihumwa Village Government for providing field sites for my research.

I am especially thankful to my wife Deborah Kimaro for her unfailing love and constant support, encouragement, and patience throughout my study program, in particular during the arrival of our dear sons Samuel and Ebenezer. I acknowledge moral support from my parents, relatives, and friends. I deeply appreciate the financial support from African Forest Research Network, SUA/NORAD research program, and the Faculty of Forestry, University of Toronto. Finally, I thank God and my Lord Jesus Christ for mercy and grace to complete this work.

## TABLE OF CONTENTS

ABSTRACT .....	ii
ACKNOWLEDGEMENTS .....	iv
TABLE OF CONTENTS .....	v
LIST OF TABLES .....	viii
LIST OF FIGURES .....	ix
CHAPTER 1: INTRODUCTION.....	1
CHAPTER 2: LITERATURE REVIEW.....	9
2.0    Soil and forest resource degradation in Sub-Saharan Africa .....	9
2.1    Agroforestry as a possible solution .....	10
2.2    Improved fallows .....	11
2.2.1    Evolution of fallow management strategies.....	11
2.2.2    Soil fertility improvement.....	12
2.2.3    Fuelwood wood supply.....	14
2.2.4    Rotational woodlots.....	15
2.2.5    Nutrient use efficiency and species choice.....	18
2.2.6    Pigeonpea-maize cropping systems.....	20
2.3    Conclusions.....	22
CHAPTER 3: NUTRIENT USE EFFICIENCY AND BIOMASS PRODUCTION OF TREE SPECIES FOR ROTATIONAL WOODLOT SYSTEMS IN SEMI-ARID MOROGORO, TANZANIA.....	24
3.0    Abstract .....	24
3.1    Introduction.....	25
3.2    Materials and methods .....	26
3.2.1    Study site .....	26
3.2.2    Experimental design and management .....	28
3.2.3    Soil sampling and analysis.....	29
3.2.4    Biomass yields and nutrient use efficiency determinations.....	30
3.2.5    Data analysis.....	31
3.3    Results and discussion .....	31
3.3.1    Changes in soil nutrients.....	31
3.3.2    Nutrient use efficiency.....	33
3.3.3    Wood production .....	35
3.3.4    Nutrient removals .....	37
3.3.5    Nutrient restitution.....	40
3.4    Conclusions.....	41
CHAPTER 4: DIFFERENTIAL RESPONSE TO TREE FALLOWES IN ROTATIONAL WOODLOT SYSTEMS IN SEMI-ARID TANZANIA: POST-FALLOW MAIZE YIELD, NUTRIENT UPTAKE, AND SOIL NUTRIENTS .....	42

4.0	Abstract .....	42
4.1	Introduction .....	43
4.2	Materials and methods .....	45
4.2.1	Maize yield trial .....	45
4.2.2	Leaf decomposition trial .....	47
4.2.3	Chemical analysis of plant and soil samples .....	48
4.2.4	Vector diagnostic analysis .....	48
4.2.5	Statistical analysis .....	50
4.3	Results and discussion .....	50
4.3.1	Post-fallow maize yield .....	50
4.3.2	Seasonal nutrient uptake by maize .....	53
4.3.3	Soil nutrient supply .....	53
4.3.4	Nutrient diagnosis of maize .....	58
4.4	Conclusions .....	63
<b>CHAPTER 5: COMPETITION BETWEEN MAIZE AND PIGEONPEA IN SEMI-ARID TANZANIA: EFFECT ON YIELDS AND NUTRITION OF CROPS.....</b>		<b>65</b>
5.0	Abstract .....	65
5.1	Introduction .....	66
5.2	Materials and methods .....	67
5.2.1	Study site and treatments .....	67
5.2.2	Soil and plant sampling .....	71
5.2.3	Pigeonpea biomass assessment .....	71
5.2.4	Chemical analysis of soil and plant samples .....	72
5.2.5	Vector competition analysis .....	72
5.2.6	Statistical analysis .....	73
5.3	Results and discussion .....	73
5.3.1	Maize and pigeonpea yields .....	73
5.3.2	Maize and pigeonpea nutrient uptake .....	79
5.3.3	Soil nutrient availability .....	82
5.3.4	Vector analysis of maize and pigeonpea: competitive effects .....	84
5.3.5	Vector analysis of maize and pigeonpea: nutrient diagnosis .....	87
5.4	Conclusions .....	89
<b>CHAPTER 6: SYNTHESIS: A PLEA FOR GREATER USE OF SEQUENTIAL AGROFORESTRY SYSTEMS IN SEMI-ARID LANDS .....</b>		<b>92</b>
6.0	Introduction .....	92
6.1	Methodology .....	93
6.2	Results and discussion .....	94
6.2.1	Reducing deforestation through on-farm wood supply .....	94
6.2.1.1	Tobacco farming scenario .....	94
6.2.1.2	Woodfuel scenario .....	97
6.2.1.3	Moisture content and fuel value index .....	98
6.2.2	Carbon sequestration potential of planted tree and shrub fallows .....	100
6.2.2.1	Wood carbon .....	100
6.2.2.2	Soil organic carbon .....	103

6.2.3	Conclusions.....	103
CHAPTER 7: MAJOR CONCLUSIONS AND FUTURE RESEARCH .....		105
7.0	Conclusions.....	105
7.1	On-farm wood supply and associated environmental impacts.....	105
7.2	Soil fertility and post-fallow maize yield.....	107
7.3	Competition between maize and pigeonpea.....	108
7.4	Recommendations.....	109
7.5	Future research.....	110
REFERENCES.....		112
APPENDICES.....		122
Appendix 1. Tree species effects on soil total inorganic N and extractable phosphorus during the first cropping season after a 5-year fallow period of the rotational woodlot system at Mkundi, Morogoro, Tanzania. ....		122
Appendix 2. Fertilizer effects on soil total inorganic N and extractable phosphorus during the first cropping season after a 5-year fallow period of the rotational woodlot system at Mkundi, Morogoro, Tanzania. ....		123
Appendix 3. Concentration ( $\text{g kg}^{-1}$ ) of foliar nitrogen, phosphorus and potassium of 5-year old tree fallows during the 12-week decomposition period at Mkundi, Morogoro, Tanzania. ....		124

## LIST OF TABLES

Table 2.1. Wood basic density and calorific value of tree species in planted tree fallows and natural forests in Tanzania and Malawi. ....	17
Table 2.2. Factors contributing to productivity decline in short-rotation tropical forest plantations based on the long-term studies in Australian, New Zealand, China, India, and Indonesia.....	19
Table 3.1. Diameter at breast height (DBH), total height and mean annual wood increment of tree species in a 5-year-old rotational woodlot at Mkundi, Morogoro, Tanzania. ....	38
Table 4.1. Decay constant ( $k$ , $\text{Week}^{-1}$ ) and chemical characteristics ( $\text{g kg}^{-1}$ ) of tree leaves used for the decomposition experiment at Mkundi, Morogoro, Tanzania. ....	46
Table 5.1. Concentration and content of nutrients in cattle manure applied to maize and pigeonpea at Ihumwa, Dodoma, Tanzania.....	70
Table 5.2. Summary of ANOVA ( $p > F$ ) testing the effects of cropping systems, cattle manure, and combined N and P fertilizers on yields (Mg.....	74
Table 5.3. Summary of ANOVA ( $p > F$ ) testing the effects of cropping systems, cattle manure, and combined N and P fertilizers on yield (Mg.....	75
Table 5.4. Biomass yield ( $\text{Mg ha}^{-1}$ ) and nutrient content ( $\text{kg ha}^{-1}$ ) of maize and pigeonpea for the 2005 cropping season for different cropping systems and cattle manure treatments without (-) or with half (+) and full (++) rates of N and P fertilizers at Ihumwa, Dodoma, Tanzania.....	81
Table 6.1. Estimated land area under rotational woodlot systems needed to produce wood for fuelwood and charcoal supply in Morogoro and tobacco curing in Tabora, Tanzania.....	95
Table 6.2. Moisture content and fuel value index of tree species for rotational woodlot systems at Mkundi, Morogoro, Tanzania. ....	99
Table 6.3. Carbon accumulation rates ( $\text{Mg ha yr}^{-1}$ ) in wood and soils under planted tree fallows in Morogoro, Tanzania. ....	102



## LIST OF FIGURES

- Figure 1.1. Agricultural practices which contribute to soil declining soil productivity in smallholder farming systems in the tropics. Shifting cultivation is a traditional form of agriculture that involves clearing of native forests for crop cultivation until yield decline to an unacceptable level due to soil nutrient depletion through erosion and repeated crop harvesting (a and b). Farmers abandon degraded fields and move to clear other portions of forests. The abandoned field regenerates naturally and can be re-cultivated after a long fallow period (10 – 20 years) to build up soil nutrients to levels sufficient for crop production. High land pressure limited shifting cultivation in most tropical countries leading to continuous cropping practice (c). Inadequate or no nutrient inputs by small-scale farmers under this practice accelerates soil degradation through nutrient mining, leading to declining productivity and soil impoverishment (d). Agroforestry, through re-introduction of fast growing leguminous trees and shrubs on farmlands to replenish soil fertility, is promoted to sustain crop and wood production while providing other ecological and economic benefits. The question mark suggests that agroforestry mimic nutrient cycling processes occurring in forest ecosystems to improve soil productivity, but it is unlikely to restore degraded soils to the natural status due to intensive management. Overall, my thesis examines the role of trees in sustaining productivity of both wood and crops in semi-arid Tanzania. ....2
- Figure 1.2. Three management phases of the rotational woodlot system at Mkundi, Morogoro, Tanzania: establishment (a tree-crop intercropping phase aimed at generating intermediate products while establishing the woodlot) [a], fallow (a tree alone phase mainly for wood supply and the provision of secondary benefits like soil fertility improvement and fodder) [b], and post-fallow (a final phase characterized by wood harvesting and sequential cropping) [c]. Note remnant tree stumps in the post-fallow phase pointed out by researchers. Arrows indicate approximate time for each phase.....4
- Figure 1.3. Pigeonpea intercropping (a) and fallowing (b) with maize at Ihumwa, Dodoma Tanzania. In both systems pigeonpea occupies the land approximately for the same period of time prior to site preparation for the subsequent cropping season. However, its impacts on productivity depend on the nature and magnitude of interactions with the associated maize crop. Such information is scanty in sub-Saharan Africa. My research assessed biomass and nutritional responses of maize and pigeonpea to reduce this knowledge gap. ....6
- Figure 3.1. Location of study sites: Mkundi village in Morogoro region (6° 40' S, 37° 39' E) and Ihumwa village in Dodoma region (6° 10' S, 35° 53' E), Tanzania, East Africa. Africa map was obtained from the University of Alabama website (<http://alabamamaps.ua.edu/contemporarymaps/world/africa/index.html>). ....27
- Figure 3.2. Effects of tree species on soil organic carbon (a), inorganic nitrogen (b), extractable phosphorus (c), exchangeable potassium (c), calcium (d) and effective exchange capacity (e) at Mkundi, Morogoro, Tanzania. AC = *Acacia crassicarpa*, AM = *Acacia mangium*, AN = *Acacia nilotica*, AP = *Acacia polyacantha*, GS = *Gliricidia sepium*, NF = Natural fallow, CC = Continuous cropping and ECEC = Effective cation exchange capacity. For each Figure, means marked by the same letter are not statistically different at  $p < 0.05$  according to Fisher's PLSD. Vertical bars indicate standard errors of means (n = 3). ....32
- Figure 3.3. Use efficiencies of nitrogen (a), phosphorus (b), potassium (c) calcium (d) and magnesium (e) in wood and aerial tree biomass of tree species in a 5-year-old rotational woodlot at Mkundi, Morogoro, Tanzania. AC = *Acacia crassicarpa*, AM = *Acacia mangium*, AN = *Acacia nilotica*, AP

= *Acacia polyacantha*, GS = *Gliricidia sepium*. For each Figure, means marked by the same letter are not statistically different at  $p < 0.05$  according to Fisher's PLSD. Vertical bars indicate standard errors of means ( $n = 3$ ).....34

Figure 3.4. Wood biomass yields of tree species in a 5-year-old rotational woodlot at Mkundi, Morogoro, Tanzania. AC = *Acacia crassicarpa*, AM = *Acacia mangium*, AN = *Acacia nilotica*, AP = *Acacia polyacantha*, GS = *Gliricidia sepium*. For each Figure, means marked by the same letter are not statistically different at  $p < 0.05$  according to Fisher's PLSD. Vertical bars indicate standard errors of means ( $n = 3$ ).....36

Figure 3.5. Nitrogen (a), phosphorus (b), potassium (c) and calcium (d) accumulated in foliage and wood biomass of tree species in a 5-year-old rotational woodlot system at Mkundi, Morogoro, Tanzania. AC = *Acacia crassicarpa*, AM = *Acacia mangium*, AN = *Acacia nilotica*, AP = *Acacia polyacantha*, GS = *Gliricidia sepium*. For each Figure, means marked by the same letter are not statistically different at  $p < 0.05$  according to Fisher's PLSD. Vertical bars indicate standard errors of means ( $n = 3$ ).....39

Figure 4.1. Effects of tree species and fertilizer treatments on maize grain yield after a 5-year fallow period of rotational woodlot culture at Mkundi, Morogoro, Tanzania. Treatments consisted of fallow types: AP = *Acacia polyacantha*, GS = *Gliricidia sepium*, AM = *Acacia mangium*, AC = *Acacia crassicarpa*, and NF = Natural fallow; and fertilizer additions: C = control (No fertilizer), P = 40 kg P ha<sup>-1</sup>, N = 80 kg N ha<sup>-1</sup> and combined N and P application. For each Figure, means marked by the same letter are not statistically different at  $p < 0.05$  according to Tukey's HSD test. Vertical bars indicate standard errors of means ( $n = 3$ ). .....51

Figure 4.2. Maize grain nutrient content as influenced by tree species (a – c) and fertilizer (d – f) treatments after a 5-year fallow period of rotational woodlot culture at Mkundi, Morogoro, Tanzania. Treatments consisted of fallow types: AP = *Acacia polyacantha*, GS = *Gliricidia sepium*, AM = *Acacia mangium*, AC = *Acacia crassicarpa*, and NF = Natural fallow; and fertilizer additions: C = control (No fertilizer), P = 40 kg P ha<sup>-1</sup>, N = 80 kg N ha<sup>-1</sup> and combined N and P application. For each Figure, means marked by the same letter are not statistically different at  $p < 0.05$  according to Tukey's HSD test. Vertical bars indicate standard errors of means ( $n = 3$ ). .....54

Figure 4.3. Tree species (a, b) and fertilizer (c, d) effects on soil total inorganic N (i.e. NO<sub>3</sub><sup>-</sup> - N + NH<sub>4</sub><sup>+</sup> - N) and extractable P during the first cropping seasons after a 5-year fallow period of rotational woodlot culture at Mkundi, Morogoro, Tanzania. Treatments consisted of fallow types: AP = *Acacia polyacantha*, GS = *Gliricidia sepium*, AM = *Acacia mangium*, AC = *Acacia crassicarpa*, and NF = Natural fallow; and fertilizer additions: C = control (No fertilizer), P = 40 kg P ha<sup>-1</sup>, N = 80 kg N ha<sup>-1</sup> and combined N and P application. Arrows indicate time of fertilizer applications. Statistical analysis was performed on log-transformed data, but points represent untransformed means. Vertical bars indicate standard errors of means ( $n = 3$ ). See appendices 1 and 2 for statistical difference between treatments. ....56

Figure 4.4. Concentration of foliar N (a), P (b) and K (c), (expressed as a percent of initial values) of tree species of a 5-year old rotational woodlot experiment during a 12-week litter bag study at Mkundi, Morogoro, Tanzania. Values below and above 100 % indicate mineralization and immobilization of nutrient, respectively. Treatments consisted of fallow types: AP = *Acacia polyacantha*, GS = *Gliricidia sepium*, AM = *Acacia mangium*, and AC = *Acacia crassicarpa*. Statistical analysis was performed on log-transformed data, but points represent untransformed means. Vertical bars indicate standard error of means ( $n = 3$ ). See appendix 3 for statistical difference between tree species.....57

- Figure 4.5. Correlation between foliar carbon-to-nitrogen (C:N) and lignin-to-nitrogen (L:N) ratios of tree species and maize grain yield during the first cropping season after a 5-year fallow period of rotational woodlot culture at Mkundi, Morogoro, Tanzania. Treatments consisted of fallow types: AP = *Acacia polyacantha*, GS = *Gliricidia sepium*, AM = *Acacia mangium*, and AC = *Acacia crassicaarpa*. .....59
- Figure 4.6. Vector nomogram of the relative change in maize biomass, nutrient concentration and nutrient content testing tree species (a) and fertilizer treatments (b) in a 5-year fallow period of rotational woodlot culture at Mkundi, Morogoro, Tanzania. Treatments consisted of fallow types: AP = *Acacia polyacantha*, GS = *Gliricidia sepium*, AM = *Acacia mangium*, AC = *Acacia crassicaarpa*, and NF = Natural fallow; and fertilizer additions: C = control (No fertilizer), P = 40 kg P ha<sup>-1</sup>, N = 80 kg N ha<sup>-1</sup>, and combined N and P application. See Figures 4.1 and 4.2 for statistical differences between treatments. To minimize clutter only the largest vector for each treatment is drawn. ....60
- Figure 4.7. Correlation between soil total inorganic N or soil extractable P and maize yield under tree fallows (a, c) and fertilizer (b, d) during the first cropping season after a 5-year fallow period of rotational woodlot culture at Mkundi, Morogoro, Tanzania.....62
- Figure 5.1. Annual and monthly rainfall received during the 2004 and the 2005 cropping seasons and the long-term average (2000 – 2006) at Ihumwa, Dodoma, Tanzania. ....68
- Figure 5.2. Maize and pigeonpea grain yields for the interactions between combined N and P fertilizers and cropping systems [sole maize, intercropping, and one-year improved fallow, (a – d)] or cattle manure (e – h) at Ihumwa, Dodoma, Tanzania. Application rates for cattle manure were: Control = No manure, Half = 5 Mg ha<sup>-1</sup>, Full = 10 Mg ha<sup>-1</sup>; and for inorganic fertilizers were: Control = No fertilizer, Half = 40 kg N ha<sup>-1</sup> and 20 kg P ha<sup>-1</sup>, Full = 80 kg N ha<sup>-1</sup> and 40 kg P ha<sup>-1</sup>. For each Figure, values represent least squares means of treatment combinations and those marked by the same letter are not statistically different at  $p < 0.05$  according to Tukey's HSD test. Vertical bars indicate standard error of means (n = 3). .....76
- Figure 5.3. Foliage and wood biomass of pigeonpea for the interactions between combined N and P fertilizers and cropping systems [sole maize, intercropping, and one-year improved fallow, (a and c)] or cattle manure (b and d) at Ihumwa, Dodoma, Tanzania. Application rates for cattle manure were: Control = No manure, Half = 5 Mg ha<sup>-1</sup>, Full = 10 Mg ha<sup>-1</sup>; and for inorganic fertilizers were: Control = No fertilizer, Half = 40 kg N ha<sup>-1</sup> and 20 kg P ha<sup>-1</sup>, Full = 80 kg N ha<sup>-1</sup> and 40 kg P ha<sup>-1</sup>. For each Figure, values represent least squares means of treatment combinations and those marked by the same letter are not statistically different at  $p < 0.05$  according to Tukey's HSD test. Vertical bars indicate standard error of means (n = 3). .....78
- Figure 5.4. Soil N and P status in response to interactions between combined N and P fertilizers and cropping systems [sole maize, intercropping, and one-year improved fallow, (a and c)] or cattle manure (b and d) at Ihumwa, Dodoma, Tanzania. Application rates for cattle manure were: Control = No manure, Half = 5 Mg ha<sup>-1</sup>, Full = 10 Mg ha<sup>-1</sup>; and for inorganic fertilizers were: Control = No fertilizer, Half = 40 kg N ha<sup>-1</sup> and 20 kg P ha<sup>-1</sup>, Full = 80 kg N ha<sup>-1</sup> and 40 kg P ha<sup>-1</sup>. For each Figure, values represent least squares means of treatment combinations and those marked by the same letter are not statistically different at  $p < 0.05$  according to Tukey's HSD range test. Vertical bars indicate standard error of means (n = 3). .....83
- Figure 5.5. Vector competition diagrams of aboveground biomass and nutrient content of maize and pigeonpea under intercropping (a – c) and one-year improved fallow (d and e) systems without (-), with half (+) or full (++) rates of N and P fertilizers at Ihumwa, Dodoma, Tanzania. Responses are expressed relative to the unfertilized fallow treatment (-IF) that was normalized to 100. Vector shifts

or direction reflect types of competitive interactions (antagonism, synergism, and compensatory) and the uptake-to-biomass vector ratio identifies specific nutritional interactions (antagonistic dilution, growth dilution, and deficiency) between maize and pigeonpea. Thus, decreases of relative uptake and biomass of both crops associated with vector ratio < 1 represented antagonistic dilution due to interspecific nutrient competition. A similar vector ratio accompanied with increases of these variables depicted growth dilution due to stimulated growth after additions of limiting nutrients. Nutrient deficiency responses were illustrated by relative increase in plant uptake and biomass and vector ratio > 1. To minimize clutter, only the biomass and the most responsive nutrient vector (arrow) are drawn. See Table 5.4 for statistically different vectors (treatments). Note scale for Fig. 5a is half that of others.....85

Figure 5.6. Vector diagnosis of the Figure 5.6. Vector diagnosis of the relative change in aboveground biomass, nutrient concentrations and content of maize and pigeonpea in response to cropping systems (a and b) and cattle manure (c and d) without (-), with half (+) or full (++) rates of inorganic fertilizers at Ihumwa, Dodoma, Tanzania. Cropping systems included: SM = Sole maize, IC = Intercropping, and IF = one-year improved fallow. Application rates for cattle manure were: Control (CM) = No manure, Half (HF) = 5 Mg ha<sup>-1</sup>, Full (FM) = 10 Mg ha<sup>-1</sup>; and for inorganic fertilizers were: Control (-) = No fertilizer, Half (+) = 40 kg N ha<sup>-1</sup> and 20 kg P ha<sup>-1</sup>, Full (++) = 80 kg N ha<sup>-1</sup> and 40 kg P ha<sup>-1</sup>. Responses are relative to controls (-SM, -CM and -IC) that were normalized to 100. To minimize clutter, only the largest vector (arrow) for each nutritional response is drawn. See Table 5.4 for statistically different vectors (treatments).....88

Figure 6.1. Carbon stocks in wood (a) and soils (b) after a 5-year fallow period of rotational woodlot culture at Mkundi, Morogoro, Tanzania. Tree species include: AC = *Acacia crassicarpa*, AM = *Acacia mangium*, AP = *Acacia polyacantha*, GS = *Gliricidia sepium*, AN = *Acacia nilotica*, NF = Natural fallow, and CC = Continuous cropping. For each Figure, means marked by the same letter are not statistically different at  $p < 0.05$  according to Tukey's HSD range test. Vertical bars indicate standard error of means (n = 3).....101

## CHAPTER 1

### INTRODUCTION

Low agricultural productivity in sub-Saharan Africa is mainly linked to soil related constraints, especially nutrient depletion (Sanchez and Jama, 2002). In the past, farmers practiced shifting cultivation with long fallows of 10 – 20 years as a remedial measure to improve soil fertility and crop yield (Fig. 1.1). Although this approach was initially successful in enhancing agricultural productivity, increase in population density and other related land use conflicts lead to the reduction of fallow length (< 4 years) and the conversion of long fallows to continuous cropping systems (Franzel and Scherr, 2002; Hauser et al., 2006). This trend accelerated nutrient depletion (mainly through crop harvesting and soil erosion) and deforestation of native forests as more land was cleared for crop production to meet the increasing needs of rapidly expanding populations (Franzel and Scherr, 2002). In addition to agricultural expansion, uncontrolled wood harvesting from native forests (Luoga et al., 2002) also contributes to declining woodfuel (i.e., firewood and charcoal) supply. In response to fuelwood scarcity, smallholder farmers usually use crop residues and livestock manure as supplementary energy sources (Mahiri, 2003). Consequently, little or no organic matter is returned to the soil, which escalates the vicious cycle of soil nutrient depletion, declining crop production, and forest degradation. Thus, agroforestry has been widely advocated in the tropics as a sustainable low input system for replenishing soil fertility and increasing crop production (Fig. 1.1).

The World Agroforestry Center defines agroforestry as “a dynamic, ecologically based, natural resources management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic, and environmental benefits for land users at all levels” ([www.worldagroforestry.org](http://www.worldagroforestry.org)). The integration of trees and crops in agroforestry leads to a more diverse system with multiple ecosystem functions including supply of food, fuelwood, fodder, and medicines; carbon storage, and conservation of soil and biodiversity (Sileshi et al.,

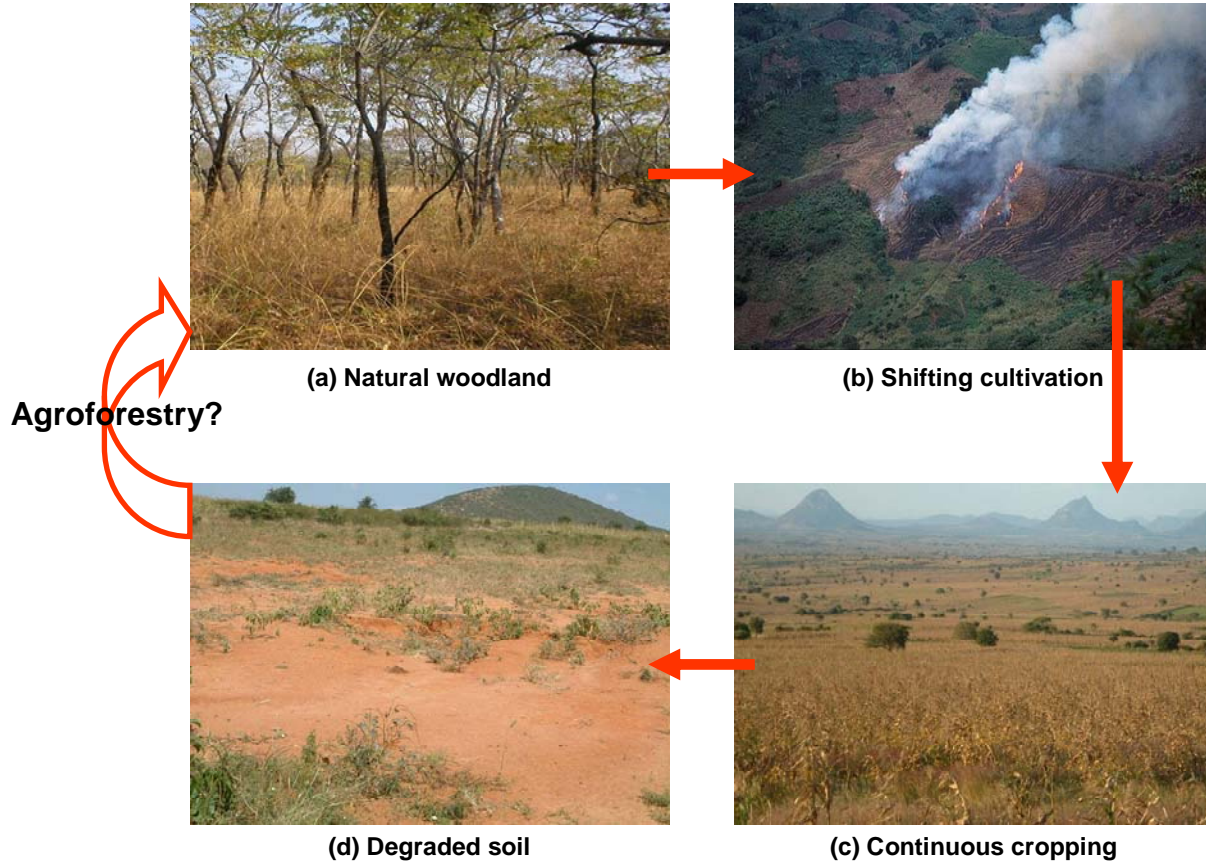


Figure 1.1. Agricultural practices which contribute to soil declining soil productivity in smallholder farming systems in the tropics. Shifting cultivation is a traditional form of agriculture that involves clearing of native forests for crop cultivation until yield decline to an unacceptable level due to soil nutrient depletion through erosion and repeated crop harvesting (a and b). Farmers abandon degraded fields and move to clear other portions of forests. The abandoned field regenerates naturally and can be re-cultivated after a long fallow period (10 – 20 years) to build up soil nutrients to levels sufficient for crop production. High land pressure limited shifting cultivation in most tropical countries leading to continuous cropping practice (c). Inadequate or no nutrient inputs by small-scale farmers under this practice accelerates soil degradation through nutrient mining, leading to declining productivity and soil impoverishment (d). Agroforestry, through re-introduction of fast growing leguminous trees and shrubs on farmlands to replenish soil fertility, is promoted to sustain crop and wood production while providing other ecological and economic benefits. The question mark suggests that agroforestry mimic nutrient cycling processes occurring in forest ecosystems to improve soil productivity, but it is unlikely to restore degraded soils to the natural status due to intensive management. Overall, my thesis examines the role of trees in sustaining productivity of both wood and crops in semi-arid Tanzania.

2007; Nair et al., 2008). Agroforestry systems are broadly categorized into simultaneous systems in which trees and crops are spatially integrated on the same piece of land like in hedgerow intercropping, and sequential systems, in which trees are rotated with crops as in improved fallows (Young, 1997; Rao et al., 1998). The latter are considered more appropriate for semi-arid conditions because of reduced interspecific competition. Moreover, the use of deep-rooted tree and shrub fallows better utilizes sub-soil moisture during the off-season (Rao et al., 1998).

Tighter nutrient cycling is the key to sustainability of agroforestry systems as it allows provision of goods and services without degrading soil resources (Nair et al., 2008; Drinkwater and Snapp, 2007). Unlike conventional agriculture, agroforestry may concurrently address the problems of unsustainable food and wood supply by integrating trees and crops on the farmland. Trees and shrubs, especially leguminous species, improve soil fertility by fixing nitrogen (N) and recycling nutrients from below the crop rooting zone, leading to increased crop production compared to natural fallow and unfertilized continuous cropping practices (Young, 1997; Sanchez and Jama, 2002; Nair et al., 2008). When managed for wood supply, agroforestry trees and shrubs may satisfy household fuelwood demand and produce wood for other domestic and commercial purposes (Nyadzi et al., 2003a; Jama et al., 2008). This in turn reduces harvesting pressure on native forests, and diverts substantial amount of time that would be spent on firewood collection to other productive activities (Ramadhani et al., 2002; Mahiri, 2003). Consequently, several agroforestry systems have been developed to increase and sustain food and fuelwood production while minimizing environmental degradation (Smithson and Giller, 2002; Kwesiga et al., 2003; Garrity, 2004; Mafongoya et al., 2006).

This thesis will focus on rotational woodlots and pigeonpea (*Cajanus cajan* L. Millsp.) fallows, which are examples of sequential agroforestry systems. These systems are promoted for both food and fuelwood production in semi-arid zones of sub-Saharan Africa (Snapp et al., 2002; Nyadzi et al., 2003a). The rotational woodlot system was developed in western Tanzania mainly for on-farm fuelwood supply, but it also provides other benefits including increased crop yield. The system involves inter-planting trees

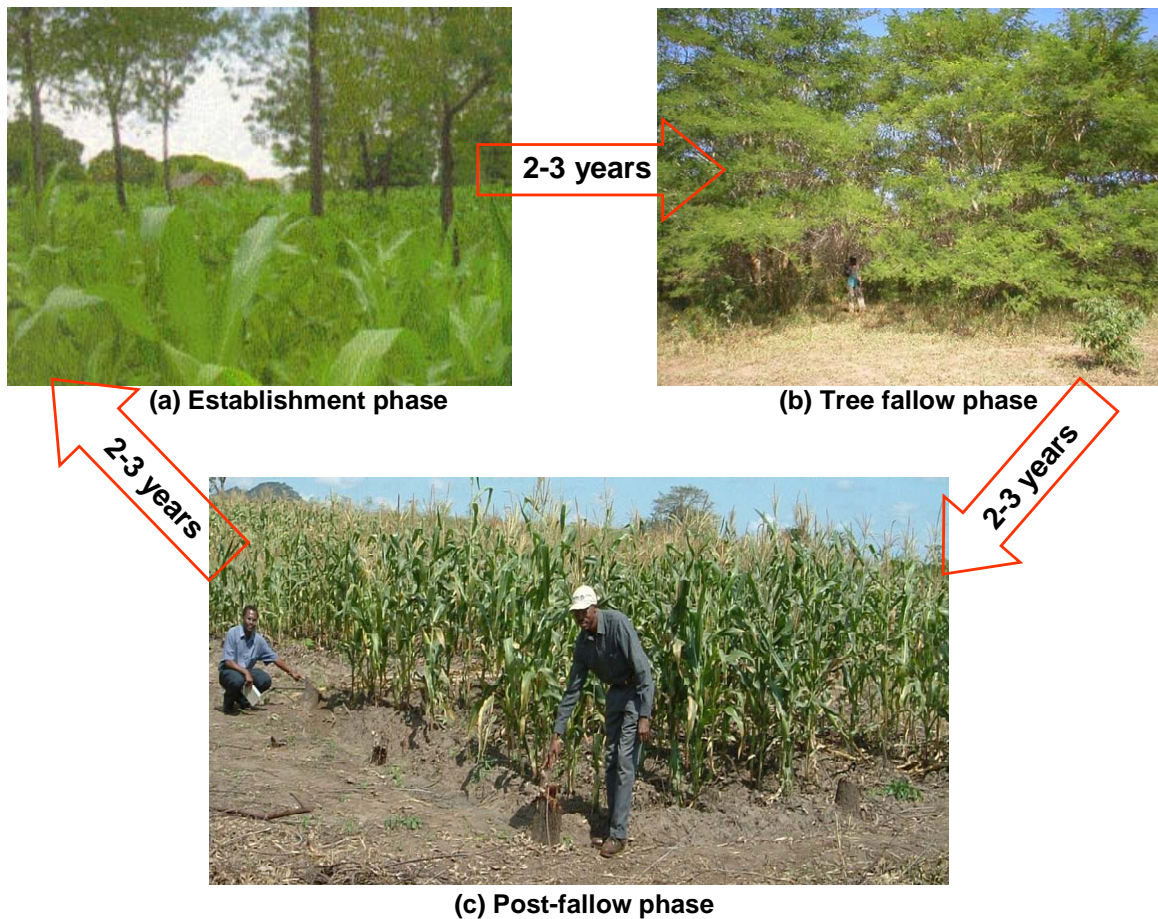


Figure 1.2. Three management phases of the rotational woodlot system at Mkundi, Morogoro, Tanzania: establishment (a tree-crop intercropping phase aimed at generating intermediate products while establishing the woodlot) [a], fallow (a tree alone phase mainly for wood supply and the provision of secondary benefits like soil fertility improvement and fodder) [b], and post-fallow (a final phase characterized by wood harvesting and sequential cropping) [c]. Note remnant tree stumps in the post-fallow phase pointed out by researchers. Arrows indicate approximate time for each phase.



with crops for the first three years, followed by three years of tree fallowing after which woody biomass is harvested while foliage biomass is retained on the site as green manure (Fig. 1.2). Finally post-fallow crops are grown for 2 – 3 consecutive seasons and the cycle starts again (Otsyna et al., 1999; Nyadzi et al., 2003a). Soil nutrient changes during these tree fallow-crop rotation cycles depend on several factors including tree species, management (e.g. length of the fallow period and stand density), climate, and initial soil status (Rao et al., 1998). For instance, short duration (< 3 years) fallows designed for soil fertility replenishment are usually established at a narrow spacing to maximize foliage biomass, which in turn compromise the amount and size of wood produced (Niang et al., 2002; Jama et al., 2008). Thus, impacts of nutrient exported in harvested wood on site productivity may be minimal since large proportions of nutrients are returned to the soil through litter fall, root turnover, and green manure application. However, in woodlots and short rotation forestry plantations continuous removals of nutrients sequestered in woody biomass may adversely affect site productivity, but this effect may be minimized by employing appropriate silvicultural techniques including selection of tree species and harvesting method (Kumar et al., 1998; Evans and Turnbull, 2004). Previous studies on fuelwood supply from planted tree fallows focused mainly on biomass yield and the associated benefit of crop yield (Herbert et al., 2002; Chirwa et al., 2003; Nyadzi et al., 2003a; Jama et al., 2008). More research is needed to advance knowledge of the potential impacts of intensive fuelwood harvesting on farm productivity.

Pigeonpea is traditionally intercropped or grown in rotation with cereal crops (Fig. 1.3), especially maize (*Zea mays* L.) in semi-arid tropics (Rao and Mathuva, 2000; Snapp et al., 2002; Ghosh et al., 2006). The legume continues to grow after maize harvesting to produce grains that are a source of food and income to smallholder farmers (Snapp et al., 2002). Pigeonpea has a slow initial growth rate relative to most cereal crops (Snapp et al., 2002; Mafongoya et al., 2006). This attribute may reduce interspecific competition in mixed culturing through partitioning of peaks of resource demand. Despite this temporal compatibility, yield of maize intercropped with pigeonpea in semi-arid conditions is often similar to or less than that of sole-cropped maize (Rao and Mathuva, 2000; Snapp et al., 2002; Myaka et al., 2006), indicating yield suppression due to competition. Although this competition may also affect

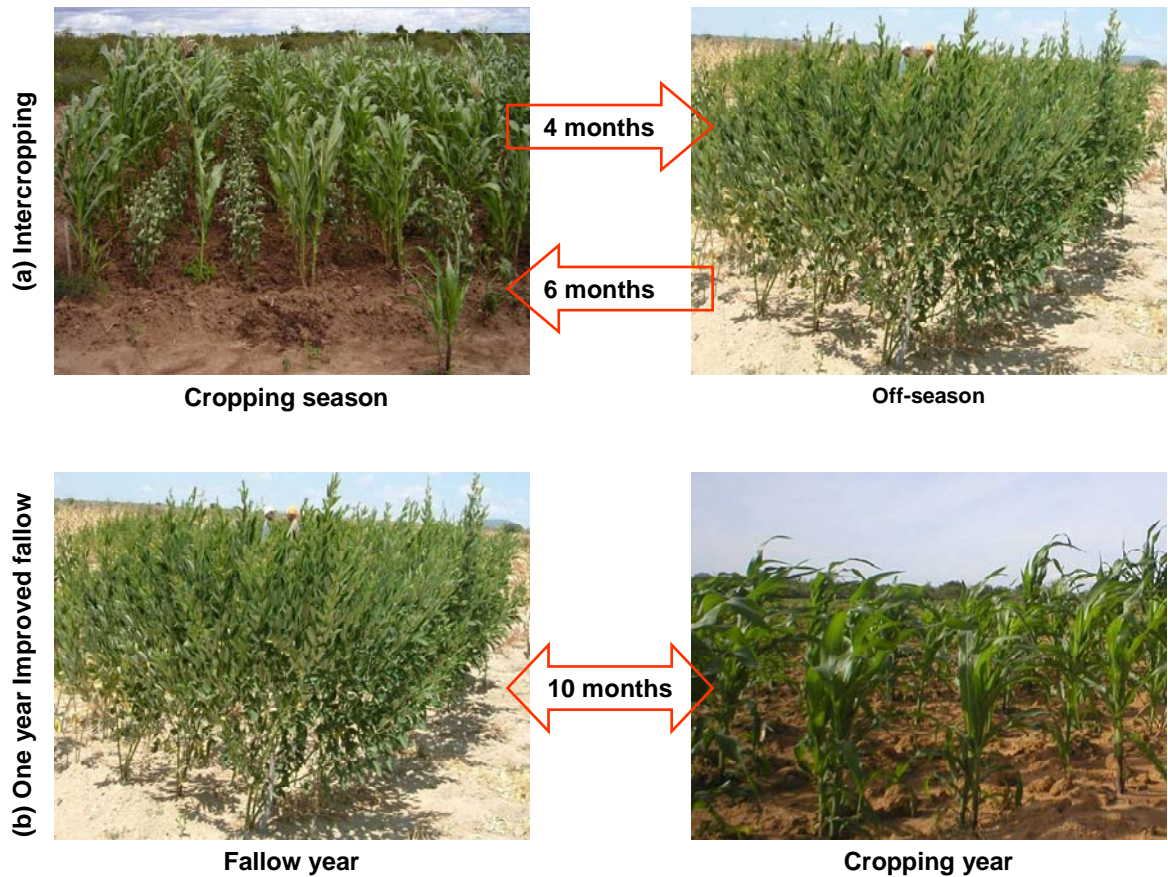


Figure 1.3. Pigeonpea intercropping (a) and fallowing (b) with maize at Ihumwa, Dodoma Tanzania. In both systems pigeonpea occupies the land approximately for the same period of time prior to site preparation for the subsequent cropping season. However, its impacts on productivity depend on the nature and magnitude of interactions with the associated maize crop. Such information is scanty in sub-Saharan Africa. My research assessed biomass and nutritional responses of maize and pigeonpea to reduce this knowledge gap.

pigeonpea yield, our understanding of the mechanisms for interspecific competition between maize and pigeonpea in tropical Africa is limited.

The first objective of this thesis was to assess nutrient use efficiency as a criterion for selecting tree species to sustain on-farm wood production. The second objective was to examine post-fallow maize yield and soil nutrient status in relation to nutrient cycling characteristics of fallow species as reflected by leaf litter quality and leaf decomposition patterns. As a case study, 5-year-old rotational woodlot systems composed of tree species [*Acacia crassicaarpa* A. Cunn., *Acacia polyacantha* Willd, *Acacia mangium* Willd., *Acacia nilotica* (L.) (Del), *Gliricidia sepium* (Jacq.) Walp] with contrasting litter quality were adopted for objectives one and two. The woodlots were harvested to determine wood and foliage biomass, plant tissues nutrient content, and soil nutrient status. Subsequently, post-maize yield was assessed for three consecutive seasons. The third objective was to examine mechanisms for interspecific nutrient interactions between maize and pigeonpea in order to propose management practices for mitigating interspecific competition. This involved testing biomass and nutritional responses of crops under intercropping and one-year fallow of pigeonpea and maize with and without the addition of cattle manure and inorganic fertilizers. Finally, the results of these studies were used to advance a plea for increased use of planted tree fallows in semi-arid zones as demonstrated by high potential of these fallows to reduce deforestation and increase carbon sequestration.

The thesis is divided in to seven related chapters. This chapter introduces the thesis and research objectives and approaches. Chapter 2 reviews the literature showing the impacts of subsistence farming practices on soil and forest resource degradation and the role of improved fallows in addressing this problem through soil fertility replenishment and fuelwood production. Detailed information on specific types of improved fallow systems studied (i.e., rotational woodlots and pigeonpea fallows) is provided to rationalize my study. Chapter 3 presents results of fuelwood supply, nutrient content, nutrient use efficiency and soil nutrient status for tree species in a 5-year-old rotational woodlot to demonstrate the capacity of this system to meet household wood supply and replenish soil fertility. Subsequently, nutrient use efficiency is proposed as an additional tree species selection criterion. Chapter 4 evaluates tree

species effects on post-fallow maize yield. Inorganic soil N and phosphorus (P), litter quality indices, and patterns of the decomposition and nutrient release of leaves were also determined in order to understand differential responses of maize to tree species. Analysis of the mechanisms for interspecific interactions between maize and pigeonpea and associated mitigating measures are discussed in Chapter 5. A plea for promoting environmental benefits of improved fallow practiced is given in Chapter 6, while conclusions, implications, recommendations, and future research agenda are summarized in Chapter 7. Chapters 3, 4 and 5 are published in referred journals (Kimaro et al., 2007; Kimaro et al., 2008; Kimaro et al., 2009). These chapters are presented here after minor modifications to conform to the theme of this thesis and avoid repetition. Permission for inclusion of the published papers has been obtained from the publishers. The plea (Chapter 6) was presented as a poster in the World Congress of Agroforestry in August, 2009 in preparation for a policy brief for publication either by the World Agroforestry Centre (ICRAF) or regional journals to reach the targeted audience.

## **CHAPTER 2**

### **LITERATURE REVIEW**

#### **2.0 Soil and forest resource degradation in Sub-Saharan Africa**

Per capita food production in sub-Saharan Africa has declined by 10 % since 1960 (Pretty, 2008). This is mainly due to low inherent soil fertility, soil degradation through nutrient and organic matter depletion, and to recurrent droughts (Sanchez, 2002; Lal, 2004; Vohland and Barry, 2009). The problem of nutrient depletion in this region has been aggravated by the fact that nutrient removal, through crop harvesting and soil erosion, exceeds inputs of inorganic fertilizers and/or manure (Dudal, 2002; Sanchez and Jama, 2002; Garity, 2004). Additionally, the depletion of soil nutrients and organic matter decrease the ability of microorganisms to recycle nutrients and reduce the water holding capacity of the soil. Finally, the common practices of livestock grazing and removal of crop residues for fuelwood and fodder after crop harvesting, also accelerate loss of nutrients and organic carbon in the soil. Therefore, replenishing soil fertility and improving water management will have a major role in increasing agricultural productivity in tropical Africa.

Declining soil fertility can indirectly lead to increased deforestation rates. This results from the clearing of native forests for farmland expansion and from the conversion of long-fallow cropping systems to continuous cropping. Although deforestation is linked to several underlying factors, it is generally acknowledged that agricultural expansion, wood extraction, and infrastructure development are the major causes of tropical deforestation (Geist and Lambin, 2002). For example, shifting cultivation has been associated with the accelerated deforestation rate in Cameroon in the 1990s. At this time, many people migrated to rural areas to engage in subsistence agriculture due to high unemployment rates in the cities (Sunderlin et al., 2002). In Tanzania, approximately 70 % of deforestation is related to woodfuel collection, either through direct removal of wood (43 %) or through conversion (27 %) of forests to agriculture where the wood is used for fuel (Makundi, 2001). Commercial charcoal production alone accounts for up to 50 % loss of forest cover in the easily accessible areas close to Dar-es-Salaam city

(Malibwi and Zahabu, 2008). Wood extraction for agro-processing operations such as tobacco curing is associated with 4 – 26 % of deforestation in eastern and southern Africa (Sileshi et al., 2007). Fuelwood energy accounts for more than 80 % of the energy used in sub-Saharan Africa (Abbot and Lowore, 1999; Makundi 2001; Mwampamba, 2007). As such, in semi-arid areas where supply from native forest is limited, domestic and commercial woodfuel harvesting may increase deforestation rate.

Agroforestry may address soil and forest degradation problems discussed here through intensification of agriculture to improve soil fertility, crop production and fuelwood supply, which in turn will reduce harvesting pressure on native forest and minimize agricultural expansion (Nyadzi et al., 2003a; Jama et al., 2008; Pretty, 2008). These issues are detailed in the next section.

## **2.1 Agroforestry as a possible solution**

Conventionally, chemical fertilizers have been applied to rapidly replenish soil fertility and improve crop yield. However, it is widely realized that high fertilizer costs deter smallholder farmers from using inorganic fertilizers at the recommended rates. Moreover, fertilizer application alone does not replenish soil organic matter that is needed to improve nutrient and water retention capacity of highly degraded soils in the tropics (Sanchez and Jama, 2002; Brady and Weil, 2004). Consequently, integrated nutrient management approaches are promoted for sustaining soil fertility in both tropical and temperate regions (Vanlauwe and Giller, 2006; Drinkwater and Snapp, 2007). These approaches advocate the combined use of organic and inorganic inputs, enhancing use efficiency of both inputs, and for Africa, the use of locally available nutrient sources. Besides providing fuelwood, agroforestry may also contribute to all these aspects of nutrient management and may play a major role in the context of resource-limited subsistence agriculture in the tropics. Trees in agroforestry can fix nitrogen, retrieve nutrients from deep soil layers, intercept nutrients leaching below the crop rooting zone, and transfer nutrients to associated crops through litter and root turnover. These processes may also build up soil organic matter and lead to more efficient use of soil nutrients in agroforestry systems compared to crop monocultures because of the comparatively tighter nutrient cycles and greater organic matter addition (Young, 1997).

The agroforestry strategy for Tanzania prepared in 2004, envisions that 60 % of rural communities will adopt and benefit from various agroforestry technologies in the country (Kitalyi et al., 2009). To contribute to this target, my thesis will focus on improved fallow systems in semi-arid areas of Morogoro and Dodoma regions of Tanzania. Over 50 % of mainland Tanzania and 40 % of eastern and southern Africa is semi-arid (Hatibu et al., 2006). Semi-arid and other agro-ecological zones are classified based on the length of growing period. This period refers to the season in a year when both moisture and temperature are conducive to crop growth, i.e., temperatures are greater than or equal to 5°C and precipitation plus moisture stored in the soil exceed half the potential evapotranspiration (Sebastian, 2009). Using this criterion, semi-arid zones are areas with a growing period of 70 – 180 days (Sebastian, 2009). Average precipitation in these areas ranges from 300 – 800 mm per year (Hatibu et al., 2006; Vonland et al., 2009). A minimum amount of precipitation required for optimum growth of annual crops like maize and beans is 375 mm during the four month-long growing season; total crop failure may occur when the precipitation is below 275 mm (Nyathi et al., 2003).

## **2.2 Improved fallows**

### **2.2.1 Evolution of fallow management strategies**

Improved fallows refer to agroforestry systems that involve purposeful planting of fast-growing trees, shrubs, and herbaceous species in rotation with crops for rapid replenishment of soil fertility (Sanchez, 1999). This system evolved as a solution to declining soil fertility caused by shortened fallow periods in shifting cultivation practices. Under shifting cultivation, the degraded farmland was abandoned to allow for soil fertility replenishment through natural vegetation succession processes. As such, this system involved no management, except for *enriched fallows*, where certain trees species were planted to produce economically valuable products including fruits, medicine, rubber, and non-timber products (Sanchez, 1999; Burgers et al., 2005). Fallow enrichment, driven by a high demand for land and desire for income generation, marked the beginning of the transition from natural (*unmanaged*) fallows to planted (*managed*) fallows. During this transition period, the pressure for land tended to accelerate soil nutrient

depletion due to reducing the fallow period while economic benefits motivated farmers to actively manage the fallow vegetation through enrichment planting. Improved fallow systems further intensified management of the fallow period by planting fast-growing trees for rapid replenishment of soil nutrients and wood supply (Burgers et al., 2005).

### 2.2.2 Soil fertility improvement

Maximizing foliage biomass production is the primary objective for managing fallow species for soil fertility restoration. This is because nutrient contributions from improved fallows are positively correlated to the amount of biomass added to the soil (Sanchez and Jama, 2002). Farmers in humid and sub-humid zones prefer herbaceous (cover crops) fallows rather than tree fallows for soil fertility improvement because herbaceous fallows produce more foliage biomass within a short period and require less labour for establishing and clearing the fallow (Hauser et al., 2006). To promote foliage biomass production, dense stands of short-rotation tree/shrub fallows are recommended in semi-arid (10,000 – 20,000 plants ha<sup>-1</sup>) and sub-humid (20,000 – 50,000 plants ha<sup>-1</sup>) areas in eastern and southern Africa (Chirwa et al., 2003; Niang et al., 2002; Chamshama et al., 2006). In fallows managed by farmers, Jama et al. (2008) observed up to 100,000 plants ha<sup>-1</sup> in highlands of western Kenya.

Tree fallowing improves soil fertility through biological N-fixation and recycling of other nutrients. Fast-growing leguminous tree-shrub fallows of *Sesbania sesban* (L.) Merrill., *C. cajan*, *G. sepium*, *Tephrosia vogelii* Hook. f., *Crotaria* spp., etc., can accumulate about 100 – 200 kg N ha<sup>-1</sup> in the above-and belowground biomass (Sanchez and Jama, 2002). A large proportion of this amount comes from biological N fixation by these plants and the rest comes from the soil (Gathumbi et al. 2002; Chikowo et al., 2004). Tree roots also can intercept nutrient leaching beyond the crop rooting zone and capture nutrients from deep soil horizons, which in turn are recycled to the top soils through litter fall. These processes are respectively referred to as “the safety net hypothesis” and the “nutrient pump hypothesis” and have been demonstrated to play an important role in the recycling of nutrients in agroforestry systems (Young 1997; Lehman and Schroth, 2003). These hypotheses represent the main



mechanisms through which non-N fixing fallow species such as *Tithonia diversifolia* (Hemsl.) A. and *Senna siamea* (Lam.) Irwin and Barneby used in agroforestry may regenerate soil fertility (Nyadzi et al., 2003b; Barrios et al., 2005). After two years, *Tithonia* fallows raised soil total N by 110 kg N ha<sup>-1</sup> (Thor Smestad et al., 2002) and significantly improved soil exchangeable cation status compared to natural fallows (Barrios et al., 2005), indicating enrichment of top soils through capture and recycling of nutrients from deep soil horizons. Recycling of P is usually limited by high P-fixation in acid soil, low mobility in the soil, and low foliar P concentration (Young, 1997). Consequently, external P input is necessary to sustain crop yield on P-deficient sites because the amount recycled by short-rotation fallows is often lower than exports through repeated crop harvest (Smithson and Giller, 2002). Fallow species also accumulate other nutrients from the soil and may alleviate nutrient deficiencies, especially for K that can arise when sufficient levels of N and P are supplied (Sanchez and Jama, 2002).

After 2 – 3 years, fallows of fast-growing leguminous trees can replenish soil N to levels sufficient to grow up to three subsequent maize crops on N-deficient sites (Mafongoya et al., 2006), doubling to quadrupling maize yields relative to natural fallows or continuous cropping without fertilizer addition (Kwesiga et al., 2003). However, the possible drawbacks of these fallows compared to continuous cropping and natural fallow practices is the high labour requirements for establishing and clearing trees or shrub species and the need for additional land for crop cultivation during the fallow period. However, economic analysis of improved fallows showed that tree species with additional benefits in terms of fuelwood, poles, timber, and fruits can be more profitable when markets for these products are available (Alegre et al., 2005; Franzel, 2004). Besides income from tree-based products, other benefits such as labour saving during the fallow period, weed suppression, and reduced site preparation costs also contributed to this high profit (Alegre et al., 2005; Franzel, 2004). Analysis of the rotational woodlot system for fuelwood supply in semi-arid Tanzania revealed a 6-times higher net present value than that of maize-natural fallow system due to revenues from firewood and post-fallow maize yield (Ramadhani et al., 2002). Similar results have been reported for planted tree fallows in Latin America (Alegre et al., 2005; Lojka et al., 2008), Zambia, and Kenya (Franzel, 2004). Farmers'

evaluation of agroforestry systems introduced by the World Agroforestry Centre (ICRAF) in southern Africa also indicated high preference for pigeonpea fallows because of the high promise of food and income generation in addition to soil fertility improvement (Kwesiga et al., 2003). Considering these social and biophysical benefits, pigeonpea intercropping systems were chosen here as a case study to examine mechanisms for improving productivity by minimizing tree-crop competition and promoting facilitation. Similarly, the rotational woodlot system was adopted as a case study for assessing sustainability of on-farm fuelwood supply.

### **2.2.3 Fuelwood wood supply**

On-farm fuelwood production using agroforestry systems such as improved fallows is a promising approach to reduce harvesting pressure on native forests, to reclaim degraded farmlands, and to increase food production among smallholder farmers in the tropics (Ramadhani et al., 2002; Kwesiga et al., 2003; Jama et al., 2008). Clearing short-rotation tree-shrub fallows established for soil fertility management can generate significant amounts of fuelwood depending on site conditions, plant species, and fallow length. Examples of fuelwood yield include: 18 – 22 Mg ha<sup>-1</sup> after 3 years (6.0 – 7.3 Mg ha<sup>-1</sup> yr<sup>-1</sup>) under semi-arid conditions in Tanzania and Zambia (Chirwa et al., 2003; Herbet et al., 2002) and 10 – 38 Mg ha<sup>-1</sup> after 18 months (6.7 – 25.3 Mg ha<sup>-1</sup> yr<sup>-1</sup>) in sub-humid western Kenya (Niang et al., 2002; Jama et al., 2008). Jama et al. (2008) estimate that these amounts of fuelwood can satisfy household demand for up to 12.8 years in western Kenya. However, wood from these fallows may be of smaller dimensions because of the high density stand and short duration of fallows established for soil fertility replenishment, as mentioned earlier (Niang et al., 2002; Chirwa et al., 2003). This can be a constraint for fallow adoption in semi-arid areas with scarcity of fuelwood.

Whereas short-rotation fallows emphasize soil fertility, rotational woodlots are mainly promoted for on-farm wood supply. This system is a variant of improved fallows as the woodlots are rotated with crops in 5-year cycles (Nyadzi et al., 2003a; Kimaro et al., 2007). This long fallow periods may result in higher fuelwood yield as compared to the 2-3 year fallows recommended for soil fertility replenishment

(Kwesiga et al., 2003; Mafongoya et al., 2006). For example, *A. crassicaarpa* may produce 56 – 77 Mg ha<sup>-1</sup> (11.2 – 19.4 Mg ha<sup>-1</sup> yr<sup>-1</sup>) of wood after 4 – 5 years (Nyadzi et al., 2003a). Similarly, Sileshi et al. (2007) also found that rotational woodlots have the highest potential to reduce harvesting pressure on native Miombo forests through wood supply compared to contour strip tree planting, and short-rotation (< 3 years) improved fallows, and natural fallows. However, high nutrient removals through frequent wood and crop harvests pose concerns for sustainability of rotational woodlot systems due to probable nutrient depletion, as predicted for intensive biomass harvesting from short-rotation plantations (Nykqvist, 2000; Scott and Dean, 2006). A brief description of this system and approaches for sustaining site productivity are provided below.

#### **2.2.4 Rotational woodlots**

The rotational woodlot system consists of three management phases embodying features of both sequential and simultaneous agroforestry systems (Fig. 1.2). Tree and crop components are established at the same time and the intercropping continues for 2 – 3 years when crop yield declines to uneconomical levels due to adverse competition for growth resources. The objective of this initial phase is to establish trees while producing food. Hence, trees are not managed to minimize interspecific competition. The initial phase is followed by a 2 – 3-year tree fallow period during which little or no management is required to maintain trees. However, the woodlot can be used as a fodder bank, an apiary, or *Ngitili* (a traditional fodder reserve) while restoring soil fertility through nutrient cycling processes. *Ngitili* is a traditional *silvopastoral* system in western Tanzania in which farmers reserve part of the grazing land at the beginning of the rainy season to provide pasture during the dry season when supply from unreserved areas is depleted. When trees grow to a desirable size, the woodlot is cleared to supply wood for uses such as building poles, firewood, and tobacco curing. The foliage biomass is retained on site as green manure. The final phase is a post-fallow period in which trees are harvested and crops are grown between tree stumps to benefit from the ameliorated soil conditions. For tree species that sprout, coppice shoots are regularly pruned to minimize above ground competition and are incorporated into the soil or used as

fodder. Another cycle starts after 2 – 3 years of sequential cropping when crop yield decline to unacceptable levels due to nutrient depletion (Otsyina et al., 1999; Nyadzi et al., 2003a) as well as due to belowground competition by remnant tree stumps. However, root competition during the post-fallow phase has not been documented possibly due to poor re-growth of stumps of the tested tree species and/or unfavorable site conditions (especially drought occurring during the off-season), which do not promote coppicing.

Operationally, rotational woodlot systems integrate wood and crop yields while providing additional benefits in terms of increased maize yields, fodder, beekeeping, erosion control, etc. As such these systems have high potential for adoption in areas with scarcity of fuelwood. Over 87 % of farmers in Tabora, Tanzania, have planted woodlots in 0.5 – 0.8 ha of their farms mainly for producing wood for tobacco curing, firewood, and construction materials (Ramadhani et al., 2002). Exotic Australian acacias (*A. crassicarpa*, *Acacia julifera* Berth., and *Acacia leptocarpa* A. cunn. Ex. Benth) are the most preferred species because of high biomass production, ranging from 21 – 77 Mg ha<sup>-1</sup> (4.2 – 19.4 Mg ha<sup>-1</sup> yr<sup>-1</sup>) compared to 22 Mg ha<sup>-1</sup> (4.4 Mg ha<sup>-1</sup> yr<sup>-1</sup>) for *S. siamea* after 4 to 5 years and 50 – 71 Mg ha<sup>-1</sup> (7.1 – 10.1 Mg ha<sup>-1</sup> yr<sup>-1</sup>) for an indigenous acacia (*A. polyacantha*) after 7 years (Nyadzi et al., 2003a). The high productivity of Australian species in semi-arid Africa may be related to high tolerance to low fertile soils reflecting mycorrhizal association and efficient use of nutrients (Doran et al., 1997). The native ranges of some of these species (e.g. *A. julifera*) extend from sub-humid and semi-arid areas (Doran et al., 1997) while others (*Acacia Auriculiformis* A. Cunn. ex Benth., *A. crassicarpa*, *A. leptocarpa*) may grow well in semi-arid Africa (Ngulube et al., 1993; Ali et al., 1997; Luhende et al., 2006). Basic density and calorific values of these species are presented in Table 2.1. Despite intensive management in woodlots, wood density values of tree species (< 6 years) were within the range reported for dominant species (*Brachystigia* spp.) in the native Miombo woodland. This similarity suggests that energy values of tree species planted in woodlots may be close to those of tree species under natural conditions. Basic densities of *A. crassicarpa* (620 kg m<sup>-3</sup>) and *A. mangium* (420 – 516 kg m<sup>-3</sup>) reported in their native range (Doran et al., 1997) and in the 12-year-old homegarden in India (Shanavas and Kumar, 2003) are also close to

Table 2.1. Wood basic density and calorific value of tree species in planted tree fallows and natural forests in Tanzania and Malawi.

Tree species	Basic density		Calorific value	
	kg m <sup>-3</sup>	Source/Country	cal kg <sup>-1</sup>	Source
<i>Acacia crasscarpa</i>	584	Luhende et al. 2006/ Tanzania	5400	AF tree database <sup>1</sup>
<i>Acacia mangium</i>	570	Ali et al. 1997/ Tanzania	4800-4900	AF tree database
<i>Acacia polyacantha</i>	705	Acacia fact sheet	-	
<i>Gliricidia sepium</i>	470	Ngulube, 1994/ Malawi	4550-4900	AF tree database
<i>Acacia nilotica</i>	700 <sup>2</sup>	Malibwi et al. 1994/ Tanzania	4500-4950	AF tree database
<i>Acacia auriculiformis</i>	617	Ali et al. 1997/ Tanzania	4700-4900	Doran et al. 1997
<i>Acacia leptocarpa</i>	693	Luhende et al. 2006/ Tanzania	-	
<i>Acacia julifera</i>	627	Luhende et al. 2006/ Tanzania	-	
<i>Combretum</i> sp.	780 <sup>2</sup>	Malibwi et al. 1994/ Tanzania	-	
<i>Brachystegia speciformis</i>	610 <sup>2</sup>	Malibwi et al. 1994/ Tanzania	-	
<i>Brachystegia boehmii</i>	750 <sup>2</sup>	Malibwi et al. 1994/ Tanzania	-	

<sup>1</sup> AF = Agroforestry tree database available at: <http://www.worldagroforestry.org/sites/TreeDBS/Aft.asp>

<sup>2</sup> Values determined from trees growing in the natural forests. The rest are values for planted trees fallows in woodlots.

those found in woodlots in Tanzania. Although there was little published information on calorific values of indigenous tree species, values found in the literature (Table 2.1) were similar for both exotic and indigenous species utilized for fuelwood supply under the rotational woodlot system.

Intensive management of rotational woodlots for fuelwood supply may exert pressure on soil water and nutrient resources because of the high demand by fast-growing species. Nyadzi et al. (2003b) assessed water use by tree species in rotational woodlots in Western Tanzania. Although the highest transpiration rate was noted for *A. crassicarapa*, this species did not cause significant decline in soil water content during the dry season when compared to the natural fallow and continuous maize cropping. The study concluded that woodlots store more soil moisture because of higher soil water content under tree fallows during the rainy season. Apart from soil N after tree fallowing (Nyadzi et al., 2003b), little information is available on the impacts of fuelwood harvesting on nutrient export and restitution for different tree species under this system. But it is widely recognized that frequent nutrient removals in harvested biomass without sufficient replenishment may contribute to declining site productivity and sustainability because of soil nutrient depletion, especially for short-rotation plantations (Fölster and Khanna, 1997; Nykvist, 2000). This effect could be critical for rotational woodlot systems where additional nutrients are lost through crop harvesting.

#### **2.2.5 Nutrient use efficiency and species choice**

A review of productivity changes in short-rotation commercial plantations (Table 2.2) suggest that yield decline over several rotations cannot be attributed to nutrient depletion alone (Evans and Turnbull, 2004). Moreover, site productivity in successive rotations can be sustained by using genetically improved germplasm, applying fertilizers, and employing other silvicultural practices that minimize weed invasion and nutrient loss through biomass harvest and site disturbances (Goncalves et al., 2004; Evans and Turnbull, 2004). In the context of smallholder farmers, stem wood only harvesting is probably the

Table 2.2. Factors contributing to productivity decline in short-rotation tropical forest plantations based on the long-term studies in Australian, New Zealand, China, India, and Indonesia.

Location	Species	Rotation cycle	Productivity change	Remarks
Australia and New Zealand	<i>Pinus radiata</i>	2 <sup>nd</sup>	30 % decline	Poor harvesting and site preparation practices that resulted in removal of organic matter Weed invasion, particularly grasses.
China	<i>Cunninghamiana lanceolata</i> (Chinese fir)	2 <sup>nd</sup>	10 % decline	Whole tree harvesting Poor harvesting practices such as litter raking that resulted in total removal of organic matter.
		3 <sup>rd</sup>	40 % decline	Intensive cultivation and slash burning that favoured bamboo and grass invasion.
India and Indonesia	<i>Tectona grandis</i> (Teak)	2 <sup>nd</sup>	Decline	Nutrient mining due to over intensive taungya (Intercropping) cultivation Delayed planting. Poor tending practices. Soil erosion

Summarized from Evans and Turnbull (2004).

main mechanism for minimizing nutrient loss in rotational woodlots while sustaining site productivity because of high costs of fertilizer inputs. Depending on tree species and site conditions, this approach may reduce nutrient export by 40 – 70 % for N and 20 – 50 % for P, K, Ca and Mg compared to whole-tree harvesting (Montagnini, 2000; Shujauddin and Kumar, 2003). Retaining slash on site may also contribute to reduce continuous nutrient removal from this system. However, this approach may have limited impacts in subsequent rotations since nutrients recycled are also lost during post-fallow period mainly through crop harvesting.

Nutrient use efficiency, defined as the ratio of biomass to nutrient uptake, describes the differential ability of tree species to produce biomass in relation to nutrient uptake. This ratio also facilitates comparisons of nutrient exported in harvested biomass (Kumar et al., 1998; Montagnini et al., 2000). Nutrient-efficient plant species retranslocate large proportions of nutrient and hence are less dependent on uptake from soils to meet subsequent nutrient requirements. These species may be suitable for planting on infertile sites (Hiremath et al., 2002). In the context of nutrient recycling characteristics, low nutrient use efficiency implies high recycling abilities, reflecting the potential of less efficient tree species to improve soil fertility and crop yield after the fallow period (Montagnini et al., 2000; Schroth et al., 2003). Hence, nutrient use efficiency has been proposed as a criterion for selecting tree species for short-rotation plantations (Hiremath et al., 2002; Safou-Matondo et al., 2005), woodlots (Wang et al., 1991; Kumar et al., 1998) and other agroforestry practices (Montagnini et al., 2000; Schroth et al., 2003). Whereas previous studies have considered biomass alone in screening trees for use in woodlots (Karach et al., 1997; Nyadzi et al., 2003a), this thesis employed nutrient use efficiency to screen low nutrient demanding tree species for on-farm fuelwood supply.

### **2.2.6 Pigeonpea-maize cropping systems**

In the semi-arid tropics of Africa and India, grain legumes [e.g. *C. cajanus* and *Glycine max* (L.) Merr. (soybean)] are often intercropped or rotated with cereals such as *Z. mays* and *Sorghum bicolor* L. Moench (sorghum) to diversify food and income sources (Fig. 1.3). Also these practices have high



potential to restore and sustain soil fertility since these legumes fix atmospheric N. For example, the net amount of N added by pigeonpea to the soil through this process has been found to be 53 kg N ha<sup>-1</sup> after 9 months in humid zones (Gathumbi et al., 2002) and 82 kg N ha<sup>-1</sup> after 2 years in semi-arid conditions (Chikowo et al., 2004). These amounts are transferred to the soil through litter fall as well as root and nodule decay. However, most of the N recycled by pigeonpea may not be immediately available to intercropped plants because the legume sheds leaves after crop harvest and the leaves have slow decomposition rates (Sakala et al., 2000). As pigeonpea growth continues during the off-season, it may re-assimilate and transfer this N to the subsequent crop through green manure.

Pigeonpea can access sparingly soluble P (Fe-P and Ca-P) in the soil through exudation of piscidic acid and citric acids in response to P deficiency, thus increasing rhizospheric P (Ishikawa et al., 2002; Shibata and Katsuya, 2003). Under low P conditions, the shrub also transfers a large proportion of P from senesced leaves to nodules to meet the demand for N fixation (Ishikawa et al., 2002; Sinclair and Vadez, 2002). These mechanisms may contribute to high P-use efficiency by pigeonpea on P-deficient sites, but are unlikely to enhance soil P because of low P reserves. However, when P is not a limiting element, pigeonpea fallowing has been reported to significantly increase soil P compared with continuous maize cropping (Chamshama et al., 2006) indicating high recycling capacity. This improvement reflects retrieval of nutrients from deep soil layers by pigeonpea roots and subsequent recycling through litter fall. Apart from soil fertility improvement, the success of pigeonpea intercropping systems may also be attributed to the combined effects of moisture supply through hydraulic lift and complementary resource use due to root niche separation (Sekiya and Yano, 2004).

Pigeonpea-based cropping systems may also benefit farmers in terms of soil fertility replenishment and increased crop yields (Chikowo et al., 2004; Chamshama et al., 2006; Rao and Mathuva, 2000). While most farmers use pigeonpea grain for food, some sell the grain to earn income (Snapp et al., 2002) possibly because the price of legume grain is 2 – 4 times higher than the price of maize grain (Rao and Mathuva, 2000). However, wood supply from pigeonpea is negligible due to its small growth habit and the short duration of fallows that are designed for soil fertility management. In

semi-arid areas where crop yields under intercropping may be suppressed by interspecific competition, overall productivity and revenues of this system can be higher than those of maize monoculture only when grain yield from pigeonpea is considered (Rao and Mathuva, 2000; Myaka et al., 2006). Although pigeonpea grain yield may contribute to the advantage of this intercropping system, there is limited information on the impacts of interspecific interactions on growth and yield of pigeonpea in sub-Saharan Africa.

Interspecific competition in legume-cereal intercropping has been studied in India and China by comparing relative yields of the two component crops (Zhang and Li, 2003; Ghosh et al., 2006). Analysis of a soybean-wheat (*Triticum aestivum* L.) intercropping system revealed that the initial growth and yield of soybean were suppressed due to competition with the wheat, but the final yield of soybean was unaffected because of compensatory growth after harvesting the companion crop (Zhang and Li, 2003). This temporal compatibility, however, was not observed when pigeonpea (the late-maturing crop) was intercropped with soybean (the early-maturing crop). The relative yield of pigeonpea was 60 % at harvest, but approached 100 % after fertilization demonstrating yield suppression due to nutrient competition (Ghosh et al. 2006). In sub-Saharan Africa, pigeonpea is also intercropped with maize, on the basis of temporal compatibility (Snapp et al., 2002; Mafongoya et al., 2006). However, empirical studies verifying this compatibility are few and limited to the yield responses alone (Rao and Mathuva, 2000) possibly because pigeonpea is considered a “bonus” crop that will not adversely compete for resources with maize (the main crop) due to its slow initial growth (Snapp et al., 2002; Mafongoya et al., 2006). Therefore, further research demonstrating biomass and nutritional interactions of pigeonpea and maize would contribute to elucidate mechanisms of interspecific competition for improved management of legumes-cereal intercropping systems in semi-arid Africa.

### **2.3 Conclusions**

This review of the literature has shown that unsustainable agricultural practices in Sub-Saharan Africa may lead to degradation of soil and forest resources. Accordingly, several agroforestry systems

have been developed to enhance and replenish soil fertility and produce fuelwood. Unlike short-rotation commercial forestry plantations, agroforestry systems promoted for wood production are not intensively managed to sustain site productivity due to limited access to fertilizer and other inputs by smallholder farmers. Therefore, more research is required to promote affordable and environmentally-friendly nutrient management options for these farmers to sustain both fuelwood and crop production. In this thesis, I advocate that future tree selection procedures for the rotational woodlot system should consider nutrient removals through fuelwood harvesting by incorporating nutrient use efficiency as an additional tree selection criterion. The review further showed that short duration fallows can rapidly improve soil fertility to levels sufficient to sustain maize yields for up to three sequential cropping seasons. However, interspecific competition may suppress crop yield under cereal-grain legume intercropping systems that are traditionally used for diversifying food and income sources to smallholder farmers while improving soil fertility. Although controlling this interaction will optimize productivity of these systems, there is insufficient information on the effects of interspecific competition on crop yield in sub-Saharan Africa. Therefore, this work uses rotational woodlot (developed for wood production) and the pigeonpea-maize cropping (legume-cereal) systems in semi-arid Tanzania as case studies to address research problems identified in the literature. The overall goal was to enhance the productivity of these systems through the use of suitable tree species for on-farm wood supply and mitigation of interspecific nutrient competition between pigeonpea and maize, thereby addressing challenges of food insecurity, poverty, and natural resource degradation associated with low agricultural productivity in sub-Saharan Africa.

### CHAPTER 3

## NUTRIENT USE EFFICIENCY AND BIOMASS PRODUCTION OF TREE SPECIES FOR ROTATIONAL WOODLOT SYSTEMS IN SEMI-ARID MOROGORO, TANZANIA

### Abstract

Frequent nutrient removals accompanying wood and crop harvests from rotational woodlot systems may contribute to declining site productivity and sustainability because of soil nutrient depletion. However, selecting for nutrient-efficient tree species may well sustain productivity under this system. To test this hypothesis, a randomized complete block experiment was carried out to assess effects of five tree species on soil nutrients status, nutrient use efficiency and wood yield in semi-arid Tanzania. After 5 years rotation, top soils under *G. sepium*, *A. polyacantha* and *A. mangium* were the most fertile with soil organic carbon and exchangeable cation status raised close to those in natural Miombo systems. Soil inorganic N and extractable P levels reached sufficiency levels for maize culture. Wood productivity in tree fallows averaged three times higher than that of Miombo woodlands indicating the high potential of the woodlot system to supply fuelwood, and consequently relieve harvesting pressures on the natural forests. *Acacia crassicarpa* produced the most wood ( $51\text{Mg ha}^{-1}$ ) at low nutrient “costs” presumably due to high nutrient use efficiency. Wood yield of this species was 42 and 120 % greater than that of *A. polyacantha* and *A. nilotica*, respectively, but contained comparatively less nutrients (42 to 60 % less for P, K, and Ca). *Gliricidia sepium* and *A. polyacantha* returned the largest amount of nutrients through slash at harvests. Of all test species, *A. crassicarpa* exhibited the most promise to sustain wood production under rotational woodlot systems due to relatively high productivity and low nutrient export at harvest.

### 3.1 Introduction

Plantations and woodlots of fast growing tree species play a significant role in meeting the rapidly increasing demands for timber, fuelwood and other wood products in the tropics. On suitable soils, fast-growing tree species such as *Pinus patula* Schldl. Cham and *Cupressus lusitanica* Mill. produce as much as 25 to 35 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup> of wood compared to 4.35 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup> produced from the natural Miombo woodlands of Tanzania (Ek 1994). Such fast growth requires ample supplies of soil nutrients and other growth resources that can be rapidly depleted without effective nutrient recycling or fertilizer supplementation. Large amounts of nutrients are exported in tree harvests; with wood accounting as much as 50 % of nutrient exports (Kumar et al., 1998). Intensive repeated harvesting may result in site degradation due to soil fertility decline in subsequent rotations (Nykvist, 2000). The deterioration may be critical on inherently infertile soils because of frequent nutrient loss accompanying repeated biomass harvests (Fölster and Khanna, 1997; Nykvist, 2000). This may also apply to agroforestry practices, such as rotational woodlot systems, because of nutrient loss through continual firewood collections as well as crop harvests.

As described in Chapter 2, section 2.3.4, the rotational woodlot system is an agroforestry technology developed recently to curb fuelwood deficit in semi-arid areas of Western Tanzania where intensive tobacco curing and livestock grazing have accelerated deforestation through forest clearing, continuous farm cropping, and high grazing pressure. Compared to simultaneous agroforestry systems such as hedgerow intercropping, the rotational woodlot system is more suitable for semi-arid conditions because sequential cropping arrangements minimize competition for growth resources, especially soil moisture (Rao et al., 1998) and produce higher wood yields due to longer tree fallows (Nyadzi et al., 2003a). Maize production from this system is usually higher than natural fallow and continuous cropping due to improved soil nutrient build up during the tree fallow phase (Nyadzi et al., 2003a).

One way to sustain soil fertility and crop production in rotational woodlot systems is to reduce the amount of nutrients exported in harvested wood by preferentially planting low nutrient demanding tree species. Nutrient use efficiency, defined as the ratio of biomass production to nutrient uptake, has been

proposed as a criterion for selecting tree species for this purpose (Wang et al., 1991; Kumar et al., 1998). This ratio describes differential abilities of tree species to use soil nutrients for growth (Marschner, 1995; Schroth et al., 2003). It also provides a basis for comparing nutrient “costs” of biomass production (Kumar et al., 1998), and the potential of plant species to grow well under conditions of limited soil nutrient supply (Marschner, 1995; Safao-Matando, 2005). The role of nutrient use efficiency in sustaining productivity of short-rotation tropical plantations by minimizing nutrient loss from harvesting has been studied before (Wang et al., 1991; Kumar et al., 1998; Safou-Matondo, 2005). The general consensus is that nutrient-efficient tree species reduce nutrient export at harvests because of low nutrient content per unit biomass.

Previous approaches for selecting tree species for woodlots in Tanzania considered rates of biomass yields and climatic adaptation alone as suitable criteria (Karachi et al., 1997; Nyadzi et al., 2003a). However, to ensure sustained productivity of the rotational woodlot system, it may be more appropriate to consider nutrient use efficiency as additional selection criteria. Ideally, trees should grow rapidly to produce high wood biomass and export few nutrients at each harvest (Wang et al., 1991). The approach in this study was to assess these factors in a five-year old rotational woodlot experiment. Specific objectives were to examine the effects of tree species on soil nutrients status, wood yield, nutrient use efficiency, and exports in order to evaluate species suitability for rotational woodlot culture. As mentioned in Chapter 1, the results will contribute to the refinement of criteria for screening tree species for such agroforestry practices.

## **3.2 Materials and methods**

### **3.2.1 Study site**

The study was carried out at Mkundi village located at 6° 40' S, 37° 39' E, about 20 km west of Morogoro, Tanzania (Fig. 3.1), at an altitude of about 475 m. The area experiences a rainfall distribution characterized by two rainfall peaks per year with a dry spell separating the short rains (October to December) from the long rains (March to May). The mean annual rainfall and air temperatures are 800

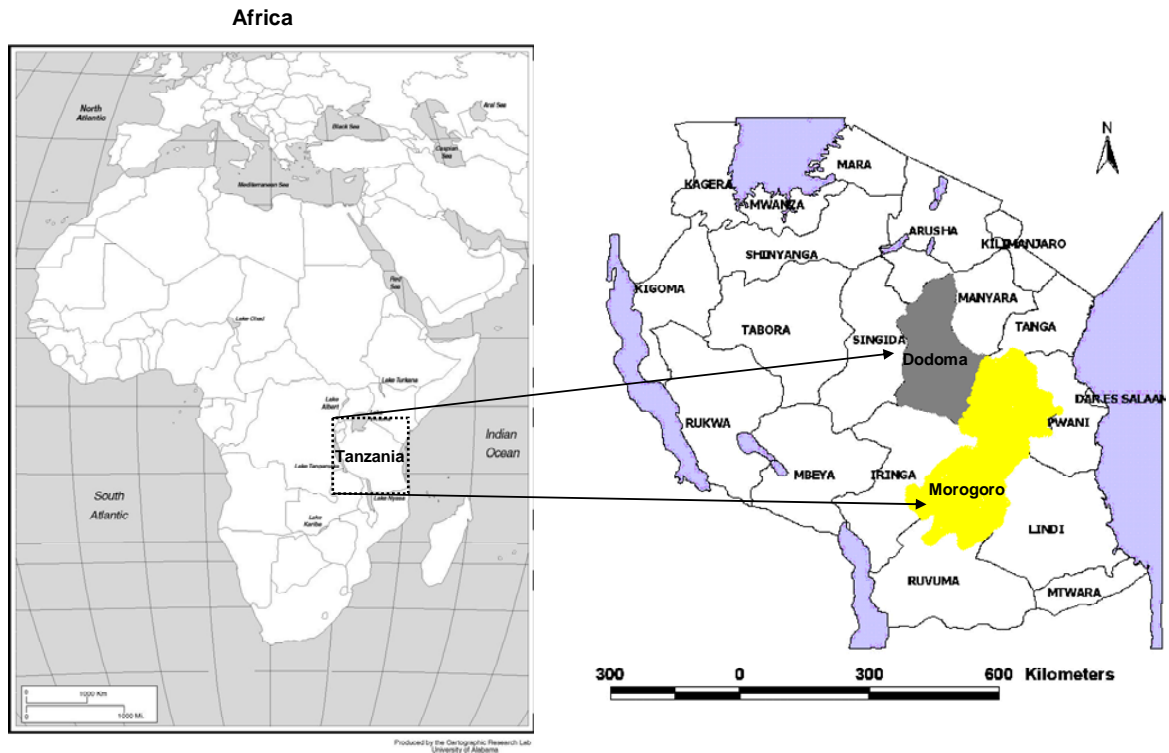


Figure 3.1. Location of study sites: Mkundi village in Morogoro region ( $6^{\circ} 40' S$ ,  $37^{\circ} 39' E$ ) and Ihumwa village in Dodoma region ( $6^{\circ} 10' S$ ,  $35^{\circ} 53' E$ ), Tanzania, East Africa. Africa map was obtained from the University of Alabama website (<http://alabamamaps.ua.edu/contemporarymaps/world/africa/index.html>).

mm and 24°C, respectively. The soils are fairly young, classified as Regosol (FAO Classification System) with predominantly kaolinitic clay mineralogy (Msanya et al., 2003). Average soil physio-chemical characteristics of the top 0-15 cm soil depth were: pH = 6.7, organic carbon = 0.61%, total nitrogen (N) = 0.083 %, extractable Bray-1 phosphorus (P) = 8.5 mg kg<sup>-1</sup>, exchangeable potassium (K) = 0.44 cmol kg<sup>-1</sup>, exchangeable calcium (Ca) = 4.30 cmol kg<sup>-1</sup>, exchangeable magnesium (Mg) = 2.10 cmol kg<sup>-1</sup>, effective cation exchange capacity = 7.26 cmol kg<sup>-1</sup>, bulk density = 1.35 g cm<sup>-3</sup>, and sandy loamy texture. For agricultural production, total N and extractable P levels in the soil were considered deficient while exchangeable K status was marginal (Msanya et al., 2003). The natural vegetation at the study site is degraded Miombo woodland dominated by scattered tree species of *Sclerocarya birrea* (A. Rich.) Hochst., *Dalbergia melanoxylon* (Guill. and Perr.), *Balanites aegyptica* (L.) Del., *Dichrostachys cinerea* (L.) Wight and Arn., *Acacia* spp., and *Albizia* spp. (Mugasha et al., 2005). The rotational woodlot experiment was carried out on-farm using continuously cropped farmland hired from local farmers.

### 3.2.2 Experimental design and management

A rotational woodlot experiment was established in March 1999 in a randomized complete block design (RCBD) with three replications. The trial comprised seven treatments evaluating soils under *A. crassicarpa*, *A. mangium*, *A. nilotica*, *A. polyacantha*, *G. sepium*, a natural fallow and a continuous cropping system. The natural fallow treatment represented typical Miombo soils recovering from degradation due to continuous crop production. The continuous cropping treatment was on land adjacent to the experiment. The planted tree species represented a wide array of nitrogen fixing trees and shrubs species that have potential to produce wood and fodder in Tanzania (Karachi et al., 1997; Nyadzi et al., 2003a). *Acacia crassicarpa*, *A. mangium*, and *G. sepium* are exotic species, but their seeds were collected locally from Tabora, Kibaha, and Morogoro regions, respectively. *Acacia nilotica* and *A. polyacantha* are indigenous species. Seeds of these species were purchased from the National Tree Seed Agency in Morogoro. The tree seedlings were raised in pots for five months in a nursery at the Sokoine University of Agriculture. The seedlings were then planted at a spacing of 3 x 3 m, giving 36 trees per plot. The size of



each plot was 16 x 16 m separated by a 4 m-wide unplanted buffer strip. The distance between blocks was 5 m. Two years after establishment, a 0.5 m wide and 1.5 m deep trench was dug around each plot yearly during long-rain seasons to minimize below-ground inter-plot interactions.

### 3.2.3 Soil sampling and analysis

At the onset of the 2004 long-rain season prior to wood yield assessment, soil samples were collected at 0 – 15 cm depth from five randomly selected points within a 10 x 10 m inner plot area using a hand hoe. The soil samples were bulked by plot, mixed thoroughly, and sub-sampled to get a composite sample for nutrient analysis. Prior to laboratory analysis, the composite samples were air-dried, ground, and sieved through a 2 mm sieve. Soil texture was determined by the hydrometer method, soil pH in 1:2.5 soil-water aqueous suspensions by pH meter, organic carbon by Walkley and Black method, extractable P by Bray-1 method. Analysis of exchangeable K, Ca, and Mg was carried using atomic absorption spectrophotometer after extraction with 1*N* ammonium acetate. Exchangeable acidity (hydrogen and aluminum) was determined by leaching air-dried soil samples with 1 *N* KCl and measured quantitatively by titration. Effective cation exchange capacity was obtained by summation of exchangeable cations and exchangeable acidity (Anderson and Ingram, 1993). Similarly, soil samples for inorganic N determination were collected at the onset of the 2004 long rain season immediately after clear felling and before site preparation for maize planting. This sampling took place 10 weeks after the first rainfall event. The soil samples were kept in a cooler, transported to the laboratory, and frozen in a deep freezer prior to analysis of inorganic N within one week after collection. Soil inorganic N was extracted using 2 *N* KCl solution, and the extracts analyzed for ammonium-N and nitrate-N, then added to obtain total inorganic N (Okalebo et al., 1993). Soil samples for bulk density determination were collected from five random points in each plot at a depth of 0 – 15 cm using 5 x 5 cm core cylinders. The samples were oven-dried at 105<sup>0</sup>C to constant weight and the bulk density calculated as described by Anderson and Ingram (1993).

#### 3.2.4 Biomass yields and nutrient use efficiency determinations

Prior to the onset of the 2004 long-rain season, all surviving trees species (maximum 16 per plot) in the 10 x 10 m inner plot area were sampled to assess height, biomass yield, nutrient contents, and nutrient use efficiency. Each sampled tree was measured for diameter at breast height (DBH). The DBH of multi-stemmed trees was estimated from the arithmetic mean of diameters of individual stems measured at 1.3 m above the ground (Nyadzi et al., 2003a). The trees were then felled using a power saw at 10 cm from the ground, measured for height, and partitioned into stems, branches, and foliage (including twigs and leaves). Each tree biomass component was tied into bundles and weighed in the field to the nearest 0.1 kg using spring balance (Philips) to determine green weight. Discs of about 2 cm thick (Kumar et al., 1998) were sampled from the base, middle and tip of stems and large branches, weighed immediately to determine green weight to the nearest 0.1 g using a portable balance (Philips). Similarly, branches and foliage components were sampled and weighed in the field. Thereafter, samples of each biomass component were oven dried at 70°C to constant weight and moisture content calculated. The moisture content was used to estimate biomass yield of each component, and the values were extrapolated to a hectare based on biomass yield per tree. The biomass yield per hectare was then divided by rotation length (i.e., 5 years) to determine mean annual increment (MAI) of each species.

The oven-dried samples of each biomass component were pooled by plot, sub-sampled and finely ground for N, P, K, Ca, and Mg analysis. Total N was determined by the Kjeldahl method following digestion of tree samples with hydrogen peroxide and sulphuric acid. Total P, Ca, K, and Mg were determined by dry ashing as described by Okalebo et al. (1993). Nutrient content of each biomass component was the product of its biomass ( $\text{Mg ha}^{-1}$ ) and corresponding concentration (%) of each nutrient and the values were expressed in  $\text{kg ha}^{-1}$ . Finally, nutrient use efficiency was expressed as a ratio of biomass to nutrient content (Shujauddin and Kumar, 2003; Safao-Matondo, 2005).

### 3.2.5 Data analysis

Analysis of variance (ANOVA) was carried out after testing for normality and constant variance (homoscedasticity) of residuals by plotting the residuals against normal scores and predicted values, respectively (Dean and Voss, 1999) using a Statistical Analysis System version 8 (SAS, 2000). Thereafter, one-way ANOVA was carried out to test tree species effects on soil nutrient, DBH, height, MAI, wood yield, nutrient content and nutrient use efficiency using the generalized linear model procedure in SAS. Following ANOVA, significant treatment means were separated using Fisher's protected least significant difference (PLSD) at  $\alpha = 5\%$ .

## 3.3 Results and discussion

### 3.3.1 Changes in soil nutrients

After a 5-year fallow period, soil organic carbon in tree fallows (0.8 - 1.3 %) were significantly higher ( $p = 0.0078$ ) than in the continuous-cropping treatment (0.6 %) (Fig. 3.2a). This improvement is usually associated with litter accumulation and fine root turn over during the fallow period as reported in other studies (Rao et al., 1998; Tian et al., 2001). Soil organic carbon under *A. mangium* (1.3 %) and under *A. nilotica* (1.1 %) was higher than in soils under the natural fallow (0.9 %), but similar to those found in the natural Miombo soils of semi-arid areas of Tanzania (Msanya et al., 2003; Dondeyne et al., 2004). This would indicate that carbon pools in our tree fallows were replenished close to natural status (Fig. 3.2a).

Tree fallows significantly improved ( $p = 0.0056$ ) soil inorganic N compared to the natural-fallow and continuous-cropping treatments (Fig. 3. 2b), probably reflecting N fixation and retrieval of nitrates from deep soil layers by trees during the fallow period. Comparatively, soil inorganic N among tree fallows was the highest in *G. sepium* and *A. polyacantha*, intermediate in *A. nilotica* and *A. mangium*, and the lowest in *A. crassicarpa*. Soils under tree fallows also contained more extractable P (13 – 23 mg P kg<sup>-1</sup>) than the soils under continuous cropping (Fig 3. 2c). These levels were even higher than those found in the natural fallowed Miombo soils in Morogoro (9.8 mg P kg<sup>-1</sup>) (Msanya et al., 2003), demonstrating the

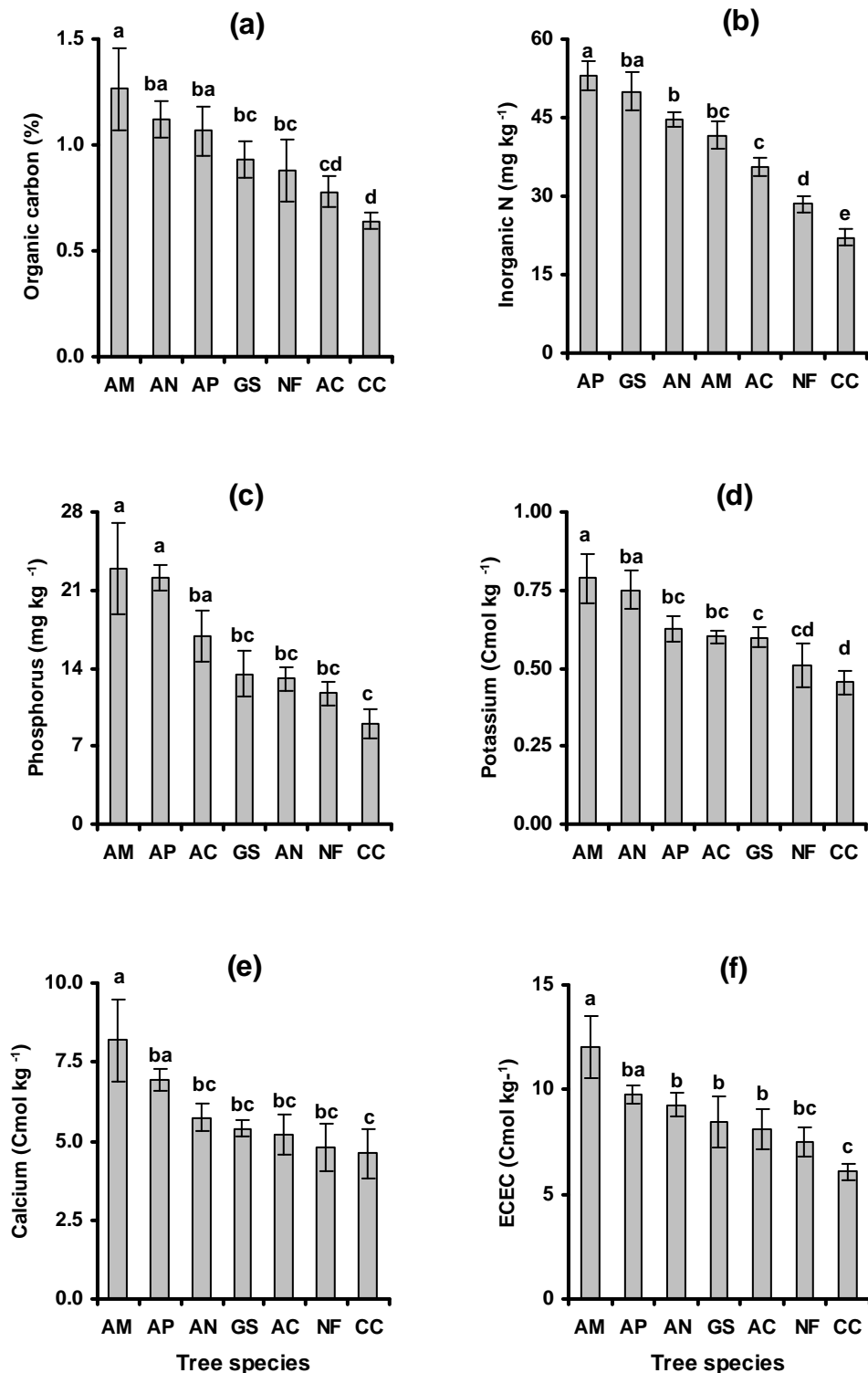


Figure 3.2. Effects of tree species on soil organic carbon (a), inorganic nitrogen (b), extractable phosphorus (c), exchangeable potassium (c), calcium (d) and effective exchange capacity (e) at Mkundi, Morogoro, Tanzania. AC = *Acacia crassicaarpa*, AM = *Acacia mangium*, AN = *Acacia nilotica*, AP = *Acacia polyacantha*, GS = *Gliricidia sepium*, NF = Natural fallow, CC = Continuous cropping and ECEC = Effective cation exchange capacity. For each Figure, means marked by the same letter are not statistically different at  $p < 0.05$  according to Fisher's PLSD. Vertical bars indicate standard errors of means ( $n = 3$ ).

capacity of tree fallows to recycle P effectively. Relative to the natural fallow, the improvement of soil extractable P was significant ( $p = 0.0074$ ) for *A. mangium*, *A. polyacantha*, and *A. crassiparva*.

Maximum soil inorganic N and extractable P levels were 53 mg N kg<sup>-1</sup> soil and 23 mg P kg<sup>-1</sup> soil, respectively, which corresponds to about 100 kg N ha<sup>-1</sup> and 40 kg P ha<sup>-1</sup> based on a top soil bulk density of 1.35 g cm<sup>-3</sup>. Initially deficient in these nutrients (Msanya et al., 2003), post-fallow soil levels were sufficient to support one cropping season of maize production (Ussiri et al., 1998), illustrating that tree fallowing can benefit subsequent maize culture. In this respect, *A. mangium*, *A. polyacantha*, and *G. sepium* were the most effective species in building up soil organic carbon, and N and P supplies (Fig. 3. 2a – c).

The fallow of *A. mangium* significantly improved soil exchangeable K ( $p = 0.0052$ ), Ca ( $p = 0.0125$ ), and effective cation exchange capacity ( $p = 0.0146$ ) compared to the continuous cropping system (Fig 3. 2d – f). Similarly, *A. nilotica* and *A. polyacantha*, respectively, increased exchangeable K and Ca (Fig 3. 2d and e) over the natural fallow. The increase in cation exchange capacity matched those of the natural Miombo fallow dominated by *Acacia* tree and *Hyperhenia* grass species and also a 7-year *Eucalyptus* planted fallow in Morogoro (Msanya et al., 2003). Soil fertility replenishment under tree fallows is usually associated with a number of enrichment and conservation mechanisms that include biological N fixation, pumping up or retrieval of nutrients from lower soil horizons, interception of nutrients that would otherwise be lost through leaching and surface runoff and release of nutrients during litter and root decomposition (Rao et al., 1998). Presumably these mechanisms contributed to the marked improvement in soil nutrients observed in this study (Fig. 3. 2).

### 3.3.2 Nutrient use efficiency

The above ground (leaves, branches and stems combined) use efficiency for N ( $p = 0.0035$ ), P ( $p < 0.0001$ ), K ( $p < 0.0001$ ), Ca ( $p = 0.001$ ), and Mg ( $p = 0.0081$ ) varied significantly among the tree species (Fig. 3. 3). In general, *A. crassiparva* was the most efficient for all nutrients except for N and Mg (Fig. 3. 3); indicating that this species produced the highest above ground biomass at lowest nutrient “costs”. Its

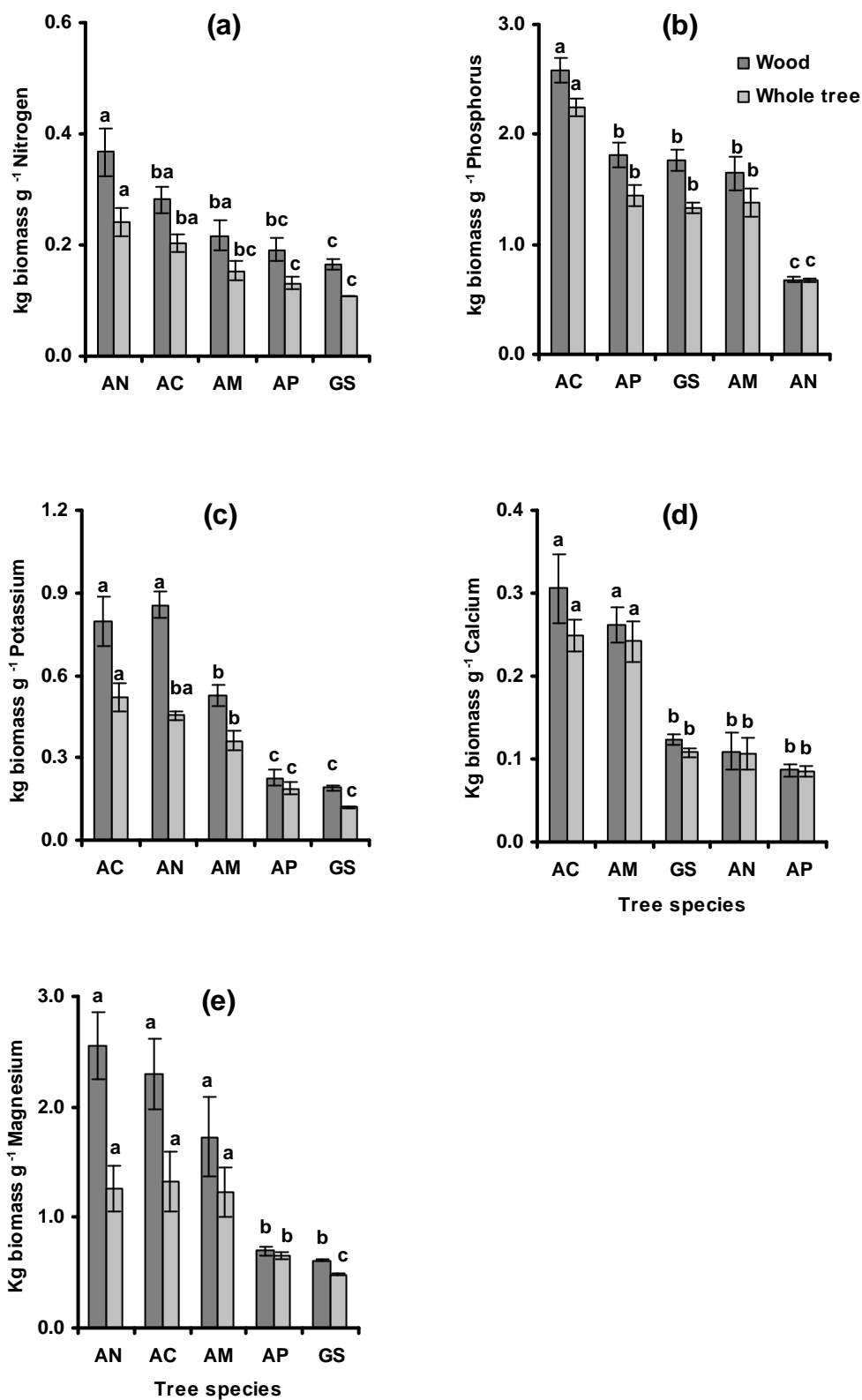


Figure 3.3. Use efficiencies of nitrogen (a), phosphorus (b), potassium (c) calcium (d) and magnesium (e) in wood and aerial tree biomass of tree species in a 5-year-old rotational woodlot at Mkundi, Morogoro, Tanzania. AC = *Acacia crassicaarpa*, AM = *Acacia mangium*, AN = *Acacia nilotica*, AP = *Acacia polyacantha*, GS = *Gliricidia sepium*. For each Figure, means marked by the same letter are not statistically different at  $p < 0.05$  according to Fisher's PLSD. Vertical bars indicate standard errors of means ( $n = 3$ ).

K-use efficiency was four times higher than that of *G. sepium* while P-use efficiency was three times as high as that of *A. nilotica*. Similar results were also observed for nutrient use efficiency based on wood production (Fig. 3. 3). Overall, nutrient use efficiency of wood was consistently higher than that of whole-tree biomass except for K, Ca, and Mg in *A. polyacantha* (Fig. 3. 3c – e), and for P and Ca in *A. nilotica* (Fig. 3. 3b and d). These results reveal the importance of harvesting wood only from the site to leave the slash as green manure because of higher nutrient concentrations of the latter (Fig. 3. 3).

The variation in nutrient use efficiency among species may be attributed to several reasons related to uptake, transport, and utilization within plants (Marchner, 1995; Schroth et al., 2003). For example, extensive root systems and abundant mycorrhizal associations are characteristics that may increase P-use efficiency of plants (Schroth et al., 2003). Higher rates of nutrient retranslocation during either vegetative or reproductive growth also increase nutrient use efficiency due to better utilization of organically bound nutrients for growth (Marchner, 1995). These mechanisms probably accounted for the observed species variability in nutrient use efficiency (Fig. 3. 3), since Australian *Acacia* species usually form mycorrhizal associations and have low litter nutrient concentrations (Doran et al., 1997; Jamaludheen and Kumar, 1999) that may reflect high nutrient retranslocation rates.

### 3.3.3 Wood production

Wood yield was highest ( $p = 0.0007$ ) in the *A. crassicarpa* (51 Mg ha<sup>-1</sup>) fallow, moderate in the *A. mangium* and *A. polyacantha* fallows, and lowest in the *A. nilotica* fallow (Fig. 3.4). Wood biomass produced by *A. crassicarpa* was comparable to yields reported in other drier parts of Tanzania (Nyadzi et al., 2003a) and Thailand where this species occurs naturally (Doran et al., 1997).

Generally, tree species with wide canopies as well as extensive and deep root systems would be expected to produce high biomass under limited supply of growth resources due to superior acquisition capacities. However, these parameters may have limited effects on the yield differences among tested species at this early stage of woodlot development because canopy closure and resource competition in

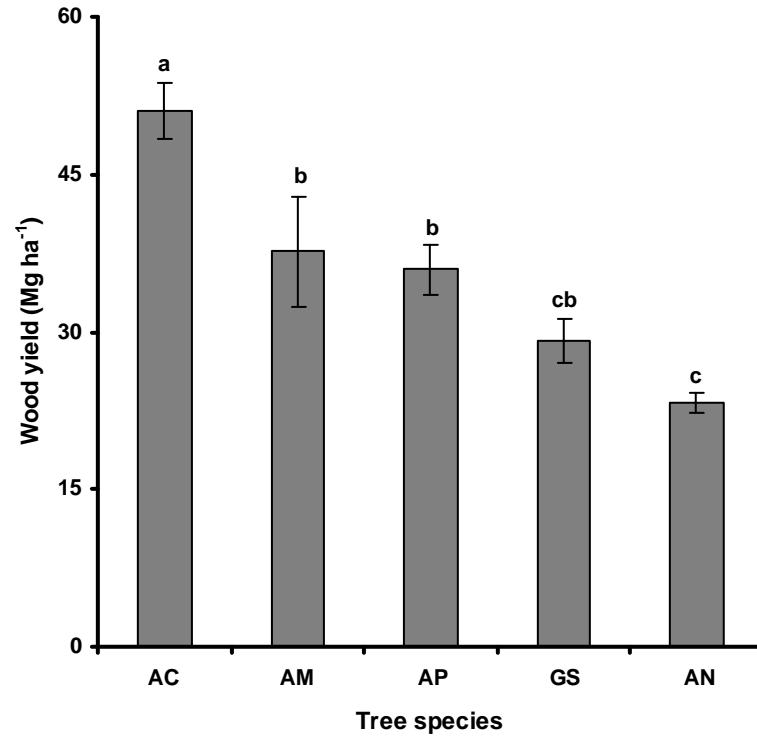


Figure 3.4. Wood biomass yields of tree species in a 5-year-old rotational woodlot at Mkundi, Morogoro, Tanzania. AC = *Acacia crassicarpa*, AM = *Acacia mangium*, AN = *Acacia nilotica*, AP = *Acacia polyacantha*, GS = *Gliricidia sepium*. For each Figure, means marked by the same letter are not statistically different at  $p < 0.05$  according to Fisher's PLSD. Vertical bars indicate standard errors of means ( $n = 3$ ).



fast growing tropical plantations usually commence 4 – 6 years after planting (Evans and Turnbull, 2004). Apparently, inherent nutrient use efficiency is a major factor driving wood production because the most efficient tree species yielded the most wood (Fig. 3. 4). Improved productivity of Australian *Acacia* species has also been attributed to lower transpirational loss of water and wider adaptability (Kumar et al., 1998).

Height, DBH, and mean annual increment of tree species were also significantly greater in *A. crassicarpa*, *A. mangium*, and *A. polyacantha* (Table 3.1). The mean annual wood increment ranged from 4.6 – 10.2 Mg ha<sup>-1</sup> year<sup>-1</sup>, which is at least three times higher compared to 0.04 – 2.91 Mg ha<sup>-1</sup> year<sup>-1</sup> of typical Miombo woodland vegetation (Kityo, 2004). Such high wood yields exemplify the significance and potential of rotational woodlot systems in meeting local firewood demands, as well as conserving natural forests that currently serve as the main local source of fuelwood in the region. Per capita firewood consumption for an average family of six dependent on the Miombo source is 10 kg per week (Biran et al., 2004). Based on this estimate, wood yields from one hectare of rotational woodlot systems utilizing our test species would be sufficient to meet the household fuelwood demands for 7 – 16 years.

### 3.3.4 Nutrient removals

Nutrient accumulation and export from the site are crucial considerations for sustained productivity of short-rotation high yield plantation systems where nutrient removal through frequent biomass harvests may exceed replenishment rates through natural processes, such as mineral weathering, atmospheric inputs, and biological fixation (Fölster and Khanna, 1997; Nykvist, 2000). The amounts of nutrient removed from the site vary with nutrient use efficiency, parts of the biomass harvested, and biomass yield of the tree species (Wang et al., 1991).

Overall, stem wood harvesting minimized nutrient export by 20 – 40 % compared to whole tree harvesting, (Fig. 3.5). The tested species, however, showed wide variation on this aspect depending on nutrient contents in wood. On a relative basis, *A. crassicarpa* produced 42 and 120 % more wood compared to *A. polyacantha* and *A. nilotica* respectively (Fig. 3.4), but contained considerably less

Table 3.1. Diameter at breast height (DBH), total height and mean annual wood increment of tree species in a 5-year-old rotational woodlot at Mkundi, Morogoro, Tanzania.

Tree species	DBH (cm)	Height (m)	MAI (Mg ha <sup>-1</sup> yr <sup>-1</sup> ) <sup>1</sup>
<i>Acacia polyacantha</i>	10.34a <sup>2</sup>	9.20a	7.20b
<i>Acacia crassicarpa</i>	10.12ba	10.10a	10.20a
<i>Acacia mangium</i>	10.25a	7.77b	7.54b
<i>Acacia nilotica</i>	7.23ba	5.37c	4.64c
<i>Gliricidia sepium</i>	4.76b	6.18c	5.83cb
<i>p</i> <sup>3</sup>	0.0303	<0.0001	0.0007
LSD <sup>4</sup>	3.736	1.046	1.3035

<sup>1</sup> MAI = Mean annual increment.

<sup>2</sup> Means within a column followed by the same letter are not significantly different at  $p < 0.05$  according to Fisher's PLSD.

<sup>3</sup> Probability for greater F-ratio.

<sup>4</sup> LSD = Least significant difference.

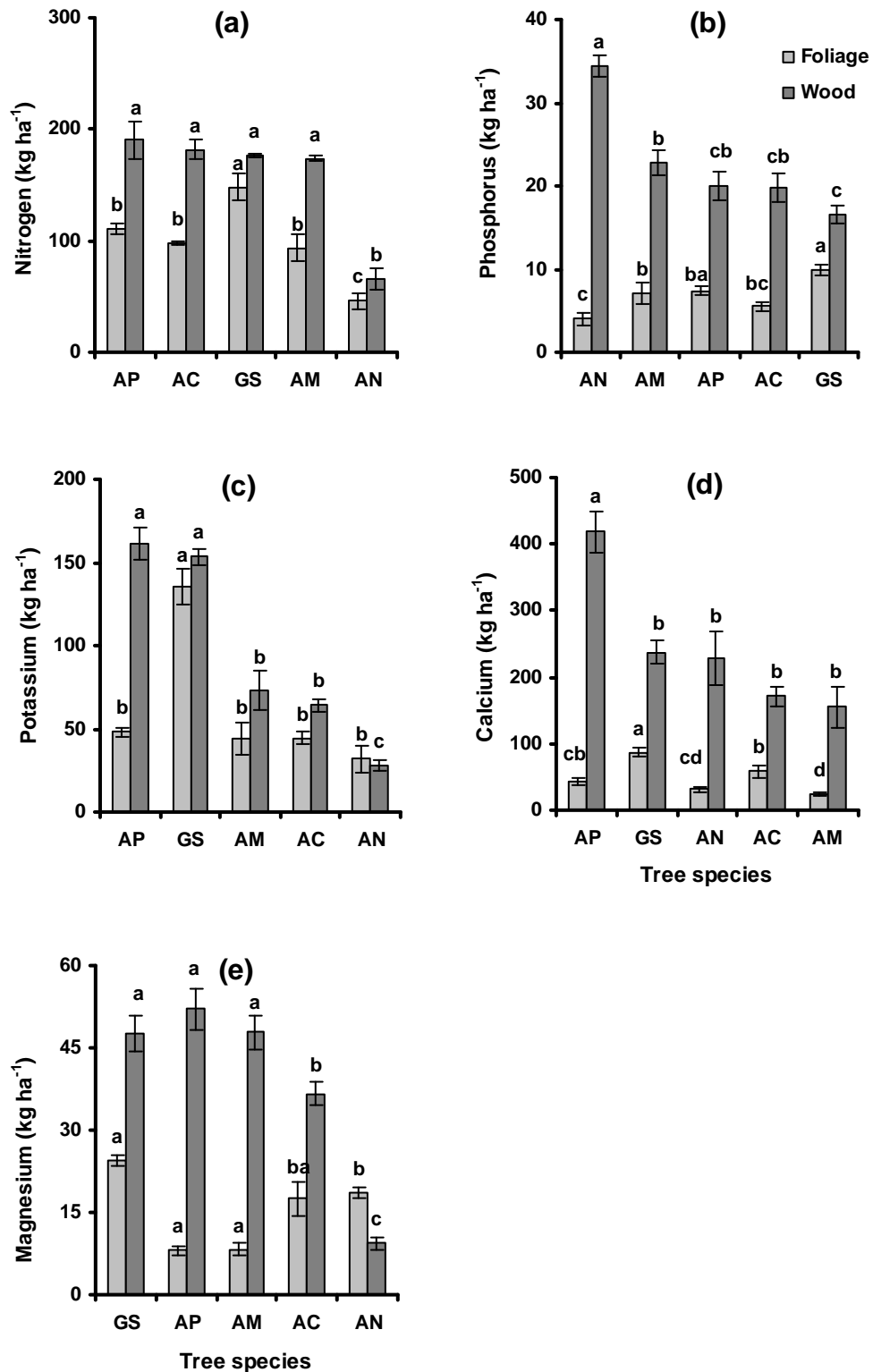


Figure 3.5. Nitrogen (a), phosphorus (b), potassium (c) and calcium (d) accumulated in foliage and wood biomass of tree species in a 5-year-old rotational woodlot system at Mkundi, Morogoro, Tanzania. AC = *Acacia crassicarpa*, AM = *Acacia mangium*, AN = *Acacia nilotica*, AP = *Acacia polyacantha*, GS = *Gliricidia sepium*. For each Figure, means marked by the same letter are not statistically different at  $p < 0.05$  according to Fisher's PLSD. Vertical bars indicate standard errors of means ( $n = 3$ ).

nutrients (Fig. 3.5). For example, wood of this species contained 42 % less P ( $p = 0.0003$ ), and 60 % less K ( $p < 0.0001$ ) and Ca ( $p = 0.0016$ ) compared to that of *A. nilotica* and *A. polyacantha*, respectively (Fig. 3.5b – d). Similarly, wood of *A. crassicarpa* contained less Ca and Mg ( $p = 0.0014$ ), but similar amounts of N and P to that of other species except for *A. nilotica*. Despite the highest biomass production, *A. crassicarpa* required relatively fewer nutrients consequently exporting fewer nutrients when harvested. These results clearly demonstrate the importance of proper tree selection to reduce nutrient exports at harvest and sustain future site productivity; since heavy nutrient drains may adversely impact long term site quality and sustained woodlot production (Kumar et al., 1998; Nykvist, 2000). Generally, nutrient-efficient tree species exported less nutrients in harvested wood biomass (Fig. 3.3 and 3.5), affirming that nutrient use efficiency is a sensitive and useful criterion to screen tree species for this purpose.

### 3.3.5 Nutrient restitution

Under a rotational woodlot system tree slash (leaves and twigs) remaining after wood harvest is usually applied as green manure to provide nutrients for subsequent crops upon decomposition (Nyadzi et al., 2003a). A previous study of this system reported limited ability of tree fallows to improve soil fertility due to an inherently short fallow period of 4 years (Nyadzi et al., 2003b). In contrast, our results involving 5-year fallows, revealed that inorganic N and extractable P status in soils increased after this period to achieve adequacy for one cropping season of maize (Fig. 3.2). Thus, given extended fallow intervals, the amounts of nutrients recycled by on-site slash retention would contribute substantially to subsequent crop responses. Among the tested tree species, slash from *A. polyacantha* and *G. sepium* restituted the most N ( $p = 0.0009$ ), P ( $p = 0.0114$ ) and K ( $p < 0.0001$ ) to the soil, ranging from 110 – 148 kg ha<sup>-1</sup>, 7 – 10 kg ha<sup>-1</sup>, and 49 – 135 kg ha<sup>-1</sup>, respectively (Fig. 3.5a – c). When decomposed, these nutrients will potentially be available to crops grown after wood harvest. Except for Ca and Mg, the most nutrient-efficient tree species returned comparatively low amounts of nutrients through slash (Figs. 3.3 and 3.5) likely because of low cellular nutrient concentrations in biomass as well as high nutrient retranslocation abilities (Schroth et al., 2003).

### 3.4 Conclusions

Although limited by a single rotation assessment, results from this study showed that tree species are effective in improving soil fertility, and have promise to sustain productivity of rotational woodlot systems. Based on soil tests, soils under *G. sepium*, *A. polyacantha*, and *A. mangium* woodlots were the most fertile. Soil organic carbon and exchangeable cation levels in tree fallows approached those of natural Miombo woodlands. Initially deficient in soil N and P for maize culture, top soils after fallowing were replenished sufficiently in nutrients to support one cropping season of maize without fertilizer supplementation. These results reflect the high potential of tree fallows to improve maize production after wood harvest. Wood productivity in rotational woodlot systems was about three times higher than that of local Miombo woodland vegetation, and was sufficient to meet household firewood demands for 7 – 16 years. Operationally, this agroforestry system exhibited the capacity to contribute appreciably to firewood supply in the region, which would in turn lead to reduced harvesting pressures on the natural forests without adversely affecting maize productivity. Incorporating nutrient use efficiency criteria in tree selection for rotational woodlot system management would minimize nutrient export through wood harvests while maintaining site productivity. Based on such criteria, *A. crassiparva* would be the preferred species for planting because of the highest wood yield produced apparently at the lowest nutrients “cost”. In addition to reducing nutrient exports this species recycled large amount of nutrients, especially N at harvest and moderately replenished other soil nutrient, affirming its suitability for sustaining wood supply.

**CHAPTER 4**

**DIFFERENTIAL RESPONSE TO TREE FALLOWS IN ROTATIONAL WOODLOT SYSTEMS  
IN SEMI-ARID TANZANIA: POST-FALLOW MAIZE YIELD, NUTRIENT UPTAKE, AND  
SOIL NUTRIENTS**

**Abstract**

Agroforestry tree species producing high quality litter may enhance post-fallow soil nutrient availability and crop yields through mineralization of soil organic matter and green manure. A split-plot field experiment was used to evaluate maize yield and soil N and P status after fallowing indigenous and exotic tree species of contrasting litter quality. Responses were compared with recommended inorganic fertilizer use. The objective was to assess efficacy of 5-year tree fallows in improving soil productivity to screen species for increased crop yield under rotational woodlot culture, an agroforestry system mainly used for on-farm fuelwood production in semi-arid Tanzania. Post-fallow maize yield and soil nutrients differed significantly among tree fallows. Low carbon (C):N and lignin (L):N ratios enhanced nutrient release from slash. *Acacia polyacantha* (indigenous) and *G. sepium* fallows doubled maize yield compared to the natural fallow probably due to high soil N and P levels resulting from net release by high quality foliage. First season maize yield was similar to that from combined N and P fertilizers indicating high capacity of the fallows to improve crop yield and reduce fertilizer inputs usually unaffordable to small-scale farmers. Comparatively low maize yield and soil N and P levels after exotic *A. crassiparpa* and *A. mangium* fallows were attributed to net N immobilization by poor quality litter during growing seasons. This study suggests that rotational woodlot systems utilizing tree species with high litter quality can improve both post-fallow maize yield and soil fertility as well as produce sufficient fuelwood. In this aspect, *A. polyacantha* would be the most appropriate species.

#### 4.1 Introduction

Soil nutrient depletion, through repeated crop harvest and soil erosion, is among the major constraints for sustainable food production in sub-Saharan Africa (Mafongoya et al., 2006). This problem is aggravated by the wide spread practice of continuous cropping that use little if any inorganic fertilizer and manure because of high farm acquisition costs (Kwesiga et al., 2003). The adoption of agroforestry practices has been advocated as an alternative to continuous cropping because of high capacity to replenish soil fertility, improve crop production, and enhance food security and household income in regions where commercial fertilizers are unaffordable to most smallholder farmers (Kwesiga et al., 2003; Mafongoya et al., 2006).

Earlier studies of rotational woodlot systems noted that indigenous tree species such as *A. polyacantha* produced less fuelwood ( $7 - 13 \text{ Mg ha}^{-1} \text{ year}^{-1}$ ) compared to exotics such as *A. crassicarpa* ( $10 - 19 \text{ Mg ha}^{-1} \text{ year}^{-1}$ ), the most productive Australian species tested under this system (Nyadzi et al., 2003a). However, Australian acacia species may have a drawback of poor nutrient recycling capacity due to slow litter decomposition and potential nutrient immobilization (Jamaldeen and Kumar, 1999) that limit soil fertility improvement, especially N (Nyadzi et al., 2003b). The species also may have adverse effects on soil moisture due to high transpiration rates (Nyadzi et al., 2003b). Thus, farmers may well benefit more by utilizing fast growing indigenous trees that are better adapted to local environments, and may have greater capacity to both produce fuelwood and improve soil fertility (Chapter 3). The present study examines these issues by assessing effects of tree species of contrasting litter quality on post-fallow soil nutrient availability and maize yield under rotational woodlot system.

The tree component in rotational woodlot systems can improve soil fertility through inputs by biological nitrogen (N) fixation, recycling of nutrients from deep soil horizons, and by reducing nutrient loss from leaching and soil erosion (Buresh and Tian, 1998; Nyadzi et al., 2003b). Trees also can increase post-fallow soil fertility through nutrient release from soil organic matter, litter, and green manure (Barrios et al., 1997; Chikowo et al., 2006). These replenishment processes are influenced by many factors that include species used, fallow length, soil type, and climatic conditions (Buresh and Tian, 1998). For

instance, mineralization of organic resources from trees is inversely related to ratios of carbon (C), lignin (L), and polyphenol contents, which are indices of organic resource quality (Baggie et al., 2004; Zingore et al., 2003). Barrios et al. (1997) have demonstrated that tree fallows with the lowest (lignin + polyphenol):N ratios in litter significantly improved N availability to crops after tree fallowing. Hence, leaf quality can be a critical factor influencing tree fallow effects on soil nutrient availability and crop yields, and may serve as a useful criterion for selecting tree species that improve both fuelwood and crop production in rotational woodlot systems.

In chapter 3, it was noted that intensive repeated nutrient exports through wood and crop harvests may adversely affect long-term site productivity under rotational woodlot systems. However, as mentioned earlier, tree species with high quality litter may be appropriate for sustaining crop production because of high nutrient recycling capacities. Hence, this chapter evaluates post-fallow soil nutrient status and maize yield under this system using indigenous and exotic N-fixing tree species of different leaf quality. As a reference, crop responses were compared to maize monoculture with recommended fertilizer prescriptions to assess efficacy of low cost agroforestry system as an alternative to continuous cropping practices needing commercial fertilizers. The experiment was conducted for three consecutive seasons after a 5-year fallow period in order to evaluate crop response persistence. *In situ* leaf decomposition and nutrient release were also assessed to evaluate the impact of litter quality on post-fallow nutrient availability to crops. It was hypothesized that post-fallow maize yield and soil N and phosphorus (P) status differed among tree species, and that C:N and L:N ratios controlled decomposition and nutrient release patterns of leafy biomass applied as green manure after fuelwood harvest. Specific objectives were to assess the effects of tree species and fertilization on maize yield and nutrient uptake, soil inorganic N and extractable P, and *in situ* leaf decomposition and nutrient release patterns of leaves. Findings will contribute to improve management of rotational woodlot systems for sustaining soil fertility and crop yield, as mentioned in Chapter 1.



## 4.2 Materials and methods

### 4.2.1 Maize yield trial

Initial site conditions for the rotational woodlot experiment were described in chapter 3, section 3.2.1. This experiment was established to assess tree fallows effects on soil fertility, nutrient use efficiency, fuelwood and maize yield. Details of the experimental establishment and management as well as assessment of soil fertility and fuelwood production after a 5-year fallow period can be found in Chapter 3. This chapter focuses on soil nutrient availability and maize yield after fuelwood harvesting. Trees remaining after fuelwood assessment were felled and stems and branches were harvested while foliage was incorporated into the soil as green manure using hand hoes during site preparation. Then maize (var. *Kito*) was sown between trees stumps at a spacing of 90 cm between rows and 45 cm within rows for three consecutive seasons, starting from 2004. This short-duration maize variety was preferred due to inherently short rainfall seasons in semi-arid areas. Stumps of *G. sepium* sprouted, but these were severed and mulched at 2-week intervals to reduce possible competition for moisture and light as well as recycling nutrients.

A split-plot experiment with three replications was laid out in a randomized complete block design (RCBD). The whole plot factor was tree species: *A. crassicarpa*, *A. mangium*, *A. polyacantha*, *G. sepium* and the natural fallow. The rationale for species selection for this experiment was described in Chapter 3. *Acacia polyacantha* and *G. sepium* leaves have higher nutrient concentrations and low C:N and L:N ratios reflecting higher leaf quality compared to those of *A. crassicarpa* and *A. mangium* (Table 4.1). Except for *A. polyacantha*, other species were exotic but their seeds were collected locally. The natural fallow treatment represented traditional shifting cultivation in which degraded farmland was abandoned to allow regeneration of native vegetation to replenish soil fertility. The sub-plot factor was inorganic N and P fertilizer additions at four levels: Control (no fertilizer), 80 kg N ha<sup>-1</sup>, 40 kg P ha<sup>-1</sup>, and a combination of N and P fertilizer rates. These rates are the recommended fertilizer rates for Morogoro area (Ussiri et al., 1998) and were applied annually. Each whole plot was split into four sub-plots of 6 x 6 m, and then fertilizer treatments were randomly allocated to each sub-plot at the onset

Table 4.1. Decay constant (k, Week<sup>-1</sup>) and chemical characteristics (g kg<sup>-1</sup>) of tree leaves used for the decomposition experiment at Mkundi, Morongo, Tanzania.

Parameter	<i>Acacia crassicarpa</i>	<i>Acacia mangium</i>	<i>Acacia polyacantha</i>	<i>Gliricidia sepium</i>	MSD <sup>1</sup>
k	-0.0305a <sup>2</sup>	-0.0452a	-0.1527b	-0.3040c	0.02
N	12.80b	16.37b	31.40a	30.53a	2.75
P	0.50d	0.70c	1.37b	1.47a	0.09
K	7.90c	12.73b	14.70b	23.17a	4.32
C	578.1a	566.3a	538.6b	514.9b	26.5
L <sup>3</sup>	137a	142a	86b	110ba	50
C:N	45.2a	34.6b	17.2c	16.9c	6.0
L:N	10.7a	8.8a	2.7b	3.6b	2.3
N:P	25.6a	23.3ba	22.9bc	20.8c	1.90

<sup>1</sup>MSD = Minimum significant difference.

<sup>2</sup>Means within a row followed by the same letter are not significantly different at  $p < 0.05$  according to Tukey's HSD test.

<sup>3</sup>L = Lignin.

of each cropping season. Sources of N and P were urea and triple super phosphate (TSP), respectively. Urea was split-applied on the 3<sup>rd</sup> and 5<sup>th</sup> week after maize planting, while TSP was applied before maize sowing. The experiment was repeated for three consecutive post-fallow seasons in order to evaluate persistence of maize responses to fallow treatments.

Soil samples were collected at 0–15 cm soil depth from 5 randomly selected points within the 4 x 4 m inner sub-plot area during each cropping season at 0, 4, 6, and 8 weeks after maize sowing. The samples were then transported in a cooler, and frozen in a deep freezer prior to analysis of N and P within one week. At the end of each cropping season, maize was harvested from the 4 x 4 m inner sub-plot area, and partitioned into grain, stover, and cobs; weighed, and sub-sampled for moisture content determinations at 70<sup>0</sup>C in the oven. The moisture content was used to estimate dry weight of each biomass component and the values were extrapolated to one hectare based on yield per area.

#### **4.2.2 Leaf decomposition trial**

A litterbag technique (Guo and Sims, 1999) was adopted to evaluate the effects of leaf quality on in situ decomposition and nutrient release of *A. crassicarpa*, *A. mangium*, *A. polyacantha*, *G. sepium* leaves. The experiment was laid out in a RCBD, adjacent to maize trials so as to reduce site-to-site variations. Seventy-two litterbags of 20 x 20 cm were constructed from nylon materials with 1mm mesh size and filled with 10 grams of air-dried leaves to obtain 18 bags per species. This mesh size was preferred because it both prevents major losses of small leaves and permits aerobic microbial activities (Guo and Sims, 1999).

Three bags per species were oven-dried to constant weight at 70<sup>0</sup>C to determine initial moisture content, ground, and analyzed for N, P, and K. The remaining bags were sealed with plastic bindings, kept in the plastic bags to minimize losses while being transported to the field. The litterbags were randomly buried to 15 cm soil depth in 1 x 1m plots located adjacent to each block of maize trials, and retrieved after 2, 4, 6, 8, and 12 weeks. Soil particles and extraneous plant materials in the retrieved leaf samples were removed manually followed by washing the leaves with distilled water and decanting

through a 0.2 mm sieve. Apparently, such brief washing may cause nutrient leaching (Anderson and Ingram, 1993), but it will not affect relative comparisons of treatments, because of systematic application to all samples. The samples were then placed in envelopes and oven dried to constant weight at 70°C to determine dry weight and for nutrient analysis. Due to fast decomposition rates, *G. sepium* samples retrieved after 6 weeks were not sufficient for nutrient analysis. Therefore, only the dry weight of these samples was recorded.

The decay constant was calculated from data on the dry weight of residual materials remaining using a single negative exponential decay model:  $M_t = M_o e^{-tk}$ , where,  $M_o$  and  $M_t$  are the leaf masses (g) initially and at time  $t$  (week), respectively, and  $k$  is the decay constant ( $\text{week}^{-1}$ ). This constant was estimated from a slope of the line of the regression between natural logarithms of the remaining leaf dry mass ( $\ln M_t$ ) against time. Nutrient content of the retrieved leaf samples was calculated as described by Guo and Sims (1999) and expressed as a percent of the initial amount.

#### **4.2.3 Chemical analysis of plant and soil samples**

Except for N and lignin, extraction and analysis of nutrients and carbon in the samples of maize, litterbags and soil were carried out as described in chapter 3, sections 3.2.3 and 3.2.4. Total N in the plant samples was determined using a Technicon II analyzer System at the Soil Science Laboratory, Faculty of Forestry, University of Toronto (Schuman et al., 1973). To assess lignin content, leaf samples were digested in a boiling detergent solution followed by hydrolysis with sulfuric acid (Anderson and Ingram, 1993).

#### **4.2.4 Vector diagnostic analysis**

Graphical vector diagnosis has been used to examine plant nutritional response to nutrient supply in both forestry and agroforestry systems (Imo and Timmer, 2000; Salifu and Timmer, 2001). Unlike the critical level approach and other nutrient diagnostic techniques based on a single measure of nutrient concentration, vector analysis concurrently compare plant biomass, nutrient concentration, and nutrient

content in one diagram. Interpretation of this diagram is based on site-specific comparisons of plant responses to nutrient supply relative to control, making the diagnosis independent of published critical ratios or levels (Gregoire and Fisher, 2004). Moreover, vector nomograms (diagrams) simplify ranking relative importance of nutrients in stimulating plant growth, discriminating single and multiple nutrient deficiencies, identify possible sufficiency or toxicities, synergism and antagonisms, luxury consumptions and dilution effects.

Vector analysis plots nutrient concentration (vertical axis), nutrient content (bottom horizontal axis), and biomass (upper horizontal axis) in a vector nomogram. This diagram reflects the function that nutrient content (or amount) in a plant (in this case maize) is the product of its nutrient concentration multiplied by its biomass. Hence, diagonals are isopleths representing changes of maize nutrient concentrations and contents at constant biomass. Changes in these parameters relate to maize responses to nutrient supply associated with treatments, i.e., tree species or inorganic fertilizers. These responses are expressed relative to the controls (natural fallow or unfertilized treatments) set as a reference that is normalized to 100 to facilitate comparisons between treatments. The relative responses are depicted by vectors (arrows) that may differ in length and direction. Vector length represents response magnitude, and vector direction identifies specific nutritional responses (Imo and Timmer, 2000; Salifu and Timmer, 2001). Thus, a shift in which both nutrient uptake and dry mass increased with decreased nutrient concentration (shift A) would reflect a growth dilution of nutrients due to accelerated growth. A similar response without change in concentration (Shift B) is associated with sufficiency since both growth and nutrient uptake increased without changes in concentration. Shift C in which biomass, nutrient concentration, and nutrient content increase; depicts a deficiency response of plants because both growth and nutrient uptake are improved (Salifu and Timmer, 2001). Vector analysis was based on the above ground maize yield data of the first cropping season at which tree fallows exhibited the highest growth responses.

#### 4.2.5 Statistical analysis

Data were tested for normality and homoscedasticity (i.e., constant variance) of residuals as described in section 3.2.5. Accordingly, dry mass of retrieved litter bags and levels of soil N and P were log-transformed to correct for deviations from these assumptions. Thereafter, a split-plot mixed model was used to carryout ANOVA for assessing the fixed effects of tree species (whole-plot factor) and fertilizer (sub-plot factor) on: maize yield, maize N, P, and K content; soil inorganic N and extractable P using procedure mix in SAS (SAS, 2000). For each sampling week, dry mass, decay constant, and N, P, and K contents of the litterbag samples were analyzed using the RCBD mixed model testing the fixed effects of tree species. Block and block-by-treatment interactions were designated as random effects in the mixed model when conducting analyses. Following ANOVA, significant treatment means were separated using Tukey's HSD test. All analyses were conducted at 5 % level of significance.

### 4.3 Results and discussion

#### 4.3.1 Post-fallow maize yield

After a 5-year-tree occupancy, tree fallowing resulted in higher maize yield than that from the natural fallow (Fig. 4.1) presumably because of soil nutrient replenishments by various tree-associated processes (Chapter 3, section 3.3.1). Maize grain yield after *A. polyacantha* and *G. sepium* fallows ranged from 1.7 – 3.4 Mg ha<sup>-1</sup> and averaged 100 % more than the mean yield obtained under the natural fallow over the three seasons (1.3 Mg ha<sup>-1</sup>). Corresponding grain yield after *A. mangium* and *A. crassicarpa* fallows ranged from 1.2 – 2.6 Mg ha<sup>-1</sup>, and averaged 50 % higher compared to yield after the natural fallow (Fig. 4.1). The higher maize yield associated with *A. polyacantha* and *G. sepium* fallows may reflect high soil fertility improvement during the fallow period. In chapter 3, it was noted that fallows of these species, respectively, accumulated more soil inorganic N (50 and 53 mg N kg<sup>-1</sup>), and extractable soil P (13 and 22 mg P kg<sup>-1</sup>) than the natural fallow (29 mg N kg<sup>-1</sup> and 12 mg P kg<sup>-1</sup>), and recycled the most nutrients through slash (Fig. 3.5).

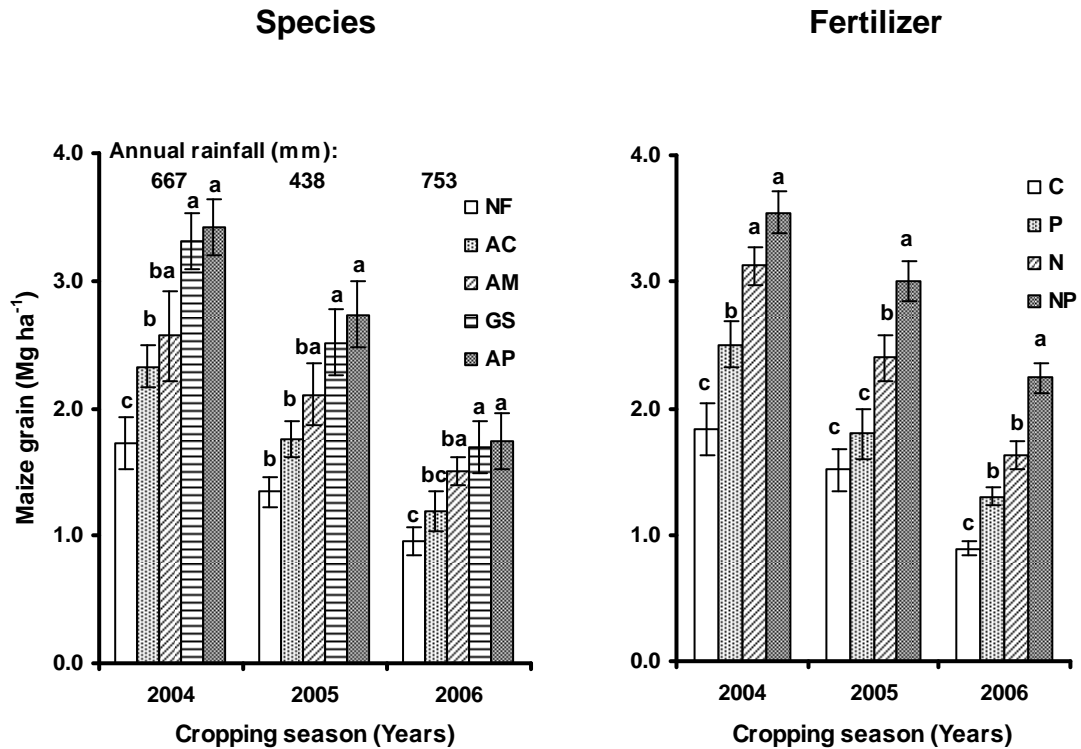


Figure 4.1. Effects of tree species and fertilizer treatments on maize grain yield after a 5-year fallow period of rotational woodlot culture at Mkundi, Morogoro, Tanzania. Treatments consisted of fallow types: AP = *Acacia polyacantha*, GS = *Gliricidia sepium*, AM = *Acacia mangium*, AC = *Acacia crassiparva*, and NF = Natural fallow; and fertilizer additions: C = control (No fertilizer), P = 40 kg P ha<sup>-1</sup>, N = 80 kg N ha<sup>-1</sup> and combined N and P application. For each Figure, means marked by the same letter are not statistically different at  $p < 0.05$  according to Tukey's HSD test. Vertical bars indicate standard errors of means ( $n = 3$ ).

Annual inorganic N and P fertilizer additions significantly increased maize grain yield over the control in all growing seasons indicating that these elements limited maize growth (Fig. 4.1). Average maize yields from N ( $2.35 \text{ Mg ha}^{-1}$ ) and P ( $1.87 \text{ Mg ha}^{-1}$ ) fertilization alone for the three seasons were, respectively, 70 % and 30 % higher than the control ( $1.41 \text{ Mg ha}^{-1}$ ). Combined applications of these fertilizers doubled maize yield relative to the control probably reflecting additive effects of mixed N and P fertilizers. These results suggest that initial soil N and P levels were deficient for maize culture as previously reported by Msanya et al. (2003). Since maize yield was more responsive to N than P, the former was considered more limiting.

In the first season, maize yield after both *A. polyacantha* and *G. sepium* fallowing ( $3.4 \text{ Mg ha}^{-1}$ ) were the highest ( $p < 0.0001$ ), and matched yields ( $3.6 \text{ Mg ha}^{-1}$ ) obtained by combined application of N and P fertilizers (Fig. 4.1). Similar results have been reported by Nyadzi et al. (2003a) for *A. polyacantha*, and by Makumba et al. (2006) for *G. sepium*. The relatively high grain yields also reflect the potential of these fallows to increase maize yield without the need of high fertilizer inputs usually unaffordable to most smallholder farmers in the tropics (Kwesiga et al., 2003; Mafongoya et al., 2006). Fertilized maize yield was comparatively higher than under tree fallows in the second and third season, but it must be kept in mind that the higher response was associated with annual reapplication of N fertilizers (Fig. 4.1). Enhanced soil nutrient availability and maize yield after tree species persisted to the third season ( $p = 0.0042$ ), except after *A. crassicaarpa* where yield declined to levels of the natural fallow (Fig. 4.1). The longer response persistence observed demonstrates the extended benefit of tree fallow system over natural fallow practices. The seasonal yield drop off was mainly attributed to soil nutrient depletion through harvests (Fig. 4.2), and other processes such as leaching and surface runoff with time (Zingore et al., 2003; Chikowo et al., 2006). Annual rainfall patterns probably had little influence on seasonal variations of maize yield because the yield trend did not match with that of rainfall (Fig. 4.1). This limited impact may be due to narrow seasonal variations in rainfall during the maize growing period (February to May) amounting to 318, 274, and 365 mm for the 2004, 2005, and 2006 cropping seasons, respectively.



### 4.3.2 Seasonal nutrient uptake by maize

Nutrient uptake of maize after tree fallows was higher than that in natural fallows, which affirmed the nutrient replenishment capacity of the planted trees (Fig. 4.2a – c). In the first post-fallow season, maize N uptake was the highest ( $p < 0.0001$ ) in fallows of *A. polyacantha* and *G. sepium*, followed by *A. mangium* and *A. crasscarpa*. The lowest uptake was found in the natural fallow (Fig. 4.2a). A similar pattern was also observed with crop P uptake in the first season (Fig 4.2b,  $p = 0.0005$ ). However, species differences in N and P uptake became less apparent in the subsequent cropping seasons probably reflecting diminishing nutrient supply due to exports by harvest as well as leaching and surface runoff as mentioned before (Zingore et al., 2003). The highest uptake of N and P by maize was associated with *A. polyacantha* and *G. sepium* fallows suggesting that these species were the most effective in enhancing soil N and P supply. Tree fallowing significantly improved maize K uptake relative to the control with highest values obtained by maize after *A. polyacantha*, *G. sepium* and *A. mangium* in the first ( $p = 0.0179$ ) and second ( $p < 0.0001$ ) season. The enhanced K uptake (Fig. 4.2c) was probably associated with the combined effects of increased soil K status after fallowing (Chapter 3, Fig. 3.2d) and the rapid K mineralization after green manuring (Zaharah and Bah, 1999).

Both N and P fertilizers, either singly or combined, significantly improved N and P uptake relative to control (Fig. 4.2d), which exemplify likely occurrence of soil N and P deficiency in this site. Uptake was the highest with combined N and P fertilization also reflecting an additive response. Sole addition of N fertilizer increased both N and P uptake, but sole P fertilizer increased only P uptake (Fig. 4.2d and e), suggesting that N was the major driver of the yield response. Potassium fertilizer was not applied, due to reported sufficiency in the soil (Msanya et al., 2003). However, sole or mixed application of N and P fertilizers improved maize K uptake (Fig. 4.2f) presumably because of enhanced nutrient uptake associated with greater biomass response (Marschner, 1995).

### 4.3.3 Soil nutrient supply

During the first cropping season, soil inorganic N in both tree fallows and fertilizer treatments

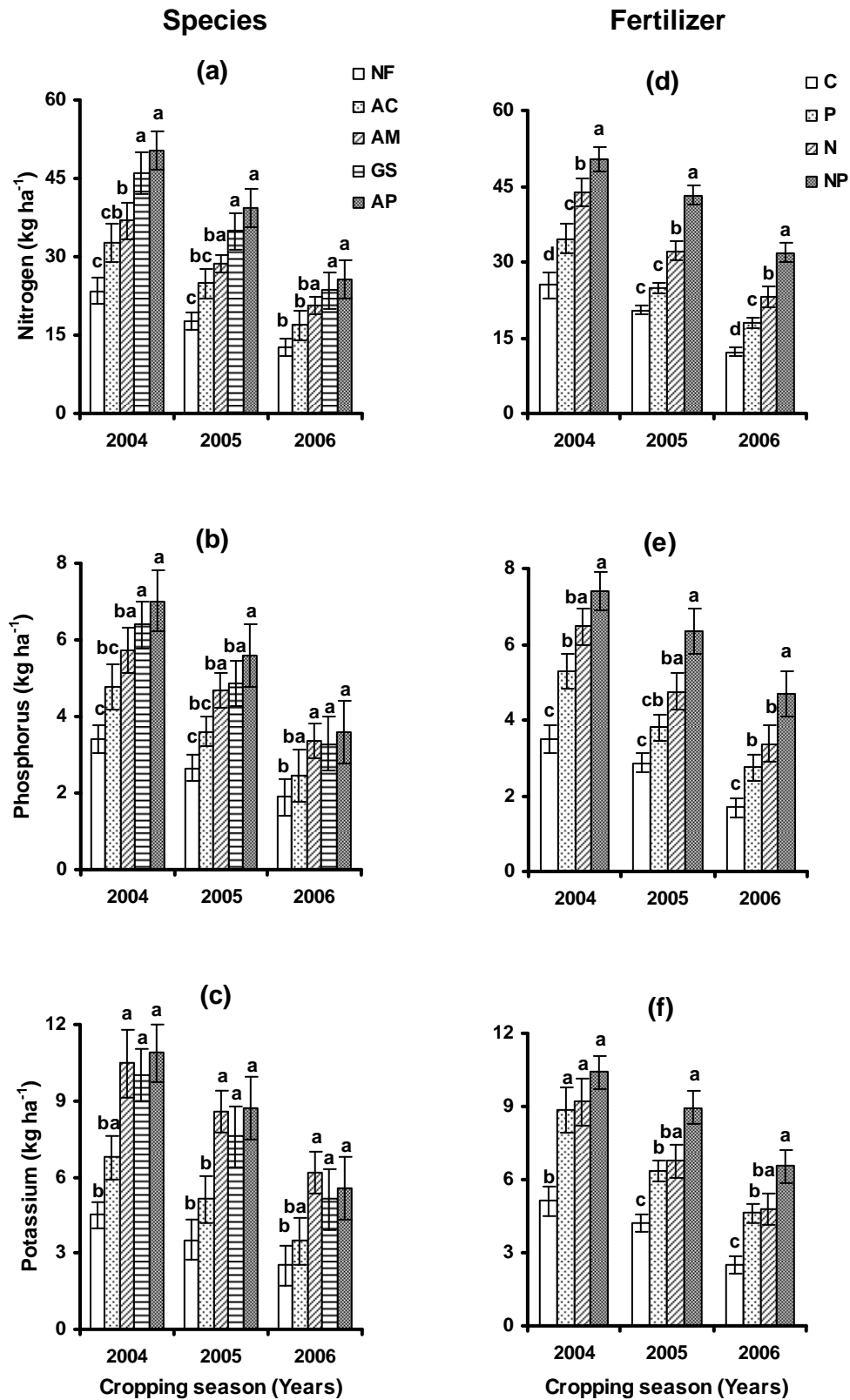


Figure 4.2. Maize grain nutrient content as influenced by tree species (a – c) and fertilizer (d – f) treatments after a 5-year fallow period of rotational woodlot culture at Mkundi, Morogoro, Tanzania. Treatments consisted of fallow types: AP = *Acacia polyacantha*, GS = *Gliricidia sepium*, AM = *Acacia mangium*, AC = *Acacia crassicarpa*, and NF = Natural fallow; and fertilizer additions: C = control (No fertilizer), P = 40 kg P  $\text{ha}^{-1}$ , N = 80 kg N  $\text{ha}^{-1}$  and combined N and P application. For each Figure, means marked by the same letter are not statistically different at  $p < 0.05$  according to Tukey's HSD test. Vertical bars indicate standard errors of means ( $n = 3$ ).

increased significantly compared to the controls (Fig. 4.3a, c, Appendices 1 and 2). Levels of total inorganic N rose consistently, culminating in the fourth ( $p = 0.0002$ ) and sixth ( $p = 0.0117$ ) week after maize planting that corresponded with the active growth period of maize (4 – 8 weeks after sowing) and peak plant nutrient demand in the tropics (Lehman et al., 1995). With fertilizers, this curvilinear trend probably reflected the split dressing schedule of N that was designed to match annual nutrient demand (Fig. 4.3c). Rapid N increase from early to mid-season after tree fallows may be associated with high release from green manure mineralization (Imo and Timmer, 2000) and other *in situ* sources of N such as turnover of labile organic matter (Chikowo et al., 2006). Soil inorganic N status in both *G. sepium* and *A. polyacantha* fallows during the fourth and sixth week after maize planting averaged  $86.5 \text{ kg N ha}^{-1}$ ; this level was similar to those obtained with N based-fertilizer treatments (Fig. 4.3a, c). The high soil N levels were attributed to input from green manure after fuelwood harvests and improved soil N during the fallow period (Figs. 3.1 and 3.4).

Foliar nutrient changes over the 12-week decomposition period differed significantly among tree species (Appendix 3). Apparently, green manure from the *G. sepium* and *A. polyacantha* stands decomposed and mineralized most rapidly (Fig. 4.4a), releasing more N when compared to other species. This pattern was attributed to low C:N and L:N ratios in leaves of the former species (Table 4.1), because such ratios are inversely related to decomposition and mineralization rates of organic materials (Zingore et al., 2003; Baggie et al., 2004). Lower soil inorganic N status in *A. crassiparpa* and *A. mangium* fallows ( $15 - 63 \text{ kg N ha}^{-1}$ ) when compared to other tree fallows was probably associated with high N immobilization (Fig. 4.4a) because of comparatively higher concentrations of foliar C and lignin and lower foliar N concentrations as green manure (Table 4.1).

Extractable soil P under tree fallows was higher than that under the natural fallow, peaking ( $33 - 40 \text{ kg P ha}^{-1}$ ) between four ( $p = 0.0003$ ) and six weeks after maize sowing (Appendix 1). These levels were similar to those obtained under P fertilization (Fig. 4.3b, d). After 5-year tree occupancy, soil P status was raised close to  $40 \text{ kg ha}^{-1}$ , the level recommended for maize culture in Morogoro (Ussiri et al., 1998). The enrichment was attributed to increased P mineralization of leafy biomass applied as green

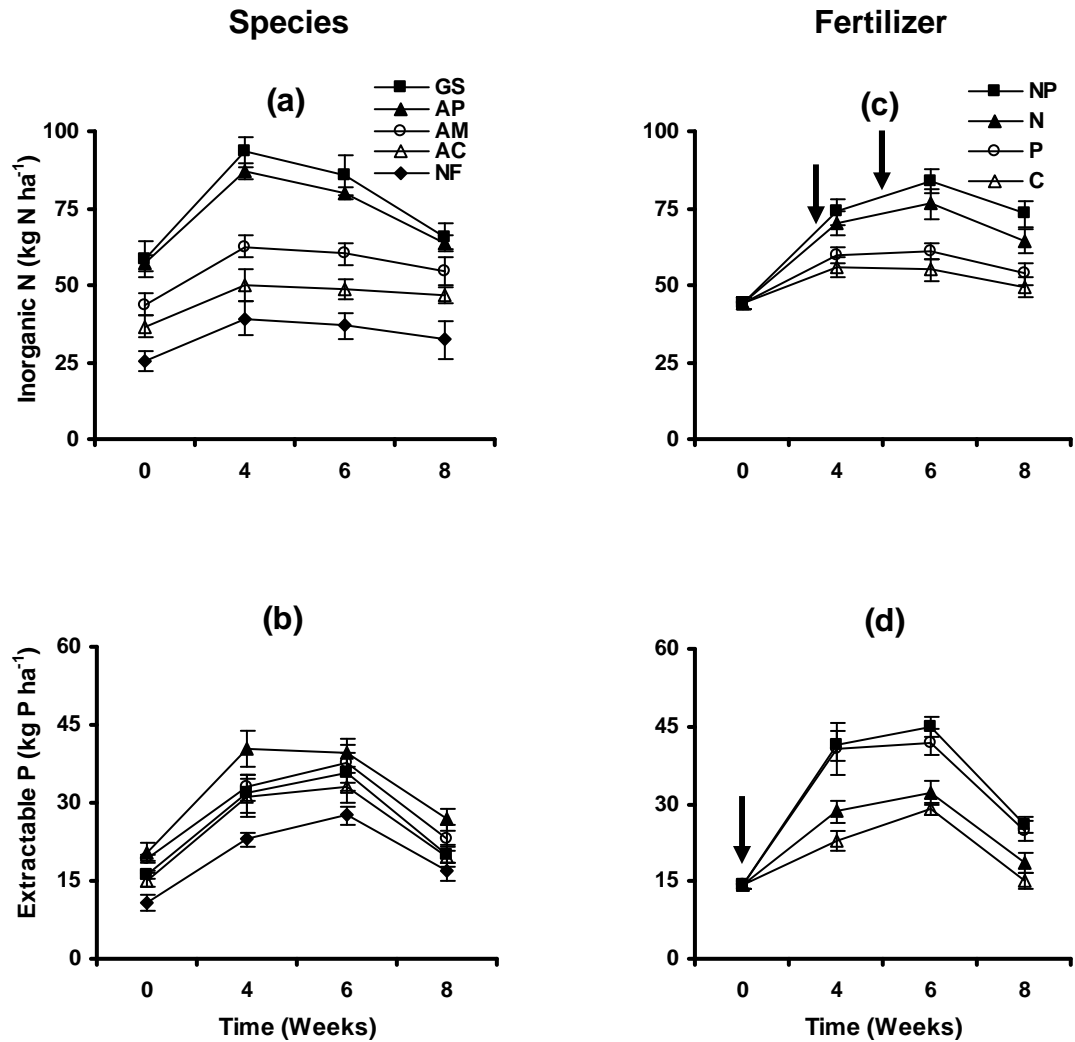


Figure 4.3. Tree species (a, b) and fertilizer (c, d) effects on soil total inorganic N (i.e.  $\text{NO}_3^- \text{ - N} + \text{NH}_4^+ \text{ - N}$ ) and extractable P during the first cropping seasons after a 5-year fallow period of rotational woodlot culture at Mkundi, Morogoro, Tanzania. Treatments consisted of fallow types: AP = *Acacia polyacantha*, GS = *Gliricidia sepium*, AM = *Acacia mangium*, AC = *Acacia crassiparpa*, and NF = Natural fallow; and fertilizer additions: C = control (No fertilizer), P = 40 kg P ha<sup>-1</sup>, N = 80 kg N ha<sup>-1</sup> and combined N and P application. Arrows indicate time of fertilizer applications. Statistical analysis was performed on log-transformed data, but points represent untransformed means. Vertical bars indicate standard errors of means (n = 3). See appendices 1 and 2 for statistical difference between treatments.

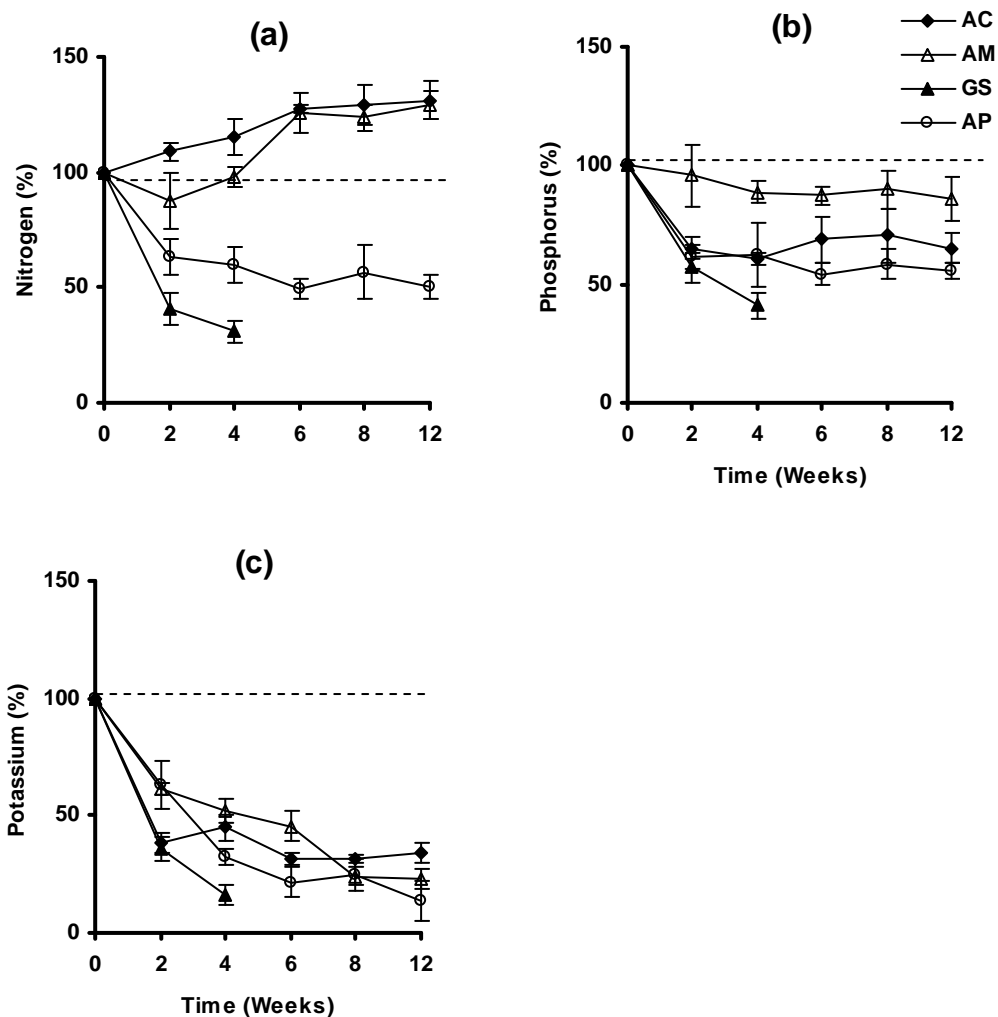


Figure 4.4. Concentration of foliar N (a), P (b) and K (c), (expressed as a percent of initial values) of tree species of a 5-year old rotational woodlot experiment during a 12-week litter bag study at Mkundi, Morogoro, Tanzania. Values below and above 100 % indicate immobilization and mineralization of nutrient, respectively. Treatments consisted of fallow types: AP = *Acacia polyacantha*, GS = *Gliricidia sepium*, AM = *Acacia mangium*, and AC = *Acacia crassicarpa*. Statistical analysis was performed on log-transformed data, but points represent untransformed means. Vertical bars indicate standard error of means (n = 3). See appendix 3 for statistical difference between tree species.

manure after wood harvest (Fig. 4.4b). Also P recycling through nutrient pumping during the fallow period (Buresh and Tian, 1998) may have partly contributed to the high post-fallow soil P levels. Unlike N, mineralization of P (Fig. 4.4b) occurred in leaves of all species, probably accounting for little variation in soil extractable P levels among tree fallows during the cropping season (Fig. 4.3b). Seasonal variation in soil P levels was attributed to rapid release from decomposing green manure accompanied by low uptake by maize during the early season, followed by a high uptake at the active growth period reducing P availability (Imo and Timmer, 2000).

Overall, lower litter C:N and L:N inputs from *G. sepium* and *A. polyacantha* resulted in higher soil mineral N and P status (Fig. 4.3a, b) and greater maize grain yield than high C:N and L:N litter from *A. crassicaarpa* and *A. mangium* (Fig. 4.5). The results demonstrate the potential of tree fallows selected for high litter quality to enhance post-fallow soil N and P availability as well as improving crop yield and wood supply as was also noted by Barrios et al. (1997). In this respect, *A. polyacantha*, an indigenous species with high capacity to produce fuelwood (Fig 3.4), would be a desirable species for incorporation in rotational woodlot systems.

#### 4.3.4 Nutrient diagnosis of maize

Crop response to nutrient supply is usually reflected in changes in plant nutrient concentration, nutrient content, and biomass yield (Marschner, 1995). These changes were simultaneously plotted in a vector nomogram to simplify comparison of key nutrients stimulating plant growth (Salifu and Timmer, 2001). Relative to the natural fallow, maize yield was increased after *G. sepium* fallows by 137 % (237 - 100) and by 141 % (241 - 100) after *A. polyacantha* fallowing (Fig. 4.6a). The increase was respectively accompanied by stimulated N concentration (25 % and 27 %) and N content (190 % and 205 %). The longest right-pointing vector in *A. polyacantha* and *G. sepium* fallows was associated with N, indicating that N was probably the most limiting nutrient (Shift C, Salifu and Timmer, 2001). This response was similar to that of combined N and P fertilizer where both elements were added (Fig. 4.6b), and suggests

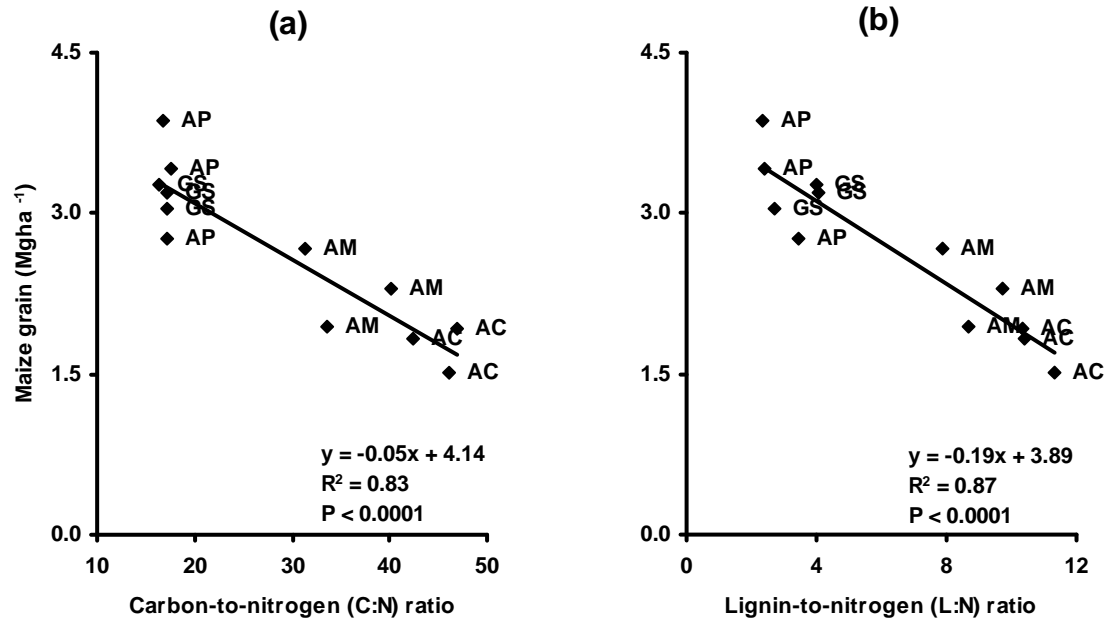


Figure 4.5. Correlation between foliar carbon-to-nitrogen (C:N) and lignin-to-nitrogen (L:N) ratios of tree species and maize grain yield during the first cropping season after a 5-year fallow period of rotational woodlot culture at Mkundi, Morogoro, Tanzania. Treatments consisted of fallow types: AP = *Acacia polyacantha*, GS = *Gliricidia sepium*, AM = *Acacia mangium*, and AC = *Acacia crassiorpa*.

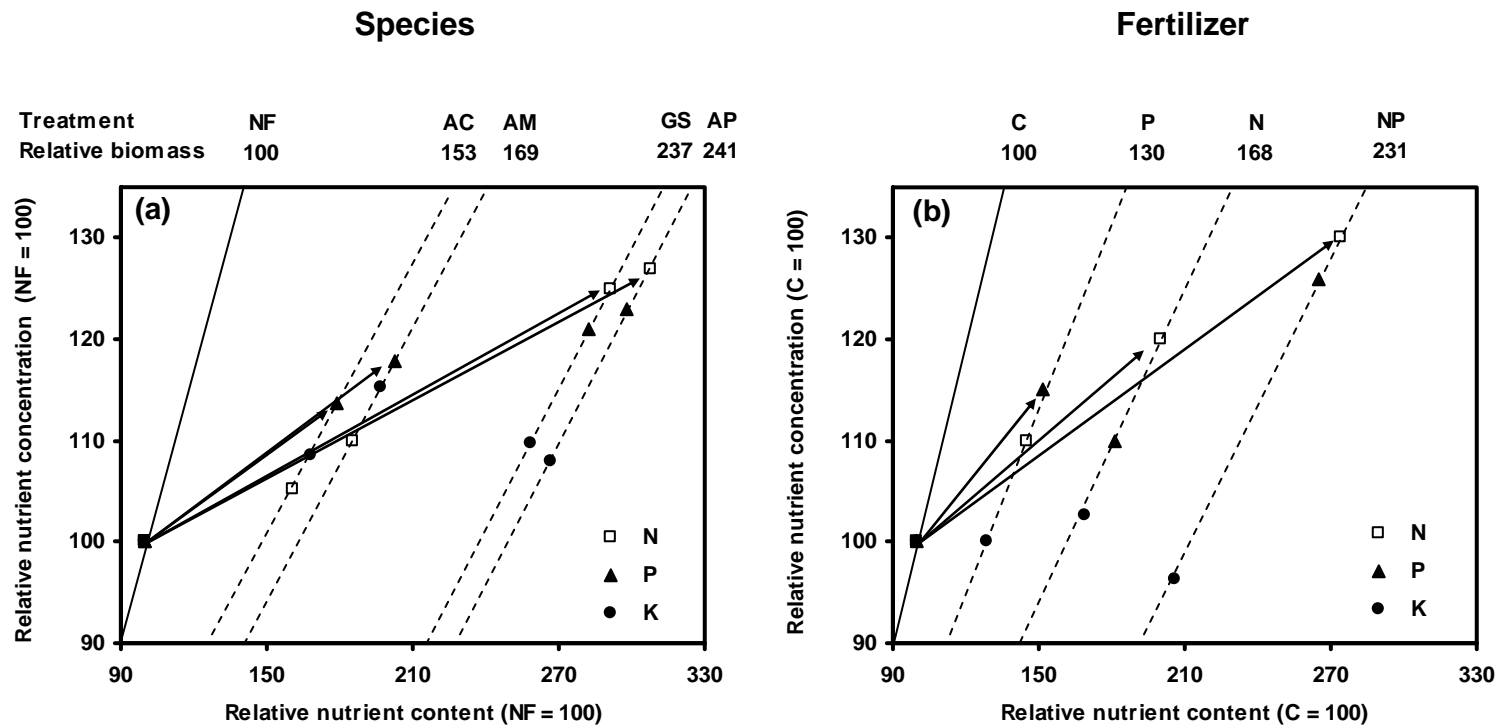


Figure 4.6. Vector nomogram of the relative change in maize biomass, nutrient concentration and nutrient content testing tree species (a) and fertilizer treatments (b) in a 5-year fallow period of rotational woodlot culture at Mkundi, Morogoro, Tanzania. Treatments consisted of fallow types: AP = *Acacia polyacantha*, GS = *Gliricidia sepium*, AM = *Acacia mangium*, AC = *Acacia crassicaarpa*, and NF = Natural fallow; and fertilizer additions: C = control (No fertilizer), P = 40 kg P ha<sup>-1</sup>, N = 80 kg N ha<sup>-1</sup>, and combined N and P application. See Figures 4.1 and 4.2 for statistical differences between treatments. To minimize clutter only the largest vector for each treatment is drawn.



that high quality litter species can similarly improve post-fallow soil N supply and crop yield. Relatively lower biomass yields after *A. mangium* (69 %) and *A. crassicarpa* (53 %) fallows (Fig. 4.6a) were associated with higher P content (103 % and 79 %) compared to N content (85 % and 61 %), probably reflecting limited N availability during the growing seasons (Fig. 4.3a) due to net N immobilization by poor quality green manure (Fig. 4.4a).

Vector analysis of fertilizer treatments revealed deficiency responses to N and P application (Shift C, Salifu and Timmer, 2001) since increase in maize yield relative to the control (131 % for combined N and P treatment) was accompanied by improved N content (175 %) and P content (166 %), as well as raised N and P concentrations (Fig. 4.6b). Apparently N was more limiting than P as it was associated with the highest yield and nutritional responses (Fig. 4.6b). As noted earlier (Figs. 4.1 and 4.2d, e), this pattern suggests N was most limiting. The lowest yield was noted after P-only treatments that showed accumulation of more P than N in the crop indicating low soil N availability without any N supplementation (Fig 4.6b).

Vector analysis also depicted a synergistic N and P interaction on maize yield (Fig. 4.6b) since relative N and P content after combined additions (N = 175 %, P = 166 %) was higher than corresponding content from either N-alone (N = 100 %, P = 80 %) or P-alone (N = 50 %, P = 46 %). This synergism was attributed to improved P assimilation following enhanced growth by N, since P is an important element in energy production required for metabolic reactions (Marschner, 1995). Positive correlations found between maize yield and soil mineral N and P under either tree fallows or fertilization (Fig. 4.7) also support vector interpretations of these deficiency responses. The stronger correlation with N (0.78 and 0.83) than with P (0.42 and 0.24) would further affirm that N was more limiting than P for maize growth.

Tree fallowing improved content and concentration of K (Fig. 4.6a), likely reflecting high recycling through litter fall during the fallow period (Chapter 3, Fig. 3.2d), and increased K mineralization of green manure applied after fuelwood harvest (Fig 4.4c). However, higher soil K supply probably had little impact on post-fallow maize yield because the largest responses were associated with either N for *A. polyacantha* and *G. sepium*, or P for *A. mangium* and *A. crassicarpa* (Fig. 4.6a). There was

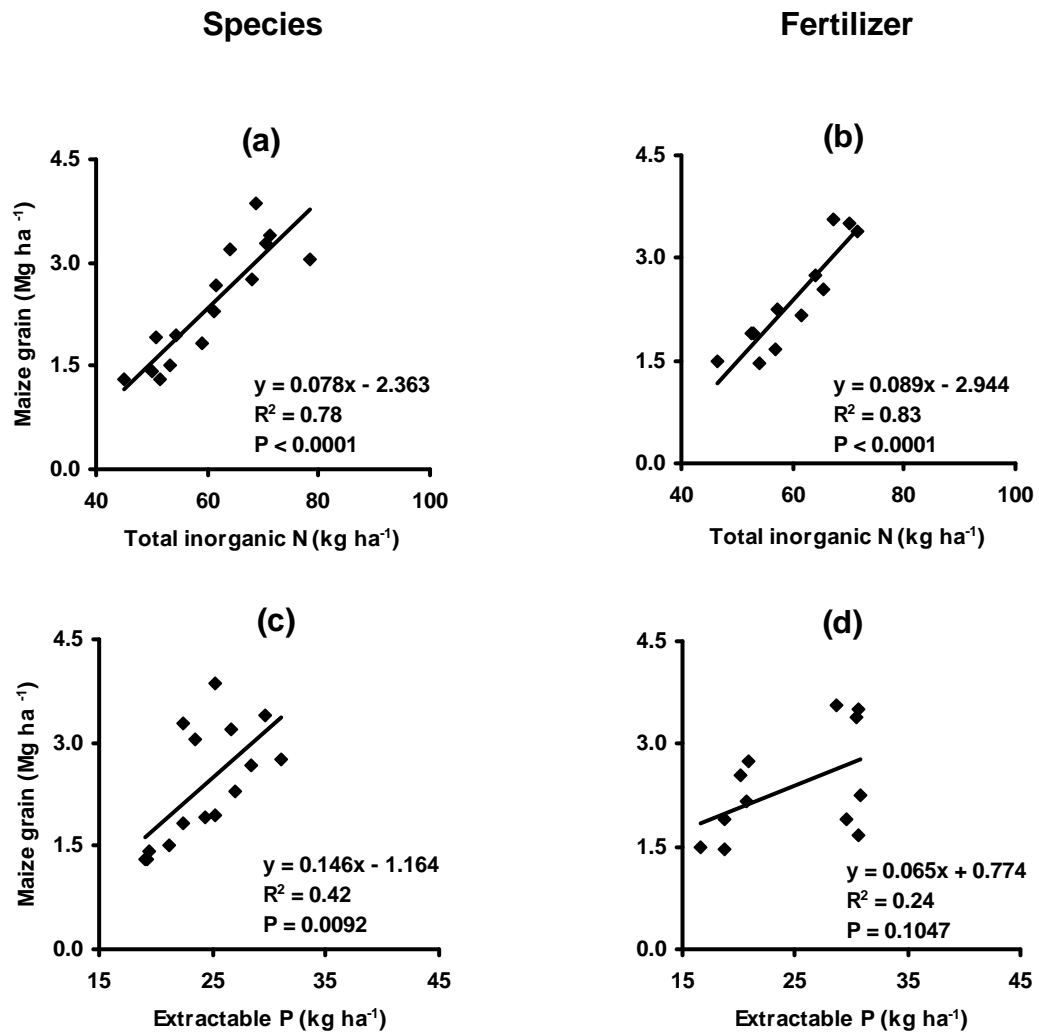


Figure 4.7. Correlation between soil total inorganic N or soil extractable P and maize yield under tree fallows (a, c) and fertilizer (b, d) during the first cropping season after a 5-year fallow period of rotational woodlot culture at Mkundi, Morogoro, Tanzania.

no significance response in K concentration after fertilization since K was not applied. Hence, despite increased maize biomass and K content after fertilization, tissue K concentration remained unchanged (Fig. 4.6b) indicating probable sufficiency of this element since K concentration was undiluted and content kept pace with growth (Shift B, Salifu and Timmer, 2001). These results corroborate an earlier study that noted adequate soil K supply for crop production (Msanya et al., 2003).

#### 4.4 Conclusions

Rotational woodlot systems utilizing tree fallows with high leaf quality (*G. sepium* and *A. polyacantha*) can improve post-fallow maize yield and soil nutrients to levels similar to those of inorganic fertilizers. The improvements reflected the high capacity of these species to enhance nutrient availability to post-fallow crops as well as to reduce the need for supplementary fertilizer inputs, usually too costly for small-scale farmers in the tropics. *Acacia polyacantha*, a fast growing indigenous tree species with high leaf quality, exhibited the most promise to enhance post-fallow soil nutrient availability and maize yields under rotational woodlot systems.

Post-fallow maize response to tree species mainly depended on nutrient release (especially N) from slash applied as green manure after wood harvest. Significant positive correlations between maize yield and soil N and P under either tree fallows or fertilizer treatments inferred that enhanced soil N and P availability during the cropping season was the main driver for the increased crop yield. Vector analysis confirmed these responses, and further revealed that N was more limiting than P. Consequently, *A. polyacantha* and *G. sepium* fallows, which produced leafy biomass with low C:N and L:N ratios, exhibited the highest soil N supply and doubled maize yields relative to the natural fallow. However, green manure of *A. crassiparva* and *A. mangium* fallows likely stimulated N immobilization during the growing season due to high foliar C:N and L:N ratios, resulting in lower maize yields compared to other fallow species. This study suggests that these ratios may be useful indicators for selecting tree species for improving post-fallow maize yield under rotational woodlot culture.

Results in Chapters 3 and 4 demonstrate a tradeoff between fuelwood supply and crop yield under the rotational woodlot system that may influence the choice of species by farmers and affect the sustainability of this system. *Acacia crassicarpa* produced the highest amount of wood, but low maize yield compared to other tree species. Low soil N replenishment during the fallow period and high N-immobilization by green manure suggest that this species may require external inputs of N to sustain post-fallow maize yield. Apparently, *A. crassicarpa* has moderate capacity to recycle other nutrients, especially P and exchangeable cations, and the highest ability to minimize nutrient exports through wood harvesting (Chapter 3, Figs. 3.2 and 3.5). Therefore, this species can be managed for wood supply alone or at longer rotation cycles to build up soil nutrients to sufficiency levels for maize culture. On the other hand, *A. polyacantha* and *G. sepium* fallows maximized post-fallow maize yield. As noted in Chapter 2, short duration fallows of these species would be more appropriate for improving soil fertility and crop yield than longer rotations under the rotational woodlot system. Tree species in short-term improved fallows are established at narrow spacing to promote biomass production for rapid replenishment of soil fertility, leading to considerable crop yield increase after 1 – 3-year fallow period. However, *A. mangium* and *A. polyacantha* hold promise to optimize productivity of both wood and maize yields because these species ranked either the first or the second in terms of maize and wood production. Contrasting nutrient recycling characteristics and productivities of the studied species also suggest that mixed-species fallows have high potential to sustain productivity of rotational woodlot systems and should be evaluated in the future.

## CHAPTER 5

### COMPETITION BETWEEN MAIZE AND PIGEONPEA IN SEMI-ARID TANZANIA: EFFECT ON YIELDS AND NUTRITION OF CROPS

#### Abstract

Productivity of maize-pigeonpea cropping systems is dependent on facilitative and competitive interactive effects on resource availability. Controlling these interactions may benefit farmers through increased productivity associated with optimized crop yields. Previous research on maize-pigeonpea culture in Sub-Saharan Africa has focused on yield and soil fertility, but provided inadequate information on the mechanisms of interspecific competition. I employed a factorial experiment to examine yield and nutritional responses of maize and pigeonpea to cropping systems (sole maize, intercropping, and improved fallow), N and P fertilizer additions, and cattle manure additions in Dodoma, Tanzania. The study objectives were to assess competition between crops and to determine how manure or fertilizer inputs may mitigate such interactions to improve yields. Intercropping enhanced maize yield over sole maize only when fertilized, reflecting probable nutrient competition. Improved fallows alone or with fertilizers ( $1.2 - 1.6 \text{ Mg ha}^{-1}$ ) increased maize yields over sole maize ( $0.6 \text{ Mg ha}^{-1}$ ). These increases were attributed to pigeonpea facilitation through soil nutrient replenishment, reduced competition by sequential cropping arrangements, and extra nutrients from fertilization. Combined fertilizer and manure applications also improved maize and pigeonpea yields. Plant nutrient diagnosis indicated primary and secondary P and Ca deficiencies, respectively associated with P-fixation and leaching of cations due to high soil acidity and exchangeable Al. Maize competed strongly in mixture suppressing biomass and grain yields of the unfertilized pigeonpea by 60 % and 33 %, respectively due to limited nutrients and/or drought. These yield reductions suggest that the intercropped pigeonpea may not recover from competition even after maize harvesting that reduced competition. Intercropping at the full fertilizer rate minimized nutrient competition and resulted in maize and pigeonpea yields similar to those of improved fallows at the half rates dose. Thus, improved fallows may alleviate interspecific competition and reduce fertilizer use by half without compromising productivity in semi-arid areas.

## 5.1 Introduction

Traditionally, farmers in the semi-arid tropics intercrop cereals with grain legumes, especially pigeonpea (*C. cajan*), as a strategy for diversifying food production and household income since the legumes are both cash and food crops (Rao and Mathuva, 2000; Mafongoya et al., 2006). Also, pigeonpea plants tolerate drought due to deep rooting, thus may provide insurance against total crop failure in low rainfall seasons (Rao and Mathuva, 2000). The legume may improve soil fertility and yields of associated crops as well through biological N fixation, nutrient pumping and incorporation of green manure (Chikowo et al., 2004; Ghosh et al., 2006). However, the yield advantage of mixed relative to monoculture cropping systems is dependent on net effects of facilitative and competitive interactions on growth resources (García-Barrios and Ong, 2004).

Deeper rooting and slower initial growth of pigeonpea relative to most cereal crops (Mafongoya et al., 2006) may reduce interspecific competition through differentiation of root niche and peak resource demand; hence facilitating coexistence of pigeonpea and maize (*Z. mays*) in mixture. For instance, the legume may access soil water below the maize rooting zone and enhance moisture supply to intercropped maize plants through hydraulic lift (Sekiya and Yano, 2004). Relay cropping systems, in which pigeonpea is planted 2 – 3 weeks after maize sowing (Akanvou et al., 2002; Gathumbi et al., 2004), may also minimize competition as pigeonpea is planted soon after the maize is established. The delayed planting as well as the slow initial growth of the legume, provides maize with an early competitive advantage. In semi-arid areas, however, growing seasons are increasingly becoming shorter because of low and sporadic rainfall patterns (Rao and Mathuva, 2000; Chikowo et al., 2004). Consequently, yield of intercropped pigeonpea can be adversely affected by the combined effects of delayed planting and drought. Thus, it is important to understand the component interactions and their impacts on resource capture and use under intercropping (simultaneous) and improved-fallow (sequential) systems in order to sustain yields of maize-pigeonpea cropping systems in semi-arid climates.

Pigeonpea plants have both physiological and morphological attributes that may reduce interspecific competition in mixed culture. However, yield of maize intercropped with pigeonpea in semi-

arid conditions is often similar or less than that of sole-cropped maize (Rao and Mathuva, 2000; Snapp et al., 2002; Chikowo et al., 2004; Myaka et al., 2006), indicating probable yield suppression due to competition for soil nutrients and/or moisture. This interaction also may affect pigeonpea yield, thereby reducing overall system productivity. As noted earlier, previous studies assessed crop yield and soil nutrient replenishment by legumes, giving insufficient information on interspecific competition for growth resources. Such information may be useful for optimizing yields of both crops to diversify food and income sources of smallholder farmers (Snapp et al., 2002; Rao and Mathuva, 2000). Yet research evaluating the mechanisms for interspecific competition between maize (cereals) and pigeonpea (grain legumes) in sub-Saharan Africa is limited.

I examined biomass and nutrient uptake of crops in response to nutrient replenishment (facilitation) and competition associated with pigeonpea fallowing or intercropping with maize and the effects of manure or fertilizer inputs in modifying these interactions. Cattle manure and inorganic fertilizer were tested because these are alternative practices for improving soil fertility and crop yield in livestock keeping areas. It was hypothesized that pigeonpea fallowing is more productive than intercropping due to reduced competition for growth resources. Specific objectives were to assess the effects of maize-pigeonpea cropping systems, cattle manure, and N and P fertilizers on yields, nutrient uptake, soil nutrient replenishment, and competition for nutrients. As mentioned in Chapter 1, the results should contribute to advancing the knowledge of plant nutritional interactions for improving productivity and management of traditional intercropping systems of maize and pigeonpea under semi-arid conditions.

## **5.2 Materials and methods**

### **5.2.1 Study site and treatments**

The research was carried out at Ihumwa village (6° 10' S, 35° 53' E), Dodoma, Tanzania (Fig. 3.1) located in a semi-arid zone (elevation of 640 m above sea level) with mean annual rainfall of 560 mm (Fig. 5.1) and a dry period of 7 – 8 months. Rainfall in the 2004 cropping season was above average, but in the 2005 season it was below average with 48 % falling towards the end of the season (March).

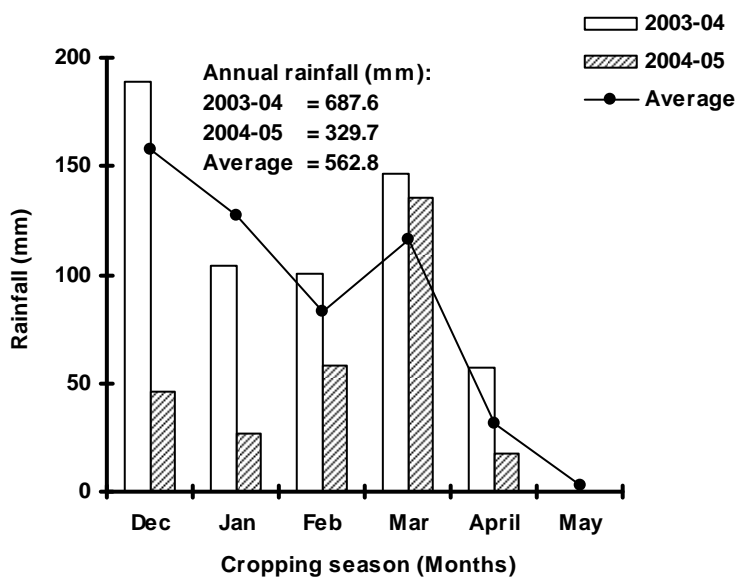


Figure 5.1. Annual and monthly rainfall received during the 2004 and the 2005 cropping seasons and the long-term average (2000 – 2006) at Ihumwa, Dodoma, Tanzania.



Apparently this seasonal precipitation changes suppressed crop yield as discussed in section 5.3.1. Soils are acidic ( $\text{pH} = 4.6 \pm 0.1$ ), classified as ferric Acrisols according to the FAO Classification System and have a sandy loamy texture. Nutrient levels at the 0 – 20 cm soil depth were low for crop production: organic carbon ( $0.35 \% \pm 0.05$ ), total N ( $0.03 \% \pm 0.003$ ), extractable P ( $7.0 \text{ mg kg}^{-1} \pm 0.9$ ), and exchangeable cations in  $\text{cmol kg}^{-1}$  ( $\text{Ca} = 0.56 \pm 0.01$ ;  $\text{K} = 0.30 \pm 0.01$ ;  $\text{Mg} = 0.24 \pm 0.02$ ;  $\text{H} = 0.4 \pm 0.07$ ;  $\text{Al} = 0.98 \pm 0.05$ ). The native vegetation was degraded Miombo woodland dominated by thickets or widely spaced bushes of *Brachystegia* spp. Major land use systems at this site are subsistence farming and livestock keeping.

A  $3^3$  factorial experiment with three replications was established in a RCBD. Treatments included cropping systems (continuous sole maize, intercropping and improved fallow) and three rates (control, half, and full) of cattle manure (Table 5.1), and combined N and P fertilizers. Intercropping and fallow treatments represented simultaneous and sequential cropping systems, respectively. The full rate of manure applied ( $10 \text{ Mg ha}^{-1}$  air dry weight) was based on local rates and falls within a range ( $10 - 15 \text{ Mg ha}^{-1}$ ) used by farmers in Sub-Saharan Africa (Mafongoya et al., 2006). The source of N was urea and P was triple super phosphate. These fertilizers were applied at  $80 \text{ kg N ha}^{-1}$  and  $40 \text{ kg P ha}^{-1}$  for full rate, which are levels used in other semi-arid areas of Tanzania (Ussiri et al., 1998).

Plots of 6 m x 6 m were laid out at the beginning of the 2004 cropping season after plowing using a farm tractor. Plots and blocks were separated by 3 m and 5 m-wide unplanted buffer strips, respectively. Maize (var. *Kito*) and pigeonpea (Var. *Babati white*) were sown at a spacing of 0.9 m between rows and 0.5 m within rows, resulting in additive mixtures for evaluating interspecific competition (Kelty and Cameron, 1995). *Kito* is a short-duration maize variety that is used in areas with low precipitation (Chapter 4) and *Babati white* is a traditional pigeonpea variety grown in semi-arid Tanzania (Myaka et al., 2006). Maize and pigeonpea were sown simultaneously in alternate rows in each plot under intercropping but were rotated annually in the fallow treatment. The fallow treatment was duplicated such that pigeonpea was sown in one plot in the 2004 cropping season followed by maize in the 2005 season and vice-versa for the second plot. This arrangement permits comparison of fallow effects with other cropping

Table 5.1. Concentration and content of nutrients in cattle manure applied to maize and pigeonpea at Ihumwa, Dodoma, Tanzania

Nutrient	Concentrations (%)	Amount applied (kg ha <sup>-1</sup> )	
		Half rate <sup>1</sup>	Full rate
Nitrogen	1.30	65	130
Phosphorus	0.28	14	28
Potassium	5.00	250	500
Calcium	1.74	87	174
Magnesium	0.77	38	77

<sup>1</sup> Application rates used were 5 Mg ha<sup>-1</sup> and 10 Mg ha<sup>-1</sup> (air dry weight) for half and full rates, respectively. Prescribed rates are 80 kg N ha<sup>-1</sup> for nitrogen and 40 kg P ha<sup>-1</sup> for phosphorus.

systems without being confounded by seasons (Rao and Mathuva, 2000).

### **5.2.2 Soil and plant sampling**

Prior to sowing crops, soil samples were collected from five random points within each block at 0 – 20 cm depth using soil auger to assess initial soil fertility status. These samples were mixed thoroughly and sub-sampled to get a composite sample. Similarly, two weeks after the onset of rain in the 2005 cropping season, soil samples were also collected from the 4 m x 4 m inner plot area (leaving 1-m border strip on both sides of each plot) to minimize boundary effects on treatment response. Then samples were transported to the laboratory in a cooler and frozen prior to analysis of inorganic N and extractable P within a week. Maize was harvested from the inner plot area partitioned into grain, stover, and cobs; weighed separately and sub-sampled for the determination of grain and aboveground biomass yields based on the ratio of dry (70°C)-to-fresh weights. Grain and biomass yields were then extrapolated to one hectare based on yield per sampled area. These sampling procedures were also used to assess pigeonpea grain yield three months after maize harvesting and to determine wood and foliage biomass of pigeonpea calculated using developed regression models. Leafy biomass was incorporated into soil as green manure during site preparation for the 2005 season while wood biomass was harvested for fuel wood supply.

### **5.2.3 Pigeonpea biomass assessment**

All pigeonpea plants in the 4 m x 4 m inner plot area were measured for height (m) and stem diameter (cm) using a graduated pole and a vernier caliper, respectively. Diameter ( $D$ ) measurements were taken at 10 cm above the ground to minimize variation. Small ( $D < 0.60$  cm), medium ( $D = 0.60 - 1.10$  cm), and large ( $D > 1.10$  cm) sized plants per plot were destructively sampled for determination of foliage and wood biomass based on dry weight (70°C). Tree measurements and sampling were carried out when at least 50 % of pigeonpea plants flowered to coincide with the active growth period. This was considered an appropriate time for evaluating interspecific competition because nutrient demand for pigeonpea was at peak and maize plants were not yet harvested. Allometric models for estimating

pigeonpea biomass were developed based on measured dimensions of 30 sampled trees: height (1.12 m – 2.7 m) and stem diameter (0.45 cm – 1.70 cm) and the remaining trees (21) were used for model validation. These variables were fitted into allometric equations:  $Y = aD^b$  and  $Y = aD^b H^c$ , where  $Y$  is the dry weight ( $\text{g tree}^{-1}$ ),  $D$  is stem diameter (cm), and  $H$  is height (m) after logarithmic transformation to fit linear regressions (Haase and Haase, 1995). The estimated biomass was multiplied by a correction factor (CF) to account for bias associated with this transformation (Sprugel, 1983) and the value was extrapolated to a hectare based on yield per sampled area. The following models were chosen to calculate tree biomass ( $\text{g tree}^{-1}$ ) based on the highest coefficient of determination ( $R^2$ ) and the lowest standard error of estimate (SEE):

$$\text{Ln (Leaves)} = 1.531 \text{ Ln}D + 3.987; R^2 = 0.79; \text{SEE} = 0.31; \text{CF} = 1.05; p < 0.0001 \quad (1)$$

$$\text{Ln (Wood)} = 1.917 \text{ Ln}D + 4.447; R^2 = 0.91; \text{SEE} = 0.24; \text{CF} = 1.03; p < 0.0001 \quad (2)$$

$$\text{Ln (Leaves + Wood)} = 1.758 \text{ Ln}D + 4.952; R^2 = 0.92; \text{SEE} = 0.20; \text{CF} = 1.02; p < 0.0001 \quad (3)$$

Where  $\text{Ln}$  is the natural logarithm and  $p$  is probability of the model.

#### 5.2.4 Chemical analysis of soil and plant samples

Analyses of soil pH, carbon and nutrients in both soil and plant samples as well as the calculation of nutrient uptake were carried out as described in Chapter 3 and 4, sections 3.2.3, 3.2.4, and 4.2.4.

#### 5.2.5 Vector competition analysis

Vector competition analysis (Imo and Timmer, 1998) was employed to examine nutrient competition between maize and pigeonpea in the 2005 cropping season because the fallow treatment generated maize data after the first season. Treatment effects on the aboveground biomass and nutrient content of intercropped and fallowed maize and pigeonpea with or without fertilizer were expressed relative to those of the unfertilized improved fallow treatment that was set as a reference (normalized to 100). Vector shifts or direction reflect the type of competitive interactions (antagonism, synergism, and compensatory) and the ratio of uptake-to-biomass vector identifies specific nutritional interactions

including antagonistic dilution, growth dilution, and deficiency of plants in mixture (maize and pigeonpea intercropping) relative to monoculture (improved fallow) cropping systems (Imo and Timmer, 1998).

Vector diagnostic analysis was also used to assess maize and pigeonpea responses to nutrient supply relative to normalized reference points (i.e., sole maize, intercropping, and cattle manure without fertilizer) as detailed in Chapter 4, section 4.2.5.

## **5.2.6 Statistical analysis**

Graphical analysis of residuals was employed to test for normality and constant variance as detailed in section 3.2.5. Soil mineral N and P measures were log-transformed to correct for deviations from these assumptions prior to conducting ANOVA. The mixed model procedure in SAS (SAS, 2000) was used to run the analyses at  $\alpha = 5\%$ . Cropping systems, manure, fertilizer, and interactions of these factors were fixed effects variables while block and block-by-treatment interaction were random effects variables in the model. The ANOVA for maize and soil data tested the effects of 3 cropping systems and 3 rates of both manure and fertilizer (a  $3^3$  factorial experiment) replicated three times in a RCBD (Table 5.2). For pigeonpea, the analysis was carried out as a  $2 \times 3^2$  factorial experiment since one level of cropping systems (i.e., sole maize) does not have pigeonpea data (Table 5.3). There was no 3-way interaction between treatments. Hence, ANOVA was repeated to compare main effects and 2-way treatment combinations. Following ANOVA, least squares means for significant treatment interactions were ranked according to Tukey's studentized range test after slicing (sorting) the interactions by fertilizer.

## **5.3 Results and discussion**

### **5.3.1 Maize and pigeonpea yields**

There was significant positive interaction between cropping systems and fertilizer input on maize and pigeonpea yields ( $p = 0.0083$ , Table 5.2 and  $p = 0.0270$ , Table 5.3) in both the 2004 and the 2005 cropping seasons (Fig. 5.2). Without fertilization, yield of intercropped maize ( $1.3 \text{ Mg ha}^{-1}$ ) in the first

Table 5.2. Summary of ANOVA ( $p > F$ ) testing the effects of cropping systems, cattle manure, and combined N and P fertilizers on yields (Mg ha<sup>-1</sup>) and nutrient content (kg ha<sup>-1</sup>) of maize and soil inorganic nitrogen and phosphorus (mg kg<sup>-1</sup>) for the 2005 cropping season at Ihumwa, Dodoma, Tanzania.

Source of variation	df <sup>1</sup>	Maize							Soil	
		Grain	Biom. <sup>2</sup>	N	P	K	Mg	Ca	N	P
Block (Blk) <sup>3</sup>	2									
Cropping systems (CS)	2	<.0001	0.0320	0.0744	0.0656	0.2207	0.2720	0.2114	0.0001	0.2800
Blk x CS	4									
Fertilizer (Fert.)	2	0.0074	<.0001	0.0034	<.0001	0.1830	0.2324	0.7580	<.0001	<.0001
Blk x Fert.	4									
CS x Fert.	4	0.0083	0.0061	0.0041	0.0046	0.0260	0.0418	0.0430	0.0051	0.0367
Blk x CS x Fert.	8									
Cattle Manure (CM)	2	0.2371	0.0119	0.2673	0.2038	<.0001	<.0001	0.0266	0.0379	0.2614
Blk x CM	4									
CS x CM	4	0.1076	0.8126	0.2297	0.0676	0.9753	0.9560	0.3455	<.0001	0.0610
Blk x CS x CM	8									
Fert x CM	4	0.0459	0.0090	0.0129	0.0304	0.0350	0.0460	0.0480	0.0202	0.0291
Blk x Fert. x CM	8									
Residual error	24									
Corrected total	80									

<sup>1</sup>df = numerator degree of freedom

<sup>2</sup>Biom. = aboveground biomass.

<sup>3</sup>No test statistics (i.e., F-ratios and probabilities) for block and block-by-treatment interaction because these were random effects variables in the mixed model that constituted error terms for testing main and interaction effects of cropping systems, fertilizer and cattle manure.

Table 5.3. Summary of ANOVA ( $p > F$ ) testing the effects of cropping systems, cattle manure, and combined N and P fertilizers on yield (Mg ha<sup>-1</sup>) and nutrient content (kg ha<sup>-1</sup>) of pigeonpea for the 2005 cropping season at Ihumwa, Dodoma, Tanzania.

Source of variation	df <sup>1</sup>	Grain	Biom. <sup>2</sup>	N	P	K	Mg	Ca
Block (Blk) <sup>3</sup>	2							
Cropping systems (CS)	1	0.0088	0.0033	0.0041	0.0004	0.0247	0.0559	0.0180
Blk x CS	2							
Fertilizer (Fert.)	2	0.0010	0.0018	0.0002	0.0008	0.0026	0.0013	0.1942
Blk x Fert.	4							
CS x Fert.	2	0.0270	0.0314	0.0322	0.0470	0.0344	0.0106	0.0473
Blk x CS x Fert.	4							
Cattle Manure (CM)	2	0.0528	0.0021	0.0007	0.0316	0.0062	0.0012	0.0120
Blk x CM	4							
CS x CM	2	0.2038	0.0167	0.0129	0.0894	0.6965	0.0456	0.0153
Blk x CS x CM	4							
Fert x CM	4	0.0339	0.0264	0.0474	0.0269	0.0230	0.0475	0.0352
Blk x Fert. x CM	8							
Residual error	12							
Corrected total	53							

<sup>1</sup> df = numerator degree of freedom

<sup>2</sup> Biom. = aboveground biomass.

<sup>3</sup> No test statistics (i.e., F-ratios and probabilities) for block and block-by-treatment interaction because these were random effects variables in the mixed model that constituted error terms for testing main and interaction effects of cropping systems, fertilizer and cattle manure.

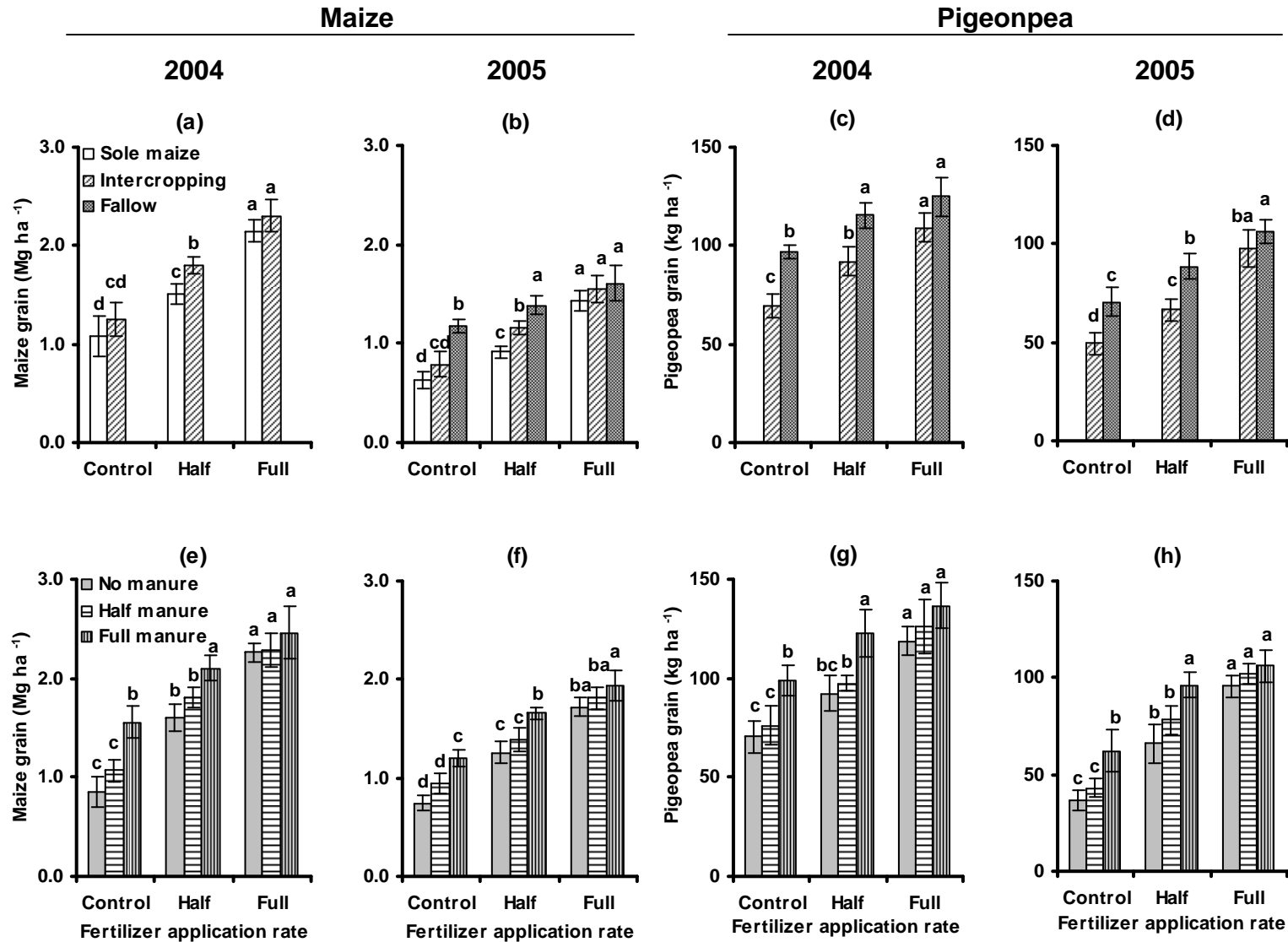


Figure 5.2. Maize and pigeonpea grain yields for the interactions between combined N and P fertilizers and cropping systems [sole maize, intercropping, and one-year improved fallow, (a – d)] or cattle manure (e – h) at Ihumwa, Dodoma, Tanzania. Application rates for cattle manure were: Control = No manure, Half = 5 Mg ha<sup>-1</sup>, Full = 10 Mg ha<sup>-1</sup>; and for inorganic fertilizers were: Control = No fertilizer, Half = 40 kg N ha<sup>-1</sup> and 20 kg P ha<sup>-1</sup>, Full = 80 kg N ha<sup>-1</sup> and 40 kg P ha<sup>-1</sup>. For each Figure, values represent least squares means of treatment combinations and those marked by the same letter are not statistically different at  $p < 0.05$  according to Tukey's HSD test. Vertical bars indicate standard error of means ( $n = 3$ ).



season was similar to that of unfertilized sole maize ( $1.1 \text{ Mg ha}^{-1}$ ), but increased by 60 % ( $1.8 \text{ Mg ha}^{-1}$ ) at the half fertilizer rate (Fig. 5.2a). Similar results were also observed for maize in the second season (Fig. 5.2b), suggesting that the intercropped pigeonpea did not provide sufficient nutrients to improve maize yield over the control. Improved fallow culture without fertilizer ( $1.2 \text{ Mg ha}^{-1}$ ) and at half fertilizer rate ( $1.4 \text{ Mg ha}^{-1}$ ) enhanced maize grain yield by 100 % and 120 % respectively, compared to  $0.6 \text{ Mg ha}^{-1}$  found in the unfertilized sole maize treatment (Fig. 5.2b). These large responses probably reflect the combined effects of enhanced soil fertility associated with pigeonpea fallows through biological N-fixation and nutrient pumping (Chikowo et al., 2004), incorporation of leafy biomass to the soil as green manure (Fig. 5.3) and reduced competition for nutrients and/or moisture due to sequential cropping arrangements. There was no difference between cropping systems at full rates of N and P fertilizers (Fig. 5.2a – d) implying that at higher addition rates growth responses were mainly driven by fertilizer inputs. The improved fallow system at half fertilizer rate produced yields of maize and pigeonpea similar to yields obtained with cropping systems at the full rate. Hence, this system could be operated at 50 % less fertilizer use without compromising crop and wood yields (Figs. 5.2 and 5.3). Significant cropping systems-by-fertilizer interaction noted in this study (Table 5.2) was possibly driven by P-fertilization because green manure usually supply insufficient amounts of P to sustain crop production due to low foliar P concentrations (Vanlauwe et al., 2006).

Enhanced maize ( $p = 0.0459$ ) and pigeonpea grain yield responses ( $p = 0.0339$ ) to the interacting effects of fertilizer and cattle manure (Fig. 5.2e – h, Tables 5.2 and 5.3) indicated that manure treatments alone were not sufficient to alleviate nutrient deficiencies. These synergistic interactions were mainly attributed to the additional P supply from fertilization because of the relatively high N content of the cattle manure when compared to prescribed rates (Table 5.1). In contrast to my study, Lupwayi et al. (1999) did not observe positive interactions between cattle manure and urea possibly due to the use of N fertilizer alone, low manure rates ( $3 \text{ Mg ha}^{-1}$ ), and differences in site conditions. Mafongoya et al. (2006) reported that livestock manures at recommended rates ( $10 - 15 \text{ Mg ha}^{-1}$ ) containing 0.49 – 1.98 % N should be adequate for maize production (Table 5.1). Lack of statistical differences between the three

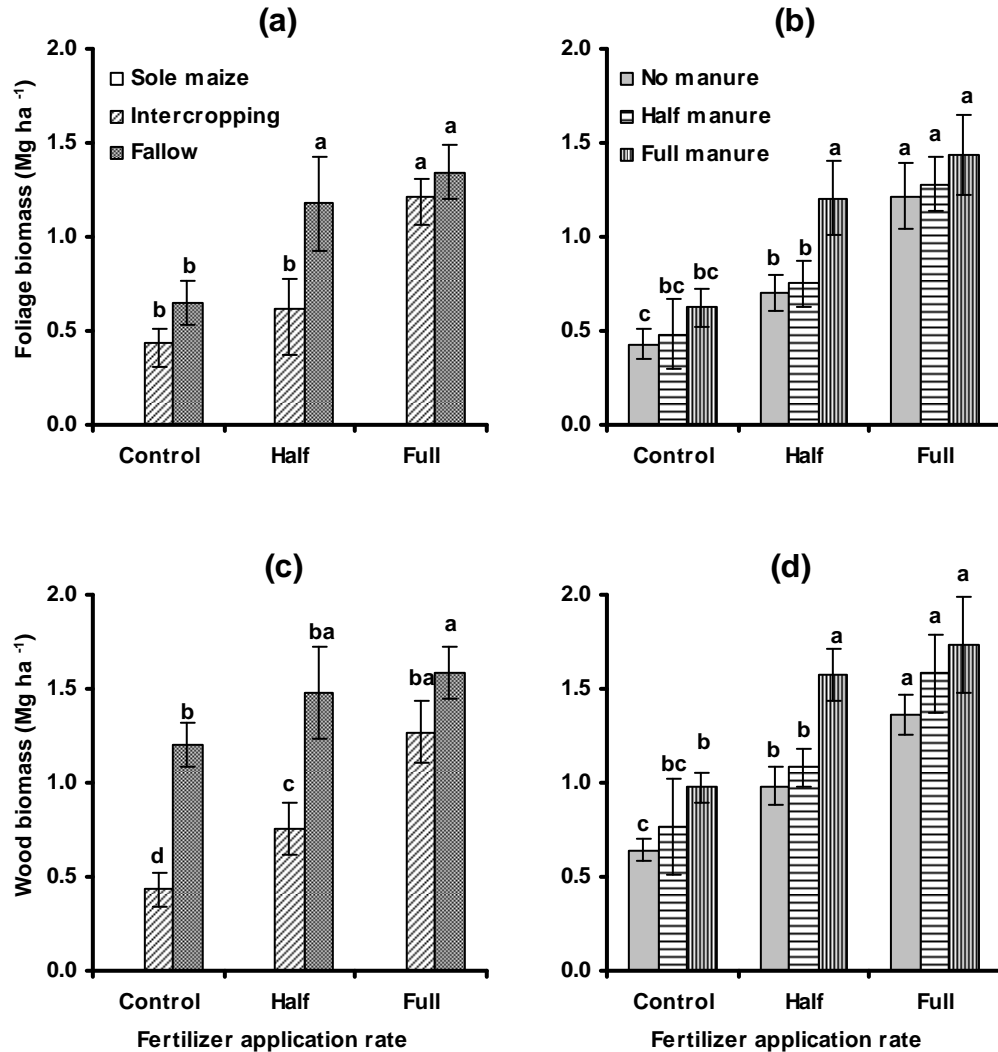


Figure 5.3. Foliage and wood biomass of pigeonpea for the interactions between combined N and P fertilizers and cropping systems [sole maize, intercropping, and one-year improved fallow, (a and c)] or cattle manure (b and d) at Ihumwa, Dodoma, Tanzania. Application rates for cattle manure were: Control = No manure, Half = 5 Mg ha<sup>-1</sup>, Full = 10 Mg ha<sup>-1</sup>; and for inorganic fertilizers were: Control = No fertilizer, Half = 40 kg N ha<sup>-1</sup> and 20 kg P ha<sup>-1</sup>, Full = 80 kg N ha<sup>-1</sup> and 40 kg P ha<sup>-1</sup>. For each Figure, values represent least squares means of treatment combinations and those marked by the same letter are not statistically different at  $p < 0.05$  according to Tukey's HSD test. Vertical bars indicate standard error of means ( $n = 3$ ).

manure treatments at full fertilizer rates also implied a fertilizer induced response. Evidently, a combination of full manure and half fertilizer rates dose was sufficient to optimize maize and pigeonpea production, because the yield associated with this treatment was similar to those obtained with manure at full fertilizer rate (Fig. 5.2e – h).

Precipitation in the 2004 season was above the long-term average and was well distributed throughout the cropping season (Fig. 5.1). However, yields of the unfertilized intercropped maize in the first and the second seasons (1.3 and 0.8 Mg ha<sup>-1</sup>) were not statistically different from yields (1.1 and 0.6 Mg ha<sup>-1</sup>) in the continuous sole maize treatment (Fig. 5.2a and b). Although such low yields are common in other semi-arid sites in southern Africa (Snapp et al., 2002; Chikowo et al., 2004; Myaka et al., 2006), these results suggest that the benefits of intercropping pigeonpea are mainly due to the additional grain and wood yields from pigeonpea (Fig. 5.2c, d and Fig. 5.3). Crop yield in 2005 was severely affected by low and sporadic rainfall patterns occurring on the study site (Fig. 5.1) such that yield declined by 20 – 30 % of the 2004 level (Fig. 5.2). Below average precipitation in February presumably affected maize growth adversely because the planted maize was in the active growth stage (6 weeks after maize sowing) requiring high supplies of growth resources (Chapter 4). Despite this drought effect, however, grain yields of maize under improved fallows without fertilizer or after modest additions of fertilizer and cattle manure were comparatively higher than the average maize yield (1 Mg ha<sup>-1</sup>) in Sub-Saharan Africa (Mafongoya et al., 2006). Thus, these treatments can be employed to minimize possible maize yield losses in legume intercropping systems in years of low precipitations that have been reported in the region (Snapp et al., 2002; Myaka et al., 2006).

### **5.3.2 Maize and pigeonpea nutrient uptake**

Significant treatment interactions, especially between fertilizer and cropping systems or manure, were noted for above ground biomass and nutrient content of maize and pigeonpea (Tables 5.2 and 5.3). Improved fallows with or without fertilizer addition increased maize N and P content relative to unfertilized sole maize, whereas intercropping treatments enhanced nutrient content only after fertilizer

application (Table 5.4) possibly because of interspecific competition that suppressed nutrient uptake and crop yield. Without fertilization, tissue N and P for the fallow treatment were higher than sole maize, but similar to those of intercropped maize with half fertilizer rate. These results are consistent with corresponding grain yield responses (Fig. 5.2b), and imply that the higher maize yield was associated with enhanced nutrition from inputs by pigeonpea fallowing or fertilizer application as mentioned earlier. Improved P nutrition after fallowing may reflect enhanced P uptake accompanying stimulated biomass production due to sequential cropping, since high P demand for N fixation may limit P recycling, especially on P deficient soils (Ishikawa et al., 2002). Except at the full fertilizer rate, the fallow treatment generally doubled N and P content of pigeonpea compared to the intercropping system (Table 5.4). This would indicate that intercropped pigeonpea plants were nutritionally poor presumably due to competition for soil nutrients with maize leading to reduced grain (Fig. 5.2c and d) and biomass yields (Fig. 5.3a and c). Positive interactions between cropping systems and fertilizer were mainly associated with N and P inputs because other elements were not provided. However, a similar effect on K, Ca, and Mg content in maize and pigeonpea were probably due to increased nutrient uptake accompanying accelerated growth after fertilization.

Cattle manure application, either alone or with N and P fertilizers increased uptake of all measured nutrients (Table 5.4), indicating that the soil was nutrient deficient for maize and pigeonpea culture. Generally, N and P content of crops in response to manure addition were masked at full fertilizer rate presumably because these elements were supplied through fertilization. In contrast, combined addition of manure and N and P fertilizers increased K, Ca, and Mg uptake by maize and pigeonpea (Table 5.4) even at higher fertilization rates indicating that these elements were supplied by cattle manure (Table 5.1). Pigeonpea N uptake increased with higher manure and fertilizer application rates (Table 5.4) suggesting that the shrub partly relied on external N sources rather than biological fixation alone, which may be depressed in acidic P deficient soils due to high P demand for fixation (Marschner, 1995; Ishikawa et al., 2002).

Table 5.4. Biomass yield ( $\text{Mg ha}^{-1}$ ) and nutrient content ( $\text{kg ha}^{-1}$ ) of maize and pigeonpea for the 2005 cropping season for different cropping systems and cattle manure treatments without (-) or with half (+) and full (++) rates of N and P fertilizers at Ihumwa, Dodoma, Tanzania.

Treatment	Maize						Pigeonpea					
	Biom. <sup>1</sup>	N	P	K	Mg	Ca	Biom.	N	P	K	Mg	Ca
<i>Cropping system x fertilizer</i> <sup>2</sup>												
-SM: unfertilized sole maize	1.73d <sup>3</sup>	12.9e	1.84e	22.3d	20.7d	2.19c						
-IC: unfertilized intercropping	1.99d	16.5de	2.52de	25.7d	24.4d	2.43bc	0.87d	14.3c	0.73c	6.68c	0.87c	6.53b
-IF: unfertilized fallow	2.52c	22.4dc	3.41dc	36.9bc	33.3bc	3.92ba	1.86b	30.6b	1.32b	13.2b	1.79b	11.2a
+SM: sole maize and half rate	2.48c	19.8d	3.25d	29.0cd	26.2cd	2.67c						
+IC: intercropping and half rate	2.91c	25.4c	4.06c	34.4c	30.6c	3.05ba	1.37c	23.9b	1.29b	10.3bc	1.36bc	9.19ba
+IF: fallow and half rate	3.52b	38.9b	6.01b	40.4bc	39.4ba	3.84ba	2.66a	46.9a	2.91a	19.0a	2.29a	13.8a
++SM: sole maize and full rate	3.68ba	40.0ba	6.61ba	41.2b	37.1b	3.67b						
++IC: intercropping and full rate	3.94a	43.9a	7.10a	49.0ba	44.0ba	4.48ba	2.48a	42.5a	2.66a	17.6a	2.14ba	12.8a
++IF: fallow and full rate	4.05a	46.5a	7.52a	52.6a	47.5a	4.89a	2.93a	52.7a	3.24a	20.9a	2.42a	14.0a
<i>Cattle manure x fertilizer</i> <sup>4</sup>												
-CM: no manure and no fert. <sup>5</sup>	1.76d	13.7d	1.81d	21.0d	19.3d	1.13d	1.17c	19.8c	0.86c	8.47c	0.96d	4.66c
-HM: half manure and no fert.	2.04d	16.3d	2.45d	27.5dc	24.3cd	1.53d	1.25c	22.5bc	1.05bc	10.7cb	1.13d	5.94bc
-FM: full manure and no fert.	2.79c	24.2c	3.81c	35.3bc	32.6bc	2.28c	1.60b	27.2bc	1.41b	12.9cb	1.35dc	7.45b
+CM: no manure and half fert.	2.89c	27.0c	4.10c	29.9c	28.8c	1.53d	1.68b	29.8b	1.55b	11.3c	1.32dc	5.94bc
+HM: half manure and half fert.	3.11c	31.7c	4.82c	40.4b	37.9b	2.83b	1.83b	31.6b	1.77b	14.5cb	1.58c	9.10b
+FM: full manure and half fert.	3.65b	39.0b	6.39b	55.3a	52.6a	3.58ba	2.78a	50.4a	2.90a	23.2a	2.54b	14.8a
++CM: No manure and full fert.	3.85ba	40.0ba	6.50ba	40.0b	38.7b	2.07c	2.58a	47.7a	2.67a	16.1b	1.92cb	8.51bc
++HM: half manure and full fert.	4.00ba	43.2ba	7.28ba	55.7a	53.0a	4.18a	2.86a	55.5a	3.22a	26.0a	2.85ba	16.7a
++FM: full manure and full fert.	4.30a	51.4a	8.27a	63.9a	60.5a	4.44a	3.17a	65.4a	3.82a	32.6a	3.47a	19.3a

<sup>1</sup>Biom. = aboveground biomass.

<sup>2</sup>Cropping system interaction fertilizer.

<sup>3</sup>Values represent least squares means and those within a column followed by the same letter are not statistically different at  $p < 0.05$  according to Tukey's HSD test.

<sup>4</sup>Cattle manure interaction fertilizer.

<sup>5</sup>Fert. = Fertilizer.

### 5.3.3 Soil nutrient availability

Soil nutrient analysis was carried out for N and P alone since these elements are the most common limiting nutrients for crop production in highly weathered tropical soils (Brady and Weil, 2004; Mafongoya et al., 2006). Apparently, availability of N and P controlled growth of maize and pigeonpea because the largest grain and biomass yields were associated with treatments containing interactions of combined N and P fertilizers with cropping systems or with cattle manure (Fig. 5.2 and Table 5.4). Without fertilization, the fallow treatment significantly increased ( $p = 0.0051$ , Table 5.2) total soil inorganic N status compared to continuous sole maize (Fig. 5.4a), which as expected reflected N enrichment by pigeonpea through biological fixation (Chikowo et al., 2004), and the incorporation of foliage biomass during site preparation (Fig. 5.3). However, significant soil P increase ( $p = 0.0367$ , Table 2) was apparent after fertilization (Fig. 5.4c) indicating that pigeonpea fallowing alone did not improve soil P levels probably due to low P inputs (Table 5.4). In P-stressed environments pigeonpea tends to maintain low foliar P concentrations (Ishikawa et al., 2002) implying limited P recycling capacity. Lack of significant soil N and P increase under intercropping without fertilizer compared to the unfertilized sole maize was associated with suppressed pigeonpea growth as reflected by low biomass yield (Table 5.4). Another study of intercropped pigeonpea and maize for two consecutive seasons in semi-arid sites also found no improved soil N both under field conditions and after anaerobic incubation (Myaka et al., 2006). Hence sequential cropping systems, such as improved fallows may be more effective than simultaneous cropping systems in replenishing soil fertility in semi-arid conditions. Soil N and P status at the full rate of fertilizer application were similar among the cropping systems, but statistically higher than levels of the unfertilized sole maize treatment (Fig. 5.4a and c), which is consistent with grain yield patterns (Fig. 5.2b and d). These results also suggest that maize and pigeonpea yields were mainly determined by soil N and P availability.

As expected, combined fertilizer and cattle manure applications enhanced soil N ( $p = 0.0202$ ) and P ( $p = 0.0291$ ) status compared to the control (Table 5.2), providing extra N and P supply (Fig. 5.4b and d) associated with improved maize and pigeonpea grain yields (Fig. 5.2e – h). Unlike soil N status, cattle

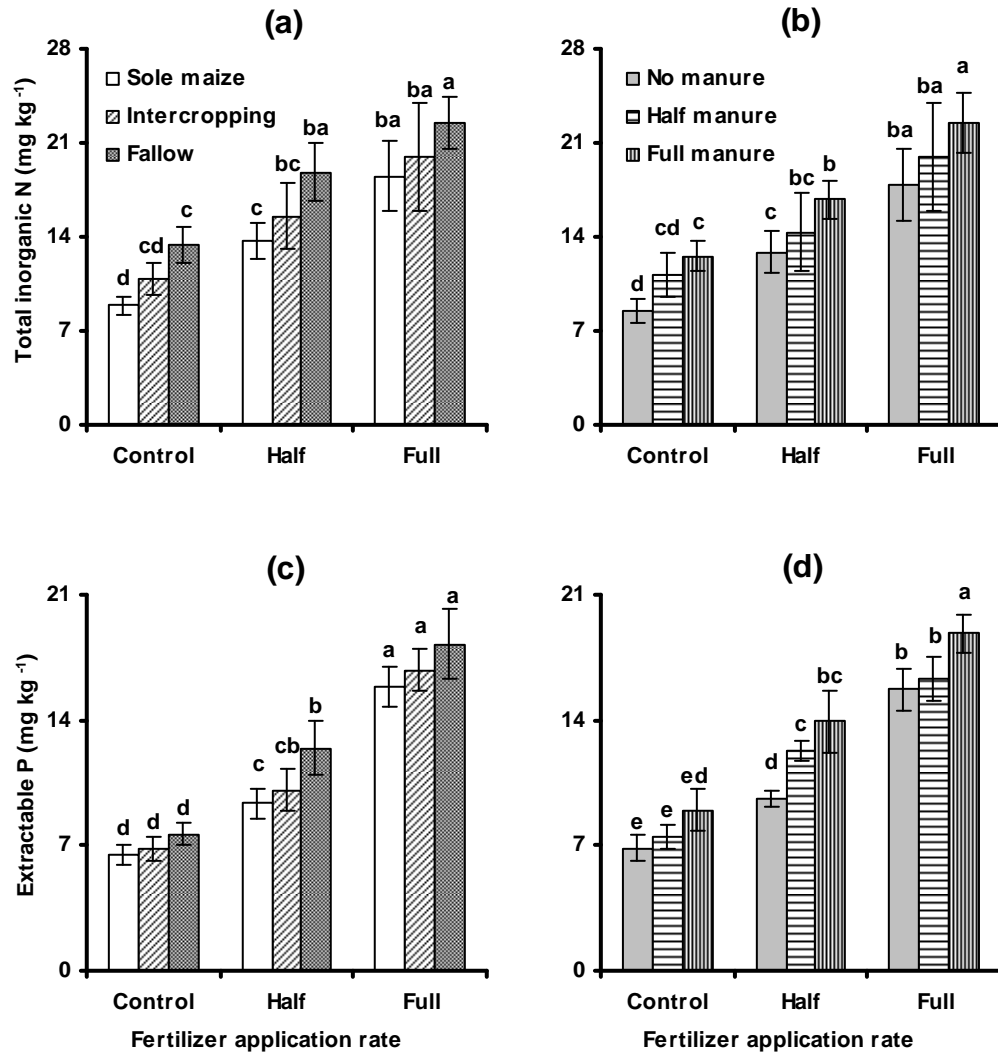


Figure 5.4. Soil N and P status in response to interactions between combined N and P fertilizers and cropping systems [sole maize, intercropping, and one-year improved fallow, (a and c)] or cattle manure (b and d) at Ihumwa, Dodoma, Tanzania. Application rates for cattle manure were: Control = No manure, Half = 5 Mg ha<sup>-1</sup>, Full = 10 Mg ha<sup>-1</sup>; and for inorganic fertilizers were: Control = No fertilizer, Half = 40 kg N ha<sup>-1</sup> and 20 kg P ha<sup>-1</sup>, Full = 80 kg N ha<sup>-1</sup> and 40 kg P ha<sup>-1</sup>. For each Figure, values represent least squares means of treatment combinations and those marked by the same letter are not statistically different at  $p < 0.05$  according to Tukey's HSD range test. Vertical bars indicate standard error of means ( $n = 3$ ).

manure used was poor in P (Table 5.1) and hence could not increase soil P over the control when applied alone (Fig. 5.4d). Thus, synergistic interactions noted between cattle manure and fertilizer on maize and pigeonpea yields may be associated with additional P supply as mentioned earlier. Ranges of soil N (8.5 – 23 mg N kg<sup>-1</sup>) and extractable P (6.5 – 19 mg P kg<sup>-1</sup>) levels reported in this study may reflect residual effects of treatments from the previous season because soil samples were collected within a week after onset of rain during sowing of maize and pigeonpea. Hence, these values may have been underestimated due to low mineralization processes at the beginning of growing seasons (Imo and Timmer, 2000; Rao and Mathuva, 2000). However, previous studies have demonstrated that pre-season nutrient levels positively correlate ( $R^2 = 0.41 - 0.71$ ) with subsequent crop yield (Ikkerla et al., 1999; Chirwa et al., 2006).

#### **5.3.4 Vector analysis of maize and pigeonpea: competitive effects**

Vector competition diagrams in Figure 5.5 illustrate interspecific nutrient competition (Fig. 5.5a) and give insight on the role of fertilizer addition in modifying this competition (Fig. 5.5b – e). Without fertilization, both yield and nutrient uptake of intercropped maize and pigeonpea decreased relative to the fallow treatment exemplifying antagonistic interactions (Fig. 5.5a). Vectors of nutrient uptake were comparatively shorter than the biomass vector (vector ratio < 1), which suggest nutrient competition (Imo and Timmer, 1998) resulting from inherently low soil fertility. Thus, besides soil nutrient replenishments (Fig. 5.4), higher grain and biomass yields noted under the fallow treatment without fertilization (Fig. 5.2b and Table 5.4) could be due to reduced competition for nutrients and other growth resources such as moisture associated with sequential cropping of pigeonpea and maize. The unfertilized intercropping treatment reduced pigeonpea biomass by 60 % (100 - 40) compared to a 30 % (100 - 70) decrease in maize, indicating a stronger competitive effect of maize (Fig. 5.5a). Apparently, the slow initial growth rate of pigeonpea (Mafongoya et al., 2006) may be the reason for its weak competitive ability.

The slow growth rate of pigeonpea relative to cereal crops is expected to minimize effects interspecific competition (Snapp et al., 2002; Mafongoya et al., 2006) since the legume may grow well



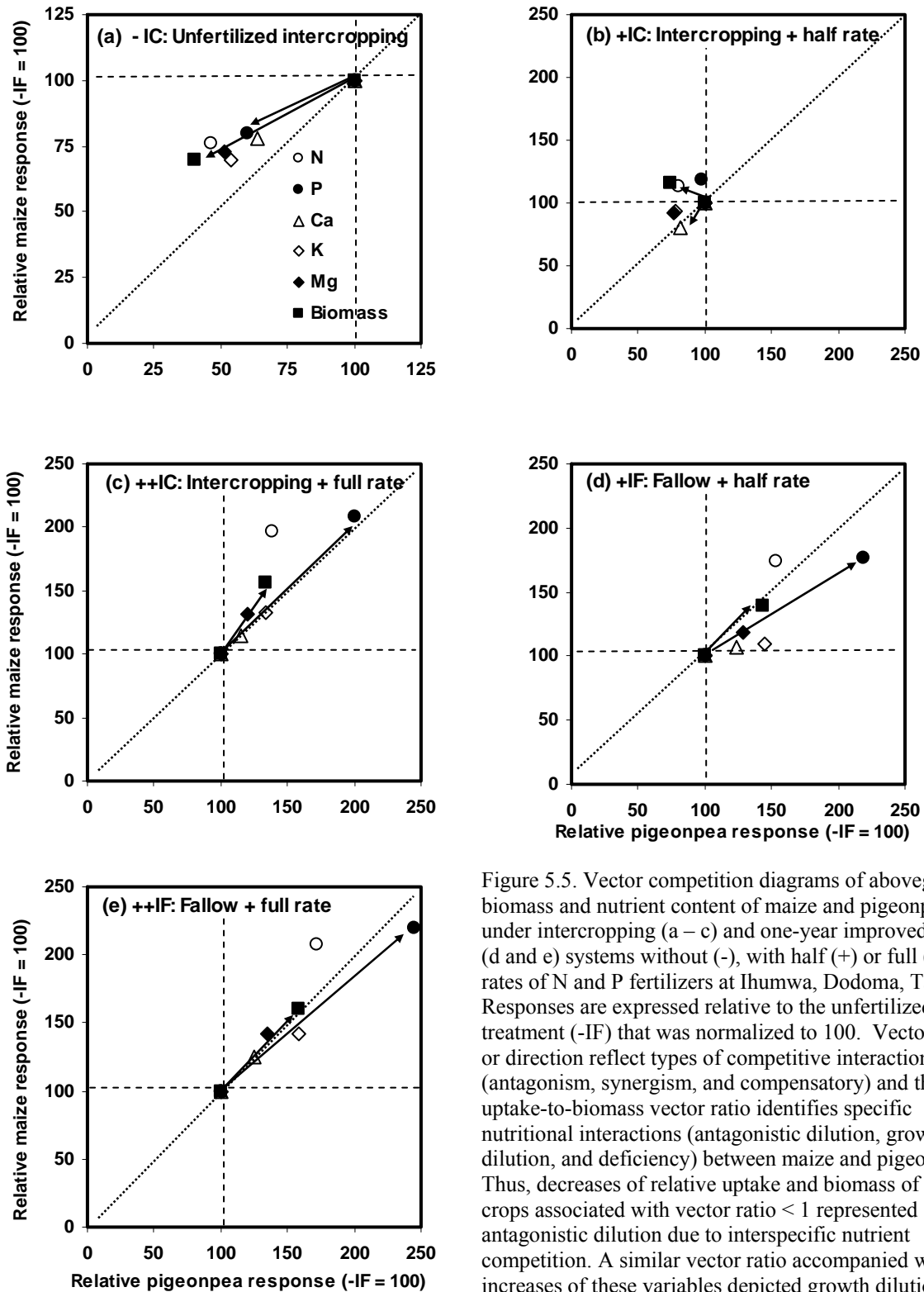


Figure 5.5. Vector competition diagrams of aboveground biomass and nutrient content of maize and pigeonpea under intercropping (a – c) and one-year improved fallow (d and e) systems without (-), with half (+) or full (++) rates of N and P fertilizers at Ihumwa, Dodoma, Tanzania. Responses are expressed relative to the unfertilized fallow treatment (-IF) that was normalized to 100. Vector shifts or direction reflect types of competitive interactions (antagonism, synergism, and compensatory) and the uptake-to-biomass vector ratio identifies specific nutritional interactions (antagonistic dilution, growth dilution, and deficiency) between maize and pigeonpea. Thus, decreases of relative uptake and biomass of both crops associated with vector ratio < 1 represented antagonistic dilution due to interspecific nutrient competition. A similar vector ratio accompanied with increases of these variables depicted growth dilution due to stimulated growth after additions of limiting nutrients. Nutrient deficiency responses were illustrated by relative increase in plant uptake and biomass and vector ratio > 1. To minimize clutter, only the biomass and the most responsive nutrient vector (arrow) are drawn. See Table 5.4 for statistically different vectors (treatments). Note scale for Fig. 5a is half that of others.

during the offseason by accessing subsoil moisture due to deeper rooting (Sekiya and Yano, 2004) possibly compensating for impaired early growth after harvesting cereal crops (Zhang and Li, 2003). However, three months after maize harvesting, pigeonpea grain yield in the unfertilized intercropping was 33 % lower than that of the unfertilized fallow treatment (Fig. 5.2d). This clearly signifies that offseason pigeonpea growth was adversely affected by earlier nutrient depletion induced by maize and/or the effects of drought (Figs. 5.1 and 5.5a). Recovery of growth and nutrient uptake after harvest of an early maturing component has been demonstrated for soybean plants in wheat-soybean intercropping systems in semi-arid China (Zhang and Li, 2003). Consistent with this study, such recovery was not observed for unfertilized pigeonpea plants in the pigeonpea-soybean intercropping system in semi-arid India due to the high competitive effect of soybean (Ghosh et al., 2006).

Apparently, additions of half rates of N and P fertilizers to intercropped maize and pigeonpea did not mitigate interspecific nutrient competition (Fig. 5.5b), because nutrient vectors (uptake) for both plants were not statistically higher than the reference point, i.e., improved fallowing without fertilizer (Table 5.4). As expected, relative biomass and nutrient uptake of both maize and pigeonpea under intercropping increased significantly relative to the unfertilized fallow treatment at full rate of fertilizer application (Fig. 5.5c and Table 5.4), reflecting reduced nutrient competition. Similar results were found for improved-fallow systems at both half and full fertilizer rates (Fig. 5.5d and e). After fertilization, the biomass vector was shorter than vectors of N and P (vector ratio > 1), but longer than vectors of other elements (Fig. 5.5c – e). Presumably this pattern indicates N and P deficiency responses to fertilization, and corresponding growth dilution of K, Mg, and Ca because these elements were not added. Overall, vector competition analysis revealed that addition of full prescribed fertilizer rates to intercropping systems is necessary to overcome nutrient competition and enhance maize and pigeonpea yields relative to the unfertilized fallow treatment (Fig. 5.5c). These outcomes may also be obtained by implementing improved fallow culture with half or full rates of fertilizer because crop yields between cropping systems were not different at full rates (Fig. 5.2 and Table 5.4). These results illustrate the benefit of sequential

cropping systems over simultaneous systems in reducing interspecific resource competition and fertilizer inputs without compromising crop and wood yields in semi-arid regions.

Farmers are concerned with yield loss of maize intercropped with grain legume, especially in drier years, when additional yield from the legumes may not offset such losses (Snapp et al., 2002). However, my results suggest that adopting improved fallows with or without fertilizer addition may stimulate crop growth and minimize such losses even in semi-arid conditions.

### **5.3.5 Vector analysis of maize and pigeonpea: nutrient diagnosis**

Vector analysis of maize and pigeonpea responses to interacting effects of cropping systems and N and P fertilizers (Fig. 5.6a and b) revealed that P was probably the most limiting nutrient since enhanced concentration and content of this element after fertilization were associated with the largest biomass increase relative to controls (Shift C, Salifu and Timmer, 2003). For instance, relative increases in concentration, content and biomass of maize in the fallow treatment with full fertilizer rate were 71 %, 309 %, and 134 %, respectively (Fig. 5.6a). High exchangeable aluminum ( $0.98 \text{ cmol kg}^{-1}$ ) at this site may have reduced P availability through fixation (Brady and Weil, 2004) making this element a major driver for plant growth (Fig. 5.2 and Table 5.4). The deficiency response of pigeonpea to P may also be attributed to high P demand for root nodulation by legumes (Marscher, 1995). Except for N, concentrations of other elements declined with increase in both content and biomass in treatment combinations containing N and P fertilizers (Fig. 5.6a and b). These responses exemplify growth dilution (Shift A, Salifu and Timmer, 2003) due to accelerated growth after fertilizer application because K, Mg, and Ca were not added. For pigeonpea, the unfertilized fallow treatment resulted in dilution of all elements (Fig. 5.6b) reflecting stimulated growth due to non-nutrient limitations such as moisture, affirming that interspecific competition suppressed growth under intercropping (Fig. 5.5a). The deficiency response of maize to the unfertilized fallow system was attributed to pigeonpea facilitation through nutrient cycling discussed earlier (Chikowo et al., 2004). A similar maize response observed in the unfertilized intercropping treatment (Fig. 5.6a) would represent luxury consumption of nutrients, or a

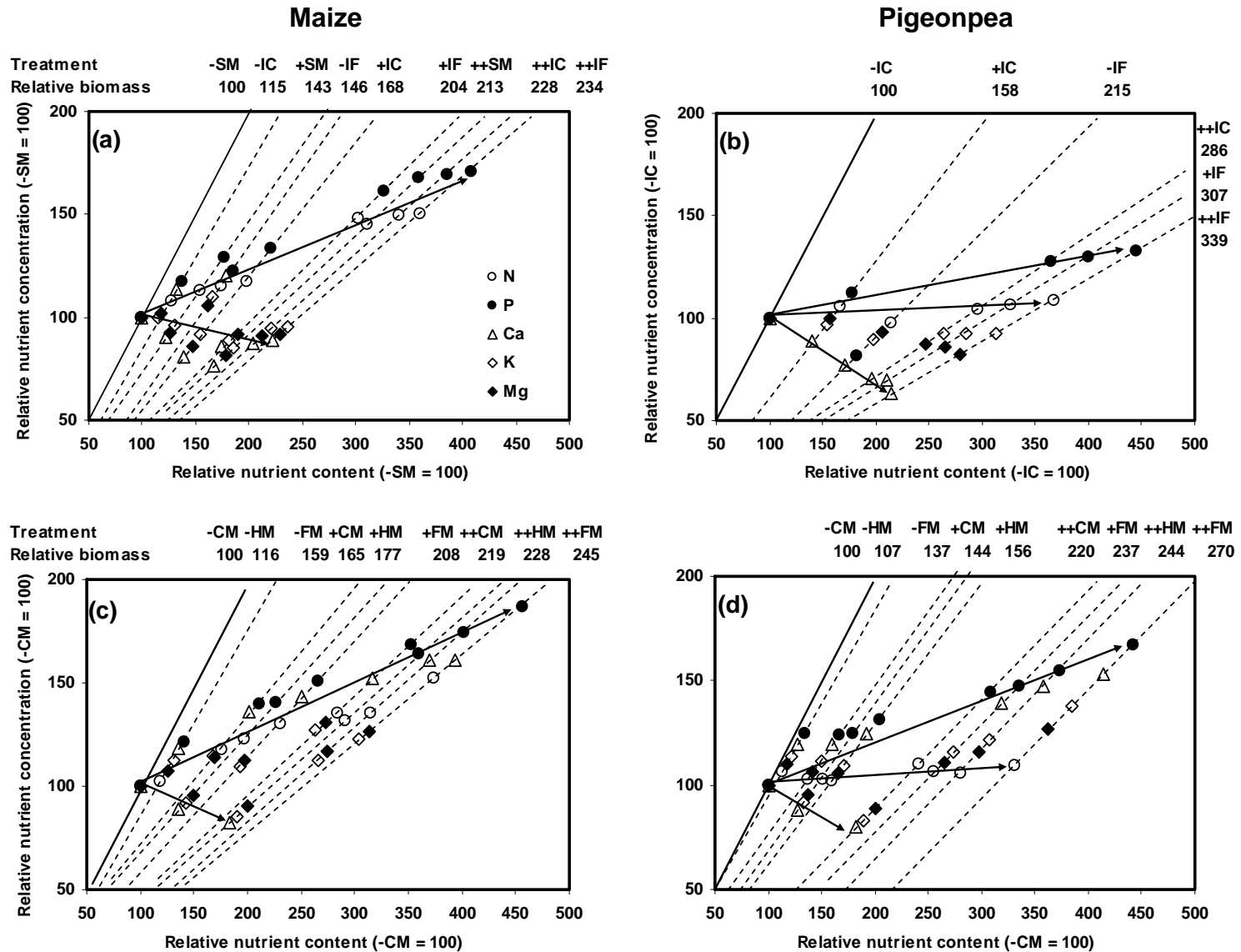


Figure 5.6. Vector diagnosis of the relative change in aboveground biomass, nutrient concentrations and content of maize and pigeonpea in response to cropping systems (a and b) and cattle manure (c and d) without (-), with half (+) or full (++) rates of inorganic fertilizers at Ihumwa, Dodoma, Tanzania. Cropping systems included: SM = Sole maize, IC = Intercropping, and IF = one-year improved fallow. Application rates for cattle manure were: Control (CM) = No manure, Half (HF) = 5 Mg ha<sup>-1</sup>, Full (FM) = 10 Mg ha<sup>-1</sup>; and for inorganic fertilizers were: Control (-) = No fertilizer, Half (+) = 40 kg N ha<sup>-1</sup> and 20 kg P ha<sup>-1</sup>, Full (++) = 80 kg N ha<sup>-1</sup> and 40 kg P ha<sup>-1</sup>. Responses are relative to controls (-SM, -CM and -IC) that were normalized to 100. To minimize clutter, only the largest vector (arrow) for each nutritional response is drawn. See Table 5.4 for statistically different vectors (treatments).

non-nutrient limitation because biomass yield between these treatments did not differ statistically (Table 5.4). Inorganic N and P fertilizers improved pigeonpea biomass and N content without changes in N concentrations relative to unfertilized intercropping (Fig. 5.6b) typifying a sufficiency response (Shift B, Salifu and Timmer, 2003). This response may imply that the N demand of pigeonpea was mainly met through biological fixation, thereby requiring little or no external inputs since the initial soil status N (0.03 %) was low for crop production. However, a previous study in semi-arid India suggests that pigeonpea can suffer N deficiency when intercropped with soybean on N-deficient sites (Ghosh et al., 2006).

In addition to P deficiency, vector diagnosis of maize and pigeonpea response to inputs of cattle manure and fertilizer showed that Ca was likely the second limiting nutrient for plant growth, as illustrated by comparative vector length (Fig. 5.6c and d). At the full rate of manure and fertilizer applications, relative increases in concentration (63 % and 53 %), content (293 % and 314 %) and biomass yields (145 % and 170 %) of maize and pigeonpea associated with Ca ranked second after P responses. Calcium deficiency noted here was attributed to the effects of high soil acidity (pH = 4.6) and exchangeable aluminum ( $0.98 \text{ cmol kg}^{-1}$ ) on Ca availability. In strong acidic conditions (pH < 5), cations may be released into soil solution due to displacement from the exchange sites on soil particles and root cell membranes by hydrogen or aluminum ions (Marscher, 1995; Brady and Weil, 2004), which in turn may promote loss through leaching. Manure also increased concentration and uptake of other nutrients, except for treatments with N and P fertilizers alone (without manure addition). These responses reflected the effects of multiple nutrient compositions of cattle manure (Table 5.1). Decreased concentration of K, Mg, and Ca accompanied with increased uptake and biomass yield in fertilizer treatments without manure (Fig 5.6c and d) indicate growth dilution due to stimulated biomass increase after fertilization.

#### **5.4 Conclusions**

Yield and nutritional interactions between maize and pigeonpea under intercropping (simultaneous) and improved fallow (sequential) systems with and without fertilizer or manure additions

were evaluated for two cropping seasons. Intercropping did not increase maize grain yield over sole maize except when fertilized with half rates of N and P fertilizers implying that nutrient competition suppressed yield of intercropped maize. On the other hand, improved fallows with or without fertilization enhanced yields of maize and pigeonpea compared to the unfertilized sole maize. This increase was mainly associated with combined effects of pigeonpea facilitation through nutrient replenishment and reduced competition for soil nutrients and/or moisture by sequential cropping arrangements. Significant treatment interaction effects on maize and pigeonpea yields were also observed between cattle manure and N and P fertilizers. Apparently, low P inputs from the pigeonpea crop and cattle manure were the main reason for these positive interactions since cropping systems or manure application supplied adequate levels of N. Maize and pigeonpea yields under cropping systems or after manure addition increased with higher fertilizer rates. Combining the half fertilizer rate and the one-year improved fallow or the full rate of cattle manure may be sufficient to optimize maize and pigeonpea production because yields associated with these treatments were similar to those found in treatment combinations at full recommended fertilizer rates. However, considering additional yields of grain and fuelwood from pigeonpea, improved fallows may be attractive to smallholder farmers for enhancing farm productivity compared to using bulky low P-content manure.

Vector competition analysis revealed antagonistic nutrient competition between maize and pigeonpea when intercropped without fertilization that was associated with inherently low soil fertility. As a result, biomass and grain yields of unfertilized pigeonpea under intercropping were decreased by 60 % and 33 %, respectively. Overcoming nutrient competition would involve addition of full rates of N and P fertilizers when intercropping. However, improved fallows may reduce fertilizer applications by half without adversely affecting crops yields due to alleviating interspecific competitions through sequential cropping arrangements. Vector diagnosis depicted multiple nutrient deficiency responses, especially for low P and Ca attributed to high soil acidity and exchangeable aluminum. Nitrogen application to pigeonpea may not be necessary even on this N-poor site because the legumes responded weakly to N additions reflecting self-sufficiency through biological fixation. This study has demonstrated that the

intercropped pigeonpea may not recover from interspecific competition even after maize harvesting possibly due to earlier depletion of nutrients and/or moisture by maize. Consequently, suppressed grain yield of pigeonpea grown simultaneously in mixture suggests that improved fallows utilizing sequential cropping may be more effective than intercropping systems in sustaining both maize and pigeonpea yields.

## CHAPTER 6

### SYNTHESIS: A PLEA FOR GREATER USE OF SEQUENTIAL AGROFORESTRY SYSTEMS IN SEMI-ARID LANDS

#### 6.0 Introduction

Previous chapters focused on the production function of agroforestry as reflected by fuelwood supply (Chapters 3), soil nutrient replenishment, increased maize and pigeonpea yields (Chapters 4 and 5), and mitigation of interspecific interactions through additions of fertilizer and/or manure as well as sequential cropping arrangements (Chapter 5). In this chapter, I will reanalyze results of woody biomass and soil carbon (Chapters 3 and 5) to assess fuelwood characteristics of tree species, the potential of tree species to meet wood demand for firewood and charcoal at Kitulangalo area, Morogoro and for tobacco curing in Tabora district and estimate carbon stocks and sequestration rates of tree species. The intention here is to demonstrate environmental benefits of sequential agroforestry systems in terms of avoiding deforestation and increasing carbon sequestration in semi-arid areas. This information will contribute to recent efforts promoting agroforestry for mitigation and adaptation to climate change in the tropics because of the high potential for sequestering carbon and income generation from carbon trading (Montagnin and Nair, 2004; Verchot et al., 2007; Takimoto et al., 2008; Nair et al., 2009). While the emphasis of agroforestry in industrialized countries is on environmental conservation, the major focus of agroforestry in developing countries is on the improvement of soil fertility and production of commodities (Nair et al., 2008, 2009).

The Tanzanian government is promoting participatory forest management programs as one of the strategies to reduce deforestation rate and carbon emission (Zahabu, 2008). While these programs have been in place since mid 1990s, it should be noted that current wood extraction rates in unprotected forests in general (public) land in the country (47 % of total forested land) are not sustainable (Luoga et al., 2002; Malimbwi et al., 2005; Mwampamba, 2007). These forests are susceptible to degradation and overutilization through many forces including high grazing pressures, shifting cultivation, and wildfires



due to lack of proper management and ownership (Zahabu, 2008). However, agroforestry holds high promise to reduce such degradation through intensification of agriculture and on-farm fuelwood supply to minimize harvesting pressure and agricultural expansion (Dixon et al., 1995; Nyadzi et al. 2003a) while sequestering atmospheric carbon (Montagnini and Nair, 2004; Oilbermann et al., 2004, Nair et al., 2009). On-farm wood production may also reduce the risk of *leakage* (i.e., the possibility that forest conservation in one area could stimulate deforestation in another area to satisfy wood demand) associated with forest-based carbon sequestration strategies (Zahabu, 2008). In this way agroforestry practices may contribute to mitigating the impacts of climate change while enhancing incomes of smallholder farmers when the market for carbon sequestered through agroforestry becomes available (Nair et al. 2008; Verchot et al., 2007). This market can be created in the future through the proposed post-Kyoto carbon trading scheme known as Reducing Emissions from Deforestation and forest Degradation (REDD) (Swallow et al., 2007), which is also advocated in Tanzania (Zahabu, 2008).

Early studies promoting agroforestry as a carbon management tool focused on carbon-rich multistrata agroforestry systems in the humid tropical forest margins (Palm et al., 2004). However, there is large proportion of marginal and degraded land in semi-arid areas that may sequester carbon if converted to agroforestry land use systems to maintain or enhance tree/shrub cover and restore soil productivity (Lal, 2003; Vagen et al., 2005). Yet little is known on carbon sequestration potential of agroforestry systems in semi-arid Africa (Takimoto et al., 2008). Objectives of this chapter are to assess the effects of tree fallows on the amount and accumulation rate of carbon in wood and soils, and to evaluate the adoption potential of agroforestry systems for wood production in terms of land availability in semi-arid Tanzania.

## **6.1 Methodology**

As mentioned earlier, subsistence tobacco farmers, charcoal burners, and rural communities in Tanzania mainly depend on unprotected forests for wood supply (Luoga, 2000; Ramadhani et al., 2002; Sauer and Abdalla, 2007). Hence the first part of this chapter will focus on tobacco curing and woodfuel

scenarios to demonstrate the possible contribution of agroforestry in avoiding deforestation through on-farm wood production. Based on published information, I estimated or adapted annual wood demand and area of forest cleared annually to supply wood for fuelwood (6,960 m<sup>3</sup> yr<sup>-1</sup> and 417 ha yr<sup>-1</sup>) and charcoal (27,896 m<sup>3</sup> yr<sup>-1</sup> and 1671 ha yr<sup>-1</sup>) at Kitulangalo area, Morogoro (Luoga et al., 2000; Luoga et al., 2002) and for tobacco curing (4,551 Mg yr<sup>-1</sup> and 8,675 ha) in Tabora district (Ramadhani et al., 2002). A corresponding area of farmland required to produce wood to meet this demand was estimated based on biomass yields of tree species (Fig. 3.4) and the published wood basic density values (Table 2.1). The estimated size of farmland for each tree species was scaled down to the household level to assess feasibility of adopting rotational woodlot systems for wood supply in terms of availability of land. This approach employed secondary data on percentage of small-scale tobacco farmers (60 % of the population) in Tabora district (Ramadhani et al., 2002) and the population size (4,640 people) of Kitulangalo area (Luoga et al., 2000). Basic density of tree species was used to convert biomass to volume since this was the unit commonly used to report productivity and extraction rates of wood in the native forests. Fuel value index for tested species was calculated as a ratio of wood density (kg m<sup>-3</sup>) to moisture content (%). This index was then employed to assess fuelwood characteristics of tree species as described by Abbot and Lowore (1999). There were no published data on wood basic density for pigeonpea. Therefore, the analysis of pigeonpea-based agroforestry systems (Chapter 5) was limited to carbon sequestration alone. Carbon in wood was determined as 50% of oven dry weight of stem and branches of sampled trees and the value extrapolated to one hectare. Percent soil organic carbon was converted to Mg ha<sup>-1</sup> based on bulk density and mass of the soil within the top 15 cm depth (Chapter 3).

## **6.2 Results and discussion**

### **6.2.1 Reducing deforestation through on-farm wood supply**

#### **6.2.1.1 Tobacco farming scenario**

Land area under rotational woodlot that may be required to produce wood for curing tobacco is presented in Table 6.1. Considering wood yields of tree species (Fig. 3.4) less area per year would be

Table 6.1. Estimated land area under rotational woodlot systems needed to produce wood for fuelwood and charcoal supply in Morogoro and tobacco curing in Tabora, Tanzania

Tree species	Land area to be planted annually (ha)					
	Tobacco		Fuelwood		Charcoal	
	District <sup>1</sup>	Household	Village	Household	Village	Household
<i>Acacia crassicaarpa</i>	5439	0.24	80	0.09	319	0.34
<i>Acacia mangium</i>	7363	0.32	105	0.11	422	0.45
<i>Acacia polyacantha</i>	7714	0.33	136	0.15	546	0.59
<i>Gliricidia sepium</i>	9528	0.41	117	0.13	469	0.51
<i>Acacia nilotica</i>	11956	0.52	210	0.23	841	0.91

<sup>1</sup>No published data for tobacco yield at the village level.

needed for *A. crassicarpa* (5,439 ha), *A. mangium* (7,363 ha), and *A. polyacantha* (7,714 ha) compared to 8,675 ha of the native Miombo woodlands cleared annually for tobacco curing in Tabora district (Ramadhani et al., 2002). Utilizing less productive species such as *A. nilotica* for wood supply could exert more pressure on land than extracting wood from native forests (Table 6.1). However, these species may also reduce harvesting pressure on the Miombo woodlands since woodlots may be established on unutilized or marginal agricultural lands to restore soil fertility and enhance wood and crop yields (Chapters 3 and 4). Average farm size in Tabora and Iringa (the main tobacco growing regions in Tanzania) are 20 ha and 4.3 ha, respectively, most of which is uncultivated probably due to soil degradation and limited labour or capital (Snapp et al., 2002). In these regions small-scale farmers allocate one hectare of their farms for tobacco farming (Ramadhani et al., 2002; Sauer and Abdallah, 2007). These studies suggest that there is adequate land and labour resources for intercropping tobacco and trees on at least 0.24 – 0.52 ha of the farm annually to establish the rotational woodlot system to produce wood for curing tobacco (Table 6.1). Depending on labour availability, this system may also be established on the unutilized marginal areas of the field to restore soil fertility and enhance post-fallow crop yield (Chapters 3 and 4).

Average wood volume for Miombo woodlands in Iringa, Tanzania is  $17.5\text{m}^3\text{ ha}^{-1}$ , which is sufficient to cure one megagram (1Mg) of tobacco (Sauer and Abdalla, 2007). Based on this estimate, wood from one hectare of the tested tree species (Fig. 3.4) would cure 2 – 5 Mg of tobacco reflecting higher productivity of the intensively managed planted tree fallows compared to native Miombo forests (Chapter 3). Wood biomass produced by a 5-year old *A. crassicarpa* ( $51\text{ Mg ha}^{-1}$ ) in Morogoro (Fig. 3.4) was comparable to the yield ( $35.0 - 56.4\text{ Mg ha}$ ) of this species reported for on-farm experiments in Tabora, Tanzania after five years (Nyadzi et al, 2003a). In spite of likely differences on soil and climatic conditions, these results suggest that clearance of large areas of native forests for wood supply could be avoided if tobacco farmers in Tanzania would adopt rotational woodlot systems to meet the wood demand for curing tobacco and other uses, as described in the following section.

### 6.2.1.2 Woodfuel scenario

Fuelwood and charcoal are the main form of woodfuel providing cooking energy in both rural and urban communities in Tanzania (Mwampamba, 2007). Table 6.1 also indicates estimated land area needed to produce wood from rotational woodlot systems to meet annual demand for fuelwood and charcoal at Kitulangalo village, Morogoro. As expected, fast growing tree species required comparatively less land than slow growing tree species. For example, planting 80 ha and 319 ha of *A. crassicarpa* yearly would be sufficient to supply fuelwood and charcoal, respectively to the entire population of Kitulangalo village. Corresponding areas for *A. polyacantha* and *A. nilotica* would be two and three times higher (Table 6.1) due to low biomass yield (Fig. 3.4).

Approximately 417 ha year<sup>-1</sup> of the communal Miombo forest in Kitulangalo are cleared for fuelwood collection, and 1671 ha year<sup>-1</sup> for charcoal production (Luoga et al., 2000). Thus, about 2, 088 ha of native forests may be conserved annually if 399 – 683 ha (Table 6.1) of highly productive species would be planted to meet wood demand for both fuelwood and charcoal. Depending on tree species, one hectare of the rotational woodlot system could protect up to 5 ha of Miombo woodlands that are cleared each year for fuelwood and charcoal, consistent with previous estimates of 5 – 20 ha (Dixon, 1995). To achieve this target each household would plant 0.4 – 1.1 ha per year depending on species choice by farmers (Table 6.1). This area is smaller than the average land holding per family (4.3 ha and 20 ha) mentioned earlier (Ramadhani et al., 2002; Sauer and Abdalla, 2007). However, tree species of high calorific value and basic density as well as low content of moisture and ash are preferred by farmers for fuelwood and charcoal making (Abbot and Lowore, 1999; Shanavas and Mohan Kumar, 2003; Malimbwi et al, 2005). These qualities are discussed in the next section to evaluate energy value of tree species based of fuel value index, the commonly used variable for comparing fuelwood characteristics of tree species (Abbot and Lowore, 1999; Shanavas and Mohan Kumar, 2003).

### 6.2.1.3 Moisture content and fuel value index

Percent moisture content varied significantly ( $p = 0.003$ ) among tree species (Table 6.2) presumably reflecting differential water content in plant tissues (Shanavas and Mohan Kumar, 2003). Generally, moisture content is negatively correlated with calorific value of wood. Moisture content may indirectly influence the choice of tree species for fuelwood by farmers through its effects on weight of firewood, fire temperatures, and ignition time (Fuwape and Akindale, 1997; Abbot and Lowore, 1999; Shanavas and Mohan Kumar, 2003).

Tree species variation in fuel value index (Table 6.2) probably mirrored the influence of moisture content on calorific value because the highest indices (22.4 and 23.8) were associated with the lowest moisture content (27.4 % and 29.4 %). High wood basic density and high concentrations of extractives and lignin in wood have also been reported to increase wood calorific values (Abbot and Lowore, 1999; Shanavas and Mohan Kumar, 2003). Fuel value index for *A. manigum* (Table 6.2) is close to 11.0 noted for this species in the homegarden agroforestry system with tree age ranging from 8 – 23 years (Shanavas and Mohan Kumar, 2003). Indices for *A. polyacantha* and *A. nilotica* (18.3 and 23.8), the tested indigenous species, were also close to the values (16 – 19) reported for the most preferred tree species for fuelwood (*Cobretum apiculatum* Sond, *Pericopsi angolensis* van Meeuwen, and *Combretum molle* R. Br. ex. Don.) in the Miombo woodlands (Abbot and Lowore, 1999). Based on this index, intensively managed indigenous and exotic tree species under rotational woodlot system were similar to the naturally growing tree species in the Miombo forests. Thus the tested species may be used for charcoal or fuelwood production because fuel value index has been found to be a reliable selection criterion for tree species for fuelwood, representing most of the characteristics (e.g. high calorific value) preferred by farmers (Abbot and Lowore, 1999).

Table 6.2. Moisture content and fuel value index of tree species for rotational woodlot systems at Mkundi, Morogoro, Tanzania

Tree species	Moisture content (%)	Fuel value index (FVI) <sup>1</sup>
<i>Acacia crassicarpa</i>	27.4d <sup>2</sup>	22.4a
<i>Acacia mangium</i>	38.8b	14.8bc
<i>Acacia polyacantha</i>	38.4bc	19.2ba
<i>Gliricidia sepium</i>	49.0a	9.8c
<i>Acacia nilotica</i>	29.4cd	23.8a
MSD <sup>3</sup>	9.1	5.4
Probability	0.003	0.0015

<sup>1</sup>FVI = Wood basic density (kg m<sup>-3</sup>)/moisture content (%) (Abbot and Lowore, 1999).

<sup>2</sup>Means within a column followed by the same letter are not statistically different at  $P < 0.05$  according to Tukey's HSD test (n = 3).

<sup>3</sup>Minimum significance difference.

## 6.2.2 Carbon sequestration potential of planted tree and shrub fallows

### 6.2.2.1 Wood carbon

After a 5-year fallow period, carbon in wood (Fig. 6.1a) of *A. crassicarpa* (25.5 Mg C ha<sup>-1</sup>) as well as *A. polyacantha* and *A. mangium* (18.0 and 18.9 Mg C ha<sup>-1</sup>) were respectively higher and close to wood carbon (19.0 – 20.9 Mg C ha<sup>-1</sup>) reported from the protected Miombo woodlands (Williams et al. 2008; Zahabu, 2008). These results demonstrate the high capacity of planted tree fallows to sequester atmospheric carbon compared to native forests in semi-arid areas presumably due to faster growth, larger tree size and more intensive management (Chapter 3). Productivity and hence carbon accumulation in the dry Miombo vegetation may be suppressed by unsustainable wood harvesting, frequent and severe bush fires, and drought (Luoga et al., 2002). However, wood carbon in the intercropped and fallowed pigeonpea (shrubs-based systems) in Dodoma was 0.4 Mg C ha<sup>-1</sup> and 0.7 Mg C ha<sup>-1</sup>, respectively. These amounts are considerably lower than carbon stocks in tree fallows (12 – 25 Mg C ha<sup>-1</sup>) and native Miombo forests (20.9 Mg C ha<sup>-1</sup>) in Morogoro (Zahabu, 2008) due to the combined effects of shorter fallow periods, smaller tree size, and harsh climatic and biophysical conditions.

Wood carbon accumulation rates differed among tree fallows (Table 6.3) and were higher than the annual carbon increment (1.7 – 2.8 Mg C ha<sup>-1</sup> yr<sup>-1</sup>) in the protected Miombo woodlands in Morogoro (Zahabu, 2008). Carbon sequestration rates of tree fallows fall (Table 6.3) within the range (1.50 – 6.55 Mg C ha<sup>-1</sup> yr<sup>-1</sup>) reported for tropical agroforestry systems (Oelbermann et al., 2004; Montagnini and Nair, 2004; Nair et al., 2009). Based on the results of tested species, it will take approximately 4 – 9 years for the tree fallows to recover wood carbon lost by converting native forest reserves containing 20.9 Mg C ha<sup>-1</sup> to agriculture. This period is considerably shorter compared to 2 – 3 decades reported for re-growing Miombo woodlands after cultivation (Williams et al., 2008). These results reflect high productivity of managed systems reported in Chapter 3 and demonstrate the important role that rotational woodlot systems may play in sequestering carbon.



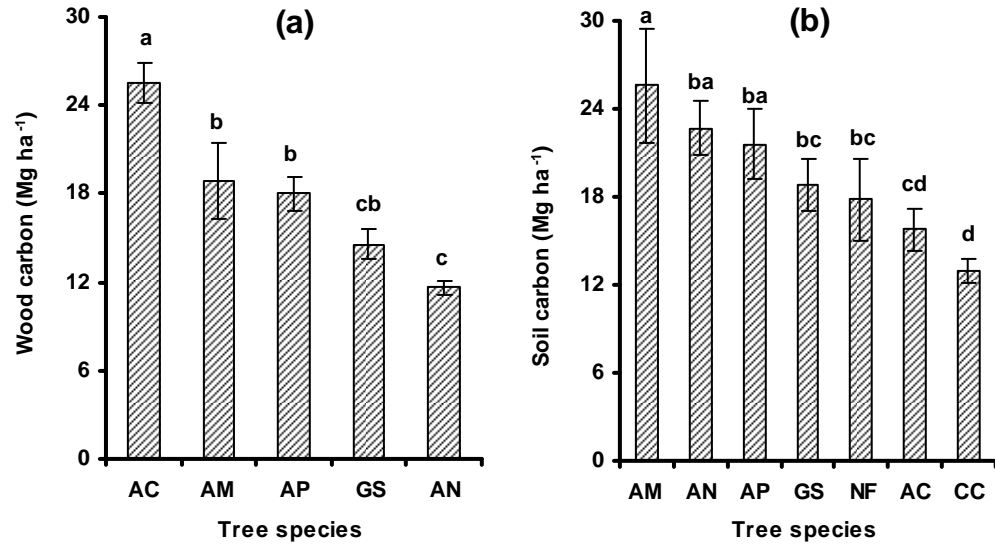


Figure 6.1. Carbon stocks in wood (a) and soils (b) after a 5-year fallow period of rotational woodlot culture at Mkundi, Morogoro, Tanzania. Tree species include: AC = *Acacia crassicarpa*, AM = *Acacia mangium*, AP = *Acacia polyacantha*, GS = *Gliricidia sepium*, AN = *Acacia nilotica*, NF = Natural fallow, and CC = Continuous cropping. For each Figure, means marked by the same letter are not statistically different at  $p < 0.05$  according to Tukey's HSD range test. Vertical bars indicate standard error of means ( $n = 3$ ).

Table 6.3. Carbon accumulation rates (Mg ha yr<sup>-1</sup>) in wood and soils under planted tree fallows in Morogoro, Tanzania

Fallow type	Wood carbon	Soil organic carbon <sup>1</sup>
<i>Acacia crassicaarpa</i>	5.10a <sup>2</sup>	0.55c
<i>Acacia mangium</i>	3.77b	2.52a
<i>Acacia polyacantha</i>	3.60b	1.72ba
<i>Gliricidia sepium</i>	2.91cb	1.16bc
<i>Acacia nilotica</i>	2.32c	1.93ba
Natural grass fallow	-	1.03bc
MSD <sup>3</sup>	1.29	0.88
Probability	0.0007	0.0071

<sup>1</sup>Annual increment based on carbon levels of the continuous cropping treatment

<sup>2</sup>Means within a column followed by the same letter are not statistically different at  $P < 0.05$  according to Tukey's HSD test (n = 3)

<sup>3</sup>Minimum significance difference

### 6.2.2.2 Soil organic carbon

Soil organic carbon after tree fallowing (15.8 – 25.6 Mg C ha<sup>-1</sup>) was significantly higher than organic carbon (13 Mg C ha<sup>-1</sup>) in the continuously cropped soils (Fig. 6.1b). This improvement was attributed to soil organic matter addition from litter and root turnover during the fallow period (Chapter 3). Overall, carbon build up rates in soils by tree fallows were lower than corresponding carbon accumulation rates in wood (Table 6.3), consistent with other agroforestry systems in semi-arid areas (Takimoto et al., 2008). Presumably, a large proportion of carbohydrate production at early tree growth is allocated for aboveground biomass increase. Tree fallowing raised top soil carbon (Fig. 6.1b) above levels obtained within 0 – 30 cm depth of the fallowed Miombo soils (9 – 15 Mg C ha<sup>-1</sup>), but close to levels (14 – 27 Mg C ha<sup>-1</sup>) obtained in the Miombo woodland reserves (Walker and Desanker, 2004).

Another study at Ihumwa, Dodoma (Ngaga et al., 2008) showed that soil organic carbon in the top 20 cm declined by 40 % (i.e., from 0.30 – 0.181%) after three years of continuous maize cropping. However, soil carbon remained unchanged in the pigeonpea fallow treatment (0.31%) and was close to the initial carbon level (0.35%) reported for the Ihumwa site (Section 5.2.1, Chapter 5). These results probably reflect soil carbon maintenance by trees/shrub fallows through root and litter turnover (Tian et al., 2001) and degradation in the continuous maize monoculture system through cultivation and removal of plant residues (Solomon et al., 2000). Although, labile fractions of soil carbon under the rotational woodlot system and pigeonpea fallowing may be lost after clearing the fallows for crop production, it has been shown that stable fractions of soil organic matter are unaffected by hand hoe cultivation during the first three years (Solomon et al., 2000). Hence these systems may not adversely affect soil carbon pools because the recommended length of the post-fallow cropping phase of rotational woodlot systems is three years.

### 6.2.3 Conclusions

Agroforestry systems utilizing fast growing tree species can reduce deforestation and rapidly (in less than 10 years) sequester atmospheric carbon to levels of the natural Miombo forest reserves in semi-

arid areas. On-farm wood supply from one hectare of planted tree fallows may conserve up to 5 ha of the forests that would be cleared annually for fuelwood and charcoal production. As expected, tree-based agroforestry systems such as rotational woodlots are more effective in sequestering carbon than shrub-based (pigeonpea) systems, which may be appropriate for improvement of carbon and nutrients in the soil. Although based on published wood density values, the fuel value indices of the studied tree species were similar to those of the most preferred tree species for fuelwood in the Miombo woodlands, implying that the tested species may have comparable energy values and would most likely be accepted by farmers. Generally, land and labour resources may not be a constraint for adopting the rotational woodlot system on a wider basis since the land requirement is smaller than average household area cultivated annually. Although wood carbon can be released after fuelwood harvesting, it represents amounts that counter increased carbon dioxide emissions from clearing local forests for wood supply or from using fossil fuels. Both rotational woodlot systems and pigeonpea fallowing hold promise to sustain soil organic carbon because stable fractions of soil organic matter are generally unaffected by cultivation and the short (1 – 3 years) post-fallow cropping period. These systems also contained higher soil carbon levels than the continuous maize monoculture system. Of the tested tree species, *A. crassicarpa*, *A. mangium*, and *A. polyacantha* showed the highest capacity to reduce deforestation and sequester carbon. Hence, these species may be useful for mitigating carbon dioxide emission through on-farm wood supply and build up of soil organic matter. Overall, this synthesis calls for a wider use of rotational agroforestry practices in semi-arid lands. These areas have a large proportion of degraded land with high carbon sink strength that can be converted to agroforestry to restore productivity, sequester carbon, and enhance other ecosystem functions.

## CHAPTER 7

### MAJOR CONCLUSIONS AND FUTURE RESEARCH

#### 7.0 Conclusions

This thesis examined nutrient cycling characteristics of tree species and ecological interactions influencing productivity and nutrient dynamics in semi-arid agroforestry systems. Nutrient use efficiency (Chapter 3) and litter quality (Chapter 4) were examined to evaluate the differential impacts of tree species on the recycling, export and availability of nutrients as well as fuelwood supply and maize yield in the rotational woodlot system. I also assessed competitive and facilitative nutrient interactions between pigeonpea and maize to determine the impacts on these interactions on the productivity of pigeonpea intercropping systems (Chapter 5). Results of these studies will hopefully advance the management of the tested sequential agroforestry systems to improve and diversify farm productivity. The following are major conclusions, implications, and recommendations drawn from studies in this thesis.

#### 7.1 On-farm wood supply and associated environmental impacts

Although my results are site-specific, concepts studied have general application to the management of agroforestry systems for fuelwood supply. Rates of biomass production as well as site nutrient removals and restitution are key considerations in planning for sustained productivity of woodlots and short-rotation plantations. The tested tree species showed considerable variations on these aspects. The results in chapter 3 clearly indicated that depending on tree species, the 5-year-old rotational woodlot system produced substantial amounts of wood (23 – 51 Mg ha<sup>-1</sup>), which in turn, may minimize deforestation and carbon emissions from native forests (Chapter 6). Adopting this practice would conserve about 2,088 – 8,675 ha of native forests that are cleared annually to provide wood for fuelwood, charcoal making, and tobacco curing in the Morogoro and Tabora regions alone (Chapter 6). The most productive tree species were Australian acacia species, especially *A. crassicarpa*. Wood yield of this species was close to the values found in other semi-arid sites in both natural and introduced ranges,

implying wide adaptability and high potential for use in other sites. Among the tested indigenous species, *A. polyacantha* grew fastest ranking second in terms of biomass yield. This would represent the locally adapted alternative tree species for on-farm wood supply.

Large amounts of nutrients are withdrawn from the site in harvested biomass. Unlike N which is fixed from the atmosphere, high nutrient export is particularly critical for P and exchangeable cations that are mainly recycled by trees within the soil-plant continuum. Therefore, the knowledge of differential impacts of tree species on nutrient removals and restitutions can help determine the potential impact of on-farm fuelwood supply on site productivity and select appropriate management strategies to conserve site nutrients, especially for impoverished soils. Relative to whole tree harvest, stem wood harvest retained about 20 – 40 % of nutrients on site as slash (Chapter 3). However, further reduction of nutrient loss was achieved by selecting for tree species with low wood nutrient contents. Nutrient use efficiency showed promise as a criterion to identify tree species for this purpose. Employing this criterion to select tree species for rotational woodlot systems reduced nutrient removals (e.g. P, K and Ca) through fuelwood harvesting by 42 – 60 %. I demonstrated in Chapter 3 that by planting the most efficient tree species (*A. crassicarpa*), wood supply could double relative to other species (*A. nilotica*) while removing comparatively low amounts of nutrients from the site. Evidently, nutrient use efficiency criterion can be a useful strategy for optimizing fuelwood supply while sustaining site productivity; hence should be promoted as an index for species selection in rotational woodlot systems. This approach may benefit smallholder farmers who can not afford high costs of inorganic fertilizers and other silvicultural techniques to sustain productivity of woodlots and/or other agroforestry systems that are intensively managed for wood supply. The finding that *A. crassicarpa* achieved the highest biomass yield on this nutrient deficient site would also support the hypothesis that nutrient use efficiency can be used to select tree species for planting on infertile soils due to its high tolerance to low nutrient supply (Hiremath et al., 2002; Scroth et al., 2003).

## 7.2 Soil fertility and post-fallow maize yield

After five years of tree fallowing, soil nutrients in the plow layer (0 – 15 cm) were significantly increased over the natural fallow reflecting the ameliorative capacity of trees mainly by N fixation and nutrient recycling from deep soil layers during the fallow period. The highest soil N levels were found in fallows of *A. polyacantha* and *G. sepium* while *A. mangium* exhibited the greatest ability to replenish soil organic carbon, extractable P, and exchangeable cations (Chapter 3). Results of the litter decomposition study (chapter 4) revealed that residue quality was a controlling factor for nutrient release from litter fall during the fallow period and from slash applied as green manure after fuelwood harvesting which in turn affect the impacts of tree species on post-fallow maize yield. Only high quality leaves of *A. polyacantha* and *G. sepium* induced net N mineralization, whereas all tree species readily released P and K during the 12-week decomposition period. Consequently, the largest increase in post-fallow maize yield relative to the natural fallow was observed after *A. polyacantha* and *G. sepium* fallows that were associated the highest amount of soil N, the most limiting nutrient at this site. However, fallows containing low quality litter, especially *A. mangium*, showed high potential for enhancing soil nutrient retention capacity through build up of organic matter. The contributions of these species in restoring soil productivity will probably increase in longer rotations or in successive short rotations of woodlots, as stable fractions of soil organic matter may not be degraded by hand hoe cultivation during the post-fallow phase (Chapter 6). Thus, in addition to avoiding deforestation and the associated carbon emissions, this agroforestry system offers high potential to sequester atmospheric carbon into the soil. I did not quantify changes of microbial communities, but replenishment of organic matter often may lead to increase in the biological activity and diversity of soil microbes (Brady and Weil, 2004).

Although improvement of soil fertility and crop yield is a secondary benefit from rotational woodlot culture, results in Chapters 3 and 4 suggest that such aspects may also influence the choice of tree species appropriate for this system depending on management objectives. Nutrient efficient tree species such as *A. crassicarpa* were the most productive and suitable for maximizing wood supply on this nutrient poor site. As discussed in Chapter 2, these species depend less on uptake from the soil due to

high retranslocation rate, limiting nutrient recycling to the top soil due to poor litter quality. However, high tolerance to low nutrient supply would help establish these species and restore productivity of marginal and degraded soils while supplying fuelwood. Alternatively, tree species with higher litter quality (*A. polyacantha* and *G. sepium*) would be more beneficial in terms of maximizing post-fallow maize yield due to higher and rapid nutrient recycling capacity. Utilizing these species may reduce the need for inorganic fertilizer inputs that are often too costly for small-scale farmers in sub-Saharan Africa. Fallows of *A. mangium* and *A. polyacantha* produced moderate amounts of wood and maize yield, hence have high potential to optimize both fuelwood and crop production under rotational woodlot. These fallow types would be most beneficial to farmers due to diversification of products. Planting *Acacia nilotica* had a drawback of producing the lowest biomass yield that contained the highest amount of P, raising concerns for rapid depletion of this second most limiting element in tropical soils. Evidently, some tree species may adversely impact site productivity, and should be avoided for planting on degraded soils.

### **7.3 Competition between maize and pigeonpea**

Grain legume (e.g. pigeonpea, cowpea, soybeans, *phaseolus* beans) have been intercropped with cereals (e.g. maize, millet and sorghum) in semi-arid Africa without sufficient background information on the impacts of interspecific competition on the yields of both components. In Chapter 5, I showed that maize and pigeonpea biomass yields were reduced by 30 % and 60 % respectively in mixture when fertilizer was not applied. This would reflect nutrient competition due to inherently low soil fertility. Addition of the full fertilizer rate to intercropping systems or the half rate to improved fallow culture would overcome such competition, and optimize yields of both maize and pigeonpea. For farmers who traditionally mix these crops to diversify food and income sources, adopting the improved fallow system will ensure sustained and increased yield as well as financial benefits while reducing fertilizer use by half. Apparently, intercropping maize and pigeonpea may be inevitable in areas with scarcity of arable land. Under this circumstance final yield of each component can be compromised, but overall system productivity may be similar or higher than that of maize monoculture only when additional yields from



pigeonpea are considered. Comparatively, pigeonpea is a weak competitor in mixture due to its slower initial growth rate than maize. Theoretically, harvesting maize was expected to reduce competition and possibly stimulate growth of intercropped pigeonpea to compensate for impaired early growth. My results, however, did not support this temporal compatibility hypothesis possibly due to the combined effects of earlier nutrient depletion (especially for P) by maize and/or drought conditions during the offseason. Thus, farmers may face high risk of productivity decline when intercropping maize and pigeonpea, especially on P deficient soils and during years of low precipitation.

The study site in the Morogoro region was N deficient and experienced less seasonal precipitation changes (Chapters 3 and 4) compared to the Dodoma site (Chapter 5). These conditions probably accounted for the higher soil fertility improvement observed under tree fallows compared to continuous maize cropping practices. In contrast, the facilitative effects of leguminous shrub species (pigeonpea) in the Dodoma region were probably suppressed by the combined effects of P limitation as well as low and sporadic rainfall distribution patterns (Chapter 5). This was noted by similar maize yields found under unfertilized intercropping compared to the sole maize treatment, which would underscore the need for combined application of organic and inorganic (i.e., inorganic P) nutrient sources advocated under the integrated nutrient management approach (Chapter 2, section 2.1). Often P replenishment by agroforestry trees and shrubs is limited by high fixation and low mobility of this element in acidic soils, as well as low foliar P concentration in the vegetation, such that external P inputs by farmers are necessary to sustain crop yield (Smithson and Giller, 2002).

#### **7.4 Recommendations**

In areas with acute fuelwood scarcity, highly productive and nutrient-efficient tree species such as *A. crassicarpa* should be given high priority for planting in woodlots to maximize and sustain on-farm wood production. Alternatively, *A. mangium* and *A. crassicarpa* can be used to optimize food and crop production under rotational woodlot systems. Further research on mixed-species fallows and carbon sequestration of this system is proposed to provide a wide array of species choice and benefits to farmers.

Planted tree fallows are highly recommended for both on-farm wood supply and carbon sequestration purposes in semi-arid regions with a large proportion of marginal lands that can be converted to agroforestry.

Improved fallows of leguminous shrubs such as pigeonpea with the half prescribed rate of N and P fertilizers are recommended for optimizing maize and pigeonpea yields on P-deficient and drought prone-sites. Future work should evaluate fertilizer requirements of this system on N-deficient sites and include other combinations of cereal and grain legume crops common in the tropics.

### **7.5 Future research**

In this thesis, I have screened tree species for on-farm wood supply and soil fertility improvement as well as elucidated mechanisms of interspecific competition and facilitation in sequential agroforestry systems under semi-arid conditions. However, the following biophysical questions necessitate further studies.

Research on rotational woodlot systems was limited to one rotation to fall within the duration of my PhD program. Previous studies evaluating the role of nutrient use efficiency in sustaining productivity of short-rotation plantations and woodlots (Wang et al., 1991; Kumar et al., 1998; Safou-Matondo, 2005) were also based on first-rotation data possibly due to limited opportunity in forestry to carry out such studies over several rotations (Evans and Turnbull, 2004). Therefore, the long-term impacts of on-farm wood production utilizing fast growing nutrient-efficient tree species on site productivity should be undertaken to corroborate and extend the conclusions drawn from short-term studies.

There is a likely trade-off between wood and crop production under rotational woodlot culture. This notion stems from observations that nutrient-efficient tree species produced the highest wood yield, but the lowest amounts of post-fallow soil nutrients and maize yield because of poor litter quality. Although the primary objective of rotational woodlot systems is to increase wood supply (Ramadhani et al., 2002; Nyadzi et al., 2003a), further investigation is required to determine whether mixed-species fallows of contrasting litter quality can optimize the yields of both wood and crop plants. Such tree

fallows may have significant advantages of increasing biodiversity, enhancing ecosystem functions (nutrient recycling, carbon sequestration, etc), and becoming popular in areas with limited land and labour resources.

It was noted in the synthesis chapter that rotational woodlots may store substantial amount of carbon in biomass and soils. This analysis, however, was based on carbon stocks in the aboveground biomass and the top 0 – 20 cm soil depth alone because my research assessed soil fertility changes at the plow layer. Future work should assess carbon stored in the subsoil horizons, evaluate factors influencing stabilization of soil carbon, and analyze economic benefits of managing sequential agroforestry systems for carbon sequestration in semi-arid areas.

The site for pigeonpea intercropping system was deficient of P. Future research should be conducted on N-deficient site to evaluate the role of biological N fixation and/or external input in modifying interspecific nutrient competition. This work may also test other cereal crops (e.g. millet and sorghum) and grain legume crops (beans and groundnuts) that are widely intercropped in semi-arid tropics, but have different morphological and physiological features from the tested crops.

## REFERENCES

- Abbot, P.G. and J.D. Lowore. 1999. Characteristics and management potential of some indigenous firewood species in Malawi. *For. Ecol. Manage.* 119: 111–121.
- Akanvou, R., M.J. Kropff, L. Bastiaans and M. Becker. 2002. Evaluating the use of two contrasting legume species as relay intercrop in upland rice cropping systems. *Field Crop Res.* 74, 23-36.
- Alegre, J.C., M. R. Rao, L.A. Arevalo, W. Guzman and M. D. Faminow. 2005. Planted tree fallows for improving land productivity in the humid tropics of Peru. *Agric. Ecosyst. Environ.* 110: 104 – 117.
- Ali, M.S., R.E. Malimbwi and S. Iddi. 1997. Comparison of volume production, basic density and stem quality between *A. mangium* and *A. auriculiformis* grown in Zanzibar. *J. Tropical For. Sci.* 10: 10 – 17.
- Anderson, J. M. and J.S.I. Ingram. 1993. *Tropical Soil Biology and Fertility: A Handbook of Methods.* 2<sup>nd</sup> ed. C.A.B. International. 221 p.
- Baggie, I., D.L. Rowell, J.S. Robinson and G.P. Warren. 2004. Decomposition and phosphorus release from organic residues as affected by residual quality and added inorganic phosphorus. *Agrofor. Syst.* 63: 125 – 131.
- Barrios, E., J.G. Cobo, I. M. Rao, R. J. Thomas, E. Amézquita, J.J. Jiménez and M.A. Rondón. 2005. Fallow management for soil fertility recovery in tropical Andean agroecosystems in Columbia. *Agric. Ecosyst. Environ.* 110: 29 – 42.
- Barrios, E., F. Kwesiga, R.J. Buresh and J.I. Sprent. 1997. Light fraction soil organic matter and available nitrogen following tree and maize. *Soil Sci. Soc. Am. J.* 61: 826 – 831.
- Biran, A., J. Abbot and R. Mace. 2004. Families and Firewood: A comparative analysis of the costs and benefits of children in firewood collection and use in two rural communities in Sub-Saharan Africa. *Human Ecology* 32: 1-25.
- Brady, N.C. and R.R. Weil. 2004. 2<sup>nd</sup> ed. *Elements of the nature and properties of soils.* Person Education, Inc. Upper Saddle River New Jersey, USA, 606 p.
- Buresh, R.J. and G. Tian. 1998. Soil improvement by trees in Sub-Saharan Africa. *Agrofor. Syst.* 38: 51-76.
- Burgers, P., Q.M. Ketterings and D.P. Garrity. 2005. Fallow management strategies and issues in Southeast Asia. *Agric. Ecosyst. Environ.* 110: 1 – 13.
- Chamshama, S. A. O., A. G. Mugasha, A. A. Kimaro and M. Ngegba. 2006. Agroforestry technologies for semi-arid and sub-humid areas of Tanzania: an overview. pp 65 – 81. In: Chamshama, S.A.O., L. Nshubemuki, S. Idd, R.E Swai, M.L. Mhando, E. Sabas, C. Balama, L. Mbwambo and M.A. Mndolwa (eds), *Proceeding of the Second National Agroforestry and Environment Workshop: Partnership and Linkages for Greater Impact in Agroforestry and Environmental Awareness.* 14 – 17 March 2006, Mkapa Hall, Mbeya Tanzania.

- Chikowo, R. P. Mapfumo, P. Nyamugafata and K.E. Giller. 2004. Woody legume fallow productivity, biological N<sub>2</sub>-fixation and residual benefits to two successive maize crops in Zimbabwe. *Plant Soil* 262, 303-315.
- Chikowo, R., P. Mapfumo, P.A. Leffelaar and K.E. Giller. 2006. Integrating legume to improve N cycling on smallholder farms in sub-humid Zimbabwe: resource quality, biophysical and environmental limitations. *Nutr. Cycl. Agroecosyst.* 76: 219 – 231.
- Chirwa, P.W., C.R. Black, C. K. Ong and J. Maghembe. 2006. Nitrogen dynamics in cropping systems in southern Malawi containing *Gliricidia sepium*, pigeonpea and maize. *Agrofor. Syst.* 67, 93-106.
- Chirwa, T.S., P.L. Mafongoya and R. Chintu. 2003. Mixed planted-fallows using coppicing and non-coppicing tree species for degraded Acrisol in eastern Zambia. *Agrofor. Syst.* 59: 243 – 251.
- Dean, A. and D. Voss. 1999. *Design and Analysis of Experiments*. Springer-Verlag New York, Inc. 740p
- Dixon, R. K. 1995. Agroforestry system: sources or sinks of greenhouse gases? *Agrofor. Syst.* 31: 99-116.
- Dondeyne, S., A. Wijffels, L.B. Emmanuel, J. Deckers and M. Hermy. 2004. Soils and vegetation of Angai forest: Ecological insights from a participatory survey in South eastern Tanzania. *Afr. J. Ecol.* 42: 198 – 207.
- Doran, J.C., J.W. Turnbull, P.N. Martensz, L.A.J. Thomson and N. Hall. 1997. Introduction to the species' digests. 89 - 384pp. In Doran, J.C. and Turnbull, J.W. (eds.), *Australian Trees and Shrubs: species for land rehabilitation and farm planting in the tropics*. ACIAR Monograph No. 24, viii.
- Drinkwater, L.E. and S.S. Snapp. 2007. Nutrients in agroecosystems: rethinking the management paradigm. *Advances in Agronomy* 92: 164 – 186.
- Dudal, R. 2002. Forty years of soil fertility work in Sub-Saharan Africa. In: Vanlauwe, B., J. Diels, N. Sanginga, R. Merckx (eds.), *Integrated plant nutrient management in Sub-Saharan Africa: From concepts to practice*. CABI publishing, Wallingford, UK pp 1 – 21.
- Ek, T. 1994. Biomass structure in Miombo woodland and semi-evergreen forest: Development in 22 permanent plots in Morogoro, Tanzania. M.Sc. Thesis. Agricultural University of Norway, Ås Norway. 53p.
- Evans, J. and J. Turnbull. 2004. *Plantations in the Tropics*. 3<sup>rd</sup> Ed. Oxford University Press, UK 467 p.
- Fölster, H. and P.K. Khanna. 1997. Dynamics of Nutrient Supply in Plantations Soils. In: Nambiar, E.S.K. and Brown, A.G. (Eds.), *Management of Soil, Nutrients and Water in Tropical Plantation Forests*. ACUAR/CSIRO/CIFOR, ACIAR, Canberra, Australia, pp. 339 – 378.
- Franzel, S. 2004. Financial analysis of agroforestry practices. *Advances in Agroforestry*. 2: 9 – 37.
- Franzel, S. and S.J. Scherr. 2002. *Trees on the farm: Assessing the adoption potential of agroforestry practices in Africa*. CABI publishing, Wallingford, UK 197 p.
- Fuwape, J.A. and S.O. Akindele. 1997. Biomass and energy value of some fast-growing multipurpose trees in Nigeria. *Biomass and Bioenergy* 12: 101– 106.

- García-Barrios, L. and C.K. Ong. 2004. Ecological interactions, management lessons and design tools in tropical agroforestry systems. *Agrof. Syst.* 61: 221– 236.
- Garrity, D.P. 2004. Agroforestry and the achievement of the Millennium development Goals. *Agrofor. Syst.* 61: 5 – 17.
- Gathumbi, S. M., G. Cadisch and K. E. Giller. 2004. Improved fallows: Effects of species interaction on growth and productivity in monoculture and mixed stands. *For. Ecol. Manage.* 187: 267 – 280.
- Gathumbi, S.M., G. Cadisch and K.E. Giller. 2002. <sup>15</sup>N natural abundance as a tool for assessing N<sub>2</sub>-fixation of herbaceous, shrub and tree legumes in improved fallows. *Soil Biology and Biochemistry* 34: 1059 – 1071.
- Geist, H.J. and E.F. Lambin. 2002. Proximate causes and underlying driving forces of tropical deforestation. *BioScience* 52: 143 – 149.
- Ghosh, P.K., M. Mohanty, K.K. Bandyopadhyay, D.K. Painuli and A.K Misra. 2006. Growth, competition, yields advantage and economics in soybean/pigeonpea intercropping system in semi-arid tropics of India II. Effect of nutrient management. *Field Crops Res.* 96: 90 – 97.
- Gonclave, J.L.M., J.L. Stape, J-P Laclau, P. Smethurst and J.L. Gava. 2004. Silvicultural effects on the productivity and wood quality of eucalyptus plantations. *For. Ecol. Manage.* 193: 45 – 61.
- Gregoire, N. and R. F. Fisher. 2004. Nutritional diagnoses in loblolly pine (*Pinus taeda* L.) established stands using three different approaches. *For. Ecol. Manage.* 126: 195 – 208.
- Guo, L.B. and R.E.H. Sims. 1999. Litter decomposition and nutrient release in New Zealand eucalyptus short rotation forests. *Agric. Ecosyst. Environ.* 75 (3): 133 – 140.
- Haase, R. and P. Haase. 1995. Above-ground biomass estimates for invasive trees and shrubs in the Pantanal of Mato Grosso, Brazil. *For. Ecol. Manage.* 73: 29 – 35.
- Hatibu N., K. Mutabazi, E.M. Senkondo and A.S.K. Msangi. 2006. Economics of rainwater harvesting for crop enterprises in semi-arid areas of East Africa. *Agricultural Water Management* 80: 74 – 86.
- Hauser, S., C. Nolte and R.J. Carsky. 2006. What role planted fallows play in the humid and sub-humid zone of West and Central Africa? *Nutr. Cycl. Agroecosyst.* 76: 297 – 318.
- Herbert, M., A.G. Mugasha and S.A.O. Chamshama. 2002. Evaluation of 19 provenances of *Calliandra calothyrsus* at Gairo and SUA Farm, Morogoro, Tanzania. *Southern African Forestry Journal* 194: 15 – 26.
- Hiremath, A.J., J.J. Ewel and T.G. Cole. 2002. Nutrient use efficiency in three fast-growing tropical trees. *For. Sci.* 48 : 662 – 672.
- Ikerra S.T., J.A. Maghembe, P.C. Smithson and R.J. Buresh 1999. Soil nitrogen dynamics and relationships with maize yields in a gliricidia–maize intercrop in Malawi. *Plant Soil* 211: 155 – 164.
- Imo, M. and V.R. Timmer. 1998. Vector competition analysis: A new approach for evaluating vegetation control methods in young black spruce plantations. *Can. J. Soil Sc.* 78: 3 – 15.

- Imo, M., V.R. Timmer. 2000. Vector competition analysis of a leucaena-maize alley cropping system in western Kenya. *For. Ecol. Manage.* 126: 255 – 268.
- Isaac, M.E., V.R. Timmer and S.J. Queshie-Sam. 2007. Shade tree effects in an 8-year-old cocoa agroforestry system: biomass and nutrient diagnosis of *Theobroma cocoa* by vector analysis. *Nutr. Cycl. Agroecosyst.* 78: 155 – 165.
- Ishikawa, S., J. J. Adu-Gyamfi, T. Nakamura, T. Yoshihara, T. Wantanabe and T. Watgatsuma. 2002. Genotypic variability in phosphorus solubilizing activity of root exudates by pigeonpea grown in low-nutrient environments. *Plant Soil* 245: 71 – 81.
- Jama, B. A., J. K. Mutegi and A. N. Njui. 2008. Potential of improved fallows to increase household and regional fuelwood supply: evidence from western Kenya. *Agrofor. Syst* 73: 155 – 166.
- Jamaludheen, V. and B. M. Kumar. 1999. Litter of multipurpose trees in Kerala, India: variations in the amount, quality, decay rates and release of nutrients. *For. Ecol. Manage.* 115: 1 – 11.
- Karachi, M., D. Shirima and N. Lemma. 1997. Evaluation of 15 tree leguminous tree and shrubs for forage and wood production in Tanzania. *Agrofor. Syst.* 37: 253 – 263.
- Kelthy, M.J. and I.R. Cameron. 1995. Plot designs for analysis of species interactions in mixed stands. *Commonw. For. Rev.* 74: 323 – 332.
- Kimaro, A.A, V.R. Timmer, A.G. Mugasha, S.O.A. Chamshama and D.A. Kimaro. 2007 Nutrient use efficiency and biomass production of tree species for rotational woodlot systems in Semi-arid Morogoro, Tanzania. *Agrofor. Syst.* 71: 175 – 184.
- Kimaro, A.A, V.R. Timmer, S.O.A. Chamshama, A.G. Mugasha and D.A. Kimaro. 2008. Differential response to tree fallows in rotational woodlot systems: Post-fallow maize yield, nutrient uptake, and soil nutrients. *Agric. Ecosyst. Environ.* 125: 73 – 83.
- Kimaro, A.A, V.R. Timmer, S.O.A. Chamshama, Ngaga, Y.N and D.A. Kimaro. 2009. Competition between maize and pigeonpea in semi-arid Tanzania: effect on yields and nutrition of crops. *Agric. Ecosyst. Environ.* 134: 115 – 125.
- Kitalyi, A., G. Nyadzi, M. Lutkamu, R. Swai and B. Gama. 2009. New climate, new agriculture: How agroforestry contributes to meeting the challenges of agricultural development in Tanzania. *Tanzania Journal of Agricultural Sciences*, *in press*.
- Kityo, P. 2004. Productivity and Utilization of natural fuel wood resources: An evaluation of the current situation in some parts of Gaza Province, Mozambique. M.Sc. Thesis. International Institute of geo-information science and earth observation, Enschede, The Netherlands. 57 p.
- Kumar, B. M., J.G. Suman, V. Jamaludheen and T.K. Suresh. 1998. Comparison of biomass production, tree allometry and nutrient use efficiency of multipurpose trees grown in woodlot and silvopastoral experiments in Kerala, India. *For. Ecol. Manage.* 122: 145 – 163.
- Kwesiga, F., F.K. Akinnifesi, P.L. Mafongoya, M.H. Mcdermott, A. Agumya. 2003. Agroforestry research and development in southern Africa during the 1990s: review and challenges ahead. *Agrofor. Syst.* 59: 173 – 186.

- Lal, R. 2003. Offsetting global CO<sub>2</sub> emissions by restoration of degraded soils and intensification of would agriculture and forestry. *Land Degrad. Develop.* 14: 309 – 322.
- Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science* 304: 1623 – 1626.
- Lehman, J., G. Schroth and W. Zech. 1995. Decomposition and nutrient release from leaves, twigs and roots of the three alley-cropped tree legumes in central Togo. *Agrofor. Syst.* 29: 21 – 36.
- Lehman, J., and G. Schroth. 2003. Nutrient leaching. pp 151 – 166. In: Schroth, G. and Sinclair, F.L. (eds.), *Trees, Crops and Soil Fertility: Concepts and Research Methods* CABI publishing, Wallingford, UK.
- Lojka, B., L. Lojkova, J. Banout, Z. Polesny and D. Preininger. 2008. Performance of an improved fallow system in the Peruvian Amazon – modeling approach. *Agrofor. Syst.* 72: 27 – 39.
- Luhende, R., G. Nyadzi and R.E. Malimbwi. 2006. Comparison of wood basic density and basal area of 5-year-old *Acacia crassicaarpa*, *A. julifera*, *A. leptocarpa*, *Leucaena pallida* and *Senna siamea* in rotational woodlots trials in western Tabora, Tanzania. *NFT News: Improvement and culture of nitrogen fixing trees.* 9: 5 – 6. <http://www.iufro.org/science/divisions/division-2/20000/20800/20802/newsletters/>. Cited on March 10<sup>th</sup>, 2009
- Luoga, E.J., E.T.F. Witkowski and K. Balkwill. 2000. Economics of charcoal production in Miombo woodlands of eastern Tanzania: some hidden costs associated with commercialization of the resources. *Ecol. Econ.* 35: 243 – 257.
- Luoga, E.J., E.T.F. Witkowski and K. Balkwill. 2002. Harvested and standing wood stocks in protected and communal miombo woodlands of eastern Tanzania. *For. Ecol. Manage.* 164: 15 – 30.
- Lupwayi, N.Z., I. Hague, A.R. Sala, D.E.K.A. Siaw. 1999. *Leucaena* hedgerow intercropping and cattle manure application in the Ethiopian highlands II. Maize yields and nutrient uptake. *Biol. Fertil. Soils* 28, 196–203.
- Mafongoya, P.L., A. Bationo, J. Kihara and B.S. Waswa. 2006. Appropriate technologies to replenish soil fertility in southern Africa. *Nutr. Cycl. Agroecosyst.* 76: 137 – 151.
- Mahiri, I.O. 2003. Rural household responses to fuelwood scarcity in Nyando district, Kenya. *Land Degrad. Develop.* 14: 163 – 171.
- Makumba, W., B. Jassen, O. Oenema, F.K. Akinnifesi, D. Mweta and F. Kwesiga. 2006. The long-term effects of a gliricidia-maize intercropping system in Sounthern Maliwi, on gliricidia and maize yields, and soil properties. *Agric. Ecosyst. Environ.* 116: 85 – 92.
- Makundi, W.R. 2001. Potential and cost of carbon sequestration in the Tanzanian forest sector. *Mitig. Adapt. Strat. Glob. Change* 6: 335 – 353.
- Makundi, W.R. and J.A. Sathaye. 2004. GHG mitigation potential and cost in tropical forestry — relative role for agroforestry. *Environ. Dev. Sustain.* 6: 235 – 260.
- Malimbwi, R.E. and E.M. Zahabu. 2008. Woodlands and the charcoal trade: the case of Dar es Salaam City. *Working Papers of the Finnish Forest Research Institute* 98: 93 – 114.



- Malimbwi, R.E., B. Solberg and E. Luoga. 1994. Estimation of biomass and volume in Miombo woodland at Kitulangalo forest reserve, Tanzania. *J. Tropical For. Sci.* 7: 230 – 242.
- Malimbwi, R.E., E.M. Zahabu, S. Misana, G. C. Monela, G. C. Jambiya and B. Mchome. 2005. Charcoal supplying potential of the miombo woodlands: The case of Kitulangalo area, Tanzania. *J. Tropical For. Sci.* 17(2): 197 – 210.
- Marschner, H. 1995. Mineral nutrition of higher plants 2nd<sup>ed</sup>. Academic Press NY. 889 p.
- Montagnini, F. 2000. Accumulation of above-ground biomass and soil storage of mineral nutrients in pure and mixed plantations in a humid tropical lowland. *For. Ecol. Manage.* 134: 257 – 270.
- Montagnini, F. and P.K.R. Nair. 2004. Carbon sequestration: an underexploited environmental benefit of agroforestry systems. *Agrofor. Syst.* 61: 281–295.
- Montagnini, F., C.F. Jordan and R. M. Machando. 2000. Nutrient cycling and nutrient use efficiency in agroforestry systems. In: Ashton, M.S. and F. Montagnini (eds.), *The Silvicultural basis of agroforestry systems*. CRC Press LLC Florida USA. 131 – 160.
- Msanya, B.M, Kaaya, A.K. Araki, S., H. Otsuka and G.I. Nyadzi. 2003. Pedological characteristics, general fertility and classification of some Benchmark soils of Morogoro District, Tanzania. *African J. Science and Technology* 4(2): 101 – 112.
- Mugasha, A.G., S.A.O. Chamshama, K.I. Singo and M.A. Mgangamundo. 2005. Early performance of *Azadirachta indica* provenances at Mkundi and Chamwino, Tanzania. *J. Trop. For. Sci.* 17 (1): 45 – 62.
- Mwampamba, T.H. 2007. Has the woodfuel crisis returned? Urban charcoal consumption in Tanzania and its implications to present and future forest availability. *Energy Policy* 35: 4221– 4234.
- Myaka, F.M, W.D. Sakala, J.J. Adu-Gyamfi, D. Kamalongo, A. Ngwira, R. Odgaard, N.E. Nielsen and H. Høgh-Jensen. 2006. Yields and accumulations of N and P in farmer-managed intercrops of maize–pigeonpea in semi-arid Africa. *Plant Soil* 285: 207 – 220.
- Nair, P. K. R., B. Mohan Kumar and V. D. Nair. 2009. Agroforestry as a strategy for carbon sequestration. *J. Plant Nutr. Soil Sci.* 172: 10 – 23.
- Nair, P.K.R., A.M. Gordon and M.R. Mosquera-Losada. 2008. Agroforestry. In: Jorgensen, S.E. and Fath, B.D. (eds.), *Ecological Engineering, Encyclopedia of Ecology*, Elsevier, Oxford, U.K. 1: 101–110.
- Ngaga, Y.M., S.A.O. Chamshama, A. A. Kimaro and W.E. Kijoti. 2008. Agroforestry technologies for management of soil water and for improving crop and wood yields in Dodoma District, Tanzania. Terminal Research Report for Project No. 012. SUA-NORAD PANTIL program, Sokoine University of Agriculture, Morogoro, Tanzania 24 p.
- Ngulube, M.R. 1993. Evaluation of *Gliricidia sepium* provenances for alley cropping in Malawi. *For. Ecol. Manage.* 64: 191 – 198.
- Ngulube, M.R., G.B.J. Chapola and L. Mwabumba. 1993. The potential of Australian dry zone acacias for agroforestry in Malawi. *For. Ecol. Manage.* 56: 83 – 97.

- Niang, A.I., B.A. Amandalo, J. de Wolf and S.M. Gathumbi. 2002. Species screening for short-term planted fallow in the highlands of Western Kenya. *Agrofor. Syst.* 56: 145 – 154.
- Nyadzi, G.I, B.H. Janssen, R.M. Otsyina, H.W.G. Booltink, C.K. Ong, O. Oenema. 2003b. Water and nitrogen dynamics in rotational woodlots of five tree species in western Tanzania. *Agrofor. Syst.* 59: 215 – 229.
- Nyadzi, G.I, R.M. Otsyina, F.M. Banzi, S.S. Bakengesa, B.M Gama, L. Mbwambo and D. Asenga. 2003a. Rotational woodlot technology in northwestern Tanzania: Tree species and crop performance. *Agrofor. Syst.* 59: 253 – 263.
- Nyathi, P., S.K. Kimani, B. Jama, P. Mapfumo, H.K. Murwira, J.R. Okalebo and A. Bationo. 2003. Soil fertility management in semi-arid areas of Eastern and Southern Africa. pp 219 – 252. In: Gichuru, M.P., A. Bationo, M.A. Bekunda, H.C., Goma, P.L. Mafongoya, D.N. Mugendi, H.M. Murwira, S.M. Nandwa, P. Nyathi and M.J. Swift (eds), *Soil fertility management in Africa: A regional perspective*. Academy Science Publishers, TSBT–CIAT, Nairobi, Kenya.
- Nykvist, N. 2000. Tropical forests can suffer from a serious deficiency of calcium after logging. *Ambio* 29: 310 – 313.
- Oelbermann, M., R.P Voroney and A.M. Gordon. 2004. Carbon sequestration in tropical and temperate agroforestry systems: a review with examples from Costa Rica and southern Canada. *Agric. Ecosyst. Environ.* 104: 359 – 377.
- Okalebo, J.R., K.W. Gathura and P.L. Woomer. 1993. *Labouratory methods of soil and plant analysis. A working manual*. KARI, SSEA, TSBF, UNESCO-ROSTA, Nairobi 88 pp.
- Otsyina, R.M., T. Ramadhani and D. Asenga. 1999. Rotational woodlots: An agroforestry approach to mitigate deforestation and natural resource degradation in Tanzania. *Faculty of Forestry Record* 72: 122 – 130.
- Palm, C. A., T. Tomich, M. van Noordwijk, S. Vosti, J. Alegre, J. Gockowski and L. Verchot. 2004. Mitigating GHG emissions in the humid tropics: Case studies from the Alternatives to Slash-and-Burn Program (ASB). *Environ. Dev. Sustain.* 6: 145 – 162.
- Pretty, J. 2008. Agricultural sustainability: concepts, principles and evidence. *Phil. Trans. R. Soc. B.* 363: 447 – 465.
- Ramadhani, T., R. Otsyina and S. Franzel. 2002. Improving household income and reducing deforestation using rotational woodlots in Tabora district, Tanzania. *Agric. Ecosyst. Environ.* 89 (3): 229 – 239.
- Rao, M.R. and M.N. Mathuva. 2000. Legumes for improving maize yields and income in semi-arid Kenya. *Agric. Ecosyst. Environ.* 78: 123 – 137.
- Rao, M.R., P.K.R. Nair and C.K. Ong. 1998. Biophysical interactions in tropical agroforestry systems. *Agrofor. Syst.* 38: 3 – 50.
- Safou-Matondo, R., P. Deleporte, J.P. Laclau and J.P. Bouillet. 2005. Hybrid and clonal variability of nutrient content and nutrient use efficiency in Eucalyptus stands in Congo. *For. Ecol. Manage.* 210: 193 – 204.

- Sakala, W.D., G. Cadisch and K.E. Giller. 2000. Interactions between residues of maize and pigeonpea and mineral N fertilizer during decomposition and N mineralization. *Soil Biology and Biochemistry* 32: 679 – 688.
- Salifu, F.K. and V.R. Timmer. 2001. Nutrient retranslocation response of *Picea meriana* seedlings to nitrogen supply. *Soil Sci. Soc. Am. J.* 65: 905 – 913.
- Salifu, F.K. and V.R. Timmer. 2003. Optimizing nitrogen loading of *Picea mariana* seedlings during nursery culture. *Can. J. For. Res.* 33: 1287 – 1294.
- Sanchez, P.A. 1999. Improved fallows come of age in the tropics. *Agrofor. Syst* 47: 3 – 12.
- Sanchez, P.A. 2002. Soil fertility and hunger in Africa. *Science* 295: 2019 – 2020.
- Sanchez, P.A. and B. A. Jama. 2002. Soil fertility replenishment takes off in East and Southern Africa. pp 23 – 45. In: Vanlauwe, B., J. Diels, N. Sanginga, R. Merckx (eds.), *Integrated plant nutrient management in Sub-Saharan Africa: From concepts to practice*. CABI publishing, Wallingford, UK.
- SAS Institute Inc. 2000. SAS version 8. Cary NC, USA.
- Sauer, J. and J.M. Abdallah. 2007. Forest diversity, tobacco production and resource management in Tanzania. *For. Policy Econ.* 9: 421 – 439.
- Schroth, G., J. Lehmann and E. Barrios. 2003. Soil nutrient availability and acidity. pp 93 – 130. In: Schroth, G. and Sinclair, F.L. (eds.), *Trees, Crops and Soil Fertility: Concepts and Research Methods* CABI publishing, Wallingford, UK.
- Schulman, G.E., M.A. Stanley and D. Knudsen. 1973. Automated total nitrogen analysis of soil and plant samples. *Soil Sci. Soc. Am. Proc.* 37: 480 – 481.
- Scott, D.A. and T.J. Dean. 2006. Energy trade-offs between intensive biomass utilization, site productivity loss, and ameliorative treatments in loblolly pine plantations. *Biomass Bioenergy* 30: 1001–1010.
- Sebastian, K. 2009. Rule set used to define agroecological zones (AEZ) for Sub-Saharan Africa – 2009. <http://harvestchoice.org/maps-etc/AEZ-rules-SSA-09.pdf>. Cited on April 6<sup>th</sup>, 2009.
- Sekiya, N. and K. Yano. 2004. Do pigeon pea and sesbania supply groundwater to intercropped maize through hydraulic lift? – Hydrogen stable isotope investigation of xylem waters. *Field Crop Res.* 86: 167 – 173.
- Shanavas, A. and B. Mohan Kumar. 2003. Fuelwood characteristics of tree species in homegardens of Kerala, India. *Agrofor. Syst.* 58: 11 – 24.
- Shanavas, A. and B.M. Kumar. 2003. Fuelwood characteristics of tree species in homegardens of Kerala, India. *Agrofor. Syst.* 58: 11 – 24.
- Shibata, R. and Y. Katsuya. 2003. Phosphorus requisition from non-labile source in peanut and pigeonpea with mycorrhizal interaction. *Appl. Soil Ecol.* 24: 133 – 141.

- Shujauddin, N. and B.M. Kumar. 2003. *Ailanthus triphysa* at different densities and fertilizer regimes in Kerala, India: growth, yield, nutrient use efficiency and nutrient export through harvest. For. Ecol. Manage. 180: 135 –151.
- Sileshi, G., F.K. Akinnifesi, O.C. Ajayi, S. Chakeredza, M. Kaonga and P.W. Matakala. 2007. Contribution of Agroforestry to ecosystem services in the Miombo eco-region of eastern and southern Africa. African J. Environmental Science and Technology 4: 68 – 80.
- Sinclair, T.R. and V. Vadez. 2002. Physiological traits for crop yield improvement in low N and P environments. Plant Soil 245: 1 – 15.
- Smithson, P.C. and K.E. Giller. 2002. Appropriate farm management practices for alleviating N and P deficiencies in low-nutrient soils of the tropics. Plant Soil 245: 169 – 180.
- Snapp, S.S., D.D. Rohrbach, F. Simtowe and H.A. Freeman. 2002. Sustainable soil management options for Malawi: can smallholder farmers grow more legumes? Agric. Ecosyst. Environ. 91: 159 – 174.
- Solomon, D., J. Lehmann and W. Zech. 2000. Land use effects on soil organic matter properties of chromic luvisols in semi-arid northern Tanzania: carbon, nitrogen, lignin and carbohydrates. Agric. Ecosyst. Environ. 78: 203 – 213.
- Sprugel, D. G. 1983. Correcting for bias in log-transformed allometric equations. Ecology 64, 209 – 210.
- Sunderlin, W.D. and J. Pokam. 2002. Economic crisis and forest cover change in Cameroon: The roles of migration, crop diversification, and gender division of labour. Econ. Develop. Cultural Change 50: 581 – 606.
- Swallow, B, M. van Noordwijk, S. Dewi, D. Murdiyarso, D. White, J. Gockowski, G. Hyman, S. Budidarsono, V. Robiglio, V. Meadu, A. Ekadinata, F. Agus, K. Hairiah, P.N. Mbile, D.J. Sonwa and S. Weise. 2007. Opportunities for Avoided Deforestation with Sustainable Benefits. An Interim Report by the ASB Partnership for the Tropical Forest Margins. ASB Partnership for the Tropical Forest Margins, Nairobi, Kenya. 42 p.
- Takimoto, A., P.K.R. Nair and V.D. Nair. 2008. Carbon stock and sequestration potential of traditional and improved agroforestry systems in the West African Sahel. Agric. Ecosyst. Environ. 125: 159 – 166.
- Thor Smestad, B., H. Tiessen and R.J. Buresh. 2002. Short fallows of *Tithonia diversifolia* and *Crotalaria grahamiana* for soil fertility improvement in western Kenya. Agrofor. Syst. 55: 181 – 194.
- Tian, G., F.K. Salako and F. Ishida. 2001. Replenishment of C, N, and P in a degraded Alfisol of fallow species and litter polyphenols. Soil Science 166: 614 – 621.
- Ussiri, D.A, P.N.S. Mnkeni, A.F. Mackenzie and J.M.R. Semoka. 1998. Soil test calibration studies for formulation of phosphorus fertilizer recommendations for maize in Morogoro district, Tanzania. II. Estimation of optimum fertilizer rates. Commun. Soil Sci. Plant Anal. 29: 2815 – 2828.
- Vagen T.G., R. Lal and B.R Singh. 2005. Soil carbon sequestration in Sub-Saharan Africa: A review. Land Degrad. Develop. 16: 53 – 71.

- Vanlauwe, B. and K.E. Giller. 2006. Popular myths around fertility management in sub-Saharan Africa. *Agric. Ecosyst. Environ.* 116: 34 – 46.
- Verchot, L.V., M. van Noordwijk, S. Kandji, T. Tomich, C. Ong, A. Albrecht, J. Mackensen, C. Bantilan, K.V. Anupama and C. Palm. 2007. Climate change: linking adaptation and mitigation through agroforestry. *Mitig. Adapt. Strat. Glob. Change* 12: 901– 918.
- Walker, S.M. and P. V Desanker. 2004. The impact of land use on soil carbon in Miombo Woodlands of Malawi. *For. Ecol. Manage.* 203: 345 – 360.
- Wang, D., F.H. Bormann, A.E. Lugo and R.D. Bowden. 1991. Comparison of nutrient use efficiency and biomass production in five tropical tree taxa. *For. Ecol. Manage.* 46: 1– 21.
- Williams, M., C. M. Ryan, R.M. Rees, E. Sambane, J. Fernando and J. Grace. 2008. Carbon sequestration and biodiversity of re-growing Miombo woodlands in Mozambique. *For. Ecol. Manage.* 254: 145 – 155.
- Young, A. 1997. *Agroforestry for soil management*. 2th ed. CAB INTERNATIONAL. Wallingford, UK 320 p.
- Zahabu, E.M. 2008. Sinks and sources: a strategy to involve forest communities in Tanzania in global climate policy. PhD thesis, University of Twente, Netherlands. 235 p.
- Zaharah, A.R. and A.R. Bah. 1999. Patterns of decomposition and nutrient release from fresh *Gliricidia* (*Gliricidia sepium*) leaves in an ultisol. *Nutr. Cycl. Agroecosyst* 55: 269 – 277.
- Zhang, F. and L. Li. 2003. Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency. *Plant Soil* 248: 305 – 312.
- Zingore, S., P. Mafongoya, P. Nyamugafata, K.E. Giller. 2003. Nitrogen mineralization and maize yields following application of tree prunings to sandy soil in Zimbabwe. *Agrofor. Syst* 57: 199 – 211.

## APPENDICES

Appendix 1. Tree species effects on soil total inorganic N and extractable phosphorus during the first cropping season after a 5-year fallow period of the rotational woodlot system at Mkundi, Morogoro, Tanzania.

Tree species	Week 0 <sup>1</sup>	Week 4	Week 6	Week 8
Soil N				
<i>Gliricidia sepium</i>	58.2a <sup>2</sup>	93.2a	85.9a	65.5a
<i>Acacia polyacantha</i>	56.9a	86.9a	79.9a	63.8a
<i>Acacia mangium</i>	43.7ba	62.7b	60.4b	54.6ba
<i>Acacia crassicarpa</i>	36.5bc	50.0bc	48.7bc	46.5bc
Natural fallow	25.1c	39.1c	36.7c	32.3c
MSD <sup>3</sup>	13.514	12.910	13.206	11.419
Probability	0.0196	0.0002	0.0117	0.0021
Soil P				
<i>Gliricidia sepium</i>	16.0ba	31.8bc	35.9a	20.0ba
<i>Acacia polyacantha</i>	20.4a	40.4a	39.5a	26.9a
<i>Acacia mangium</i>	19.1a	32.9b	37.6a	23.2ba
<i>Acacia crassicarpa</i>	15.1ba	31.0bc	32.9a	19.8ba
Natural fallow	10.7b	23.0c	27.5a	16.7b
MSD	7.138	6.6089	11.472	6.9402
Probability	0.0120	0.0003	0.1416	0.0098

<sup>1</sup> Week 0 to 8 represent sampling time after maize sowing.

<sup>2</sup> Means within a column followed by the same are not statistically different at  $p < 0.05$  according to Tukey's HSD test.

<sup>3</sup> MSD = Minimum significance difference.

Appendix 2. Fertilizer effects on soil total inorganic N and extractable phosphorus during the first cropping season after a 5-year fallow period of the rotational woodlot system at Mkundi, Morogoro, Tanzania.

Fertilizer treatments	Week 0 <sup>1</sup>	Week 4	Week 6	Week 8
	Soil N			
Control	46.7a <sup>2</sup>	55.8b	54.9c	49.2b
40 kg P ha <sup>-1</sup>	50.2a	59.8b	60.9c	53.7ba
80 kg N ha <sup>-1</sup>	44.1a	70.1a	76.4a	64.4a
N+P	45.4a	74.0a	83.8a	73.3a
MSD <sup>3</sup>	6.709	9.261	7.8473	11.130
Probability	0.1926	0.0037	<.0001	<.0001
	Soil P			
Control	14.1a	22.9c	29.0b	15.1b
40 kg P ha <sup>-1</sup>	16.9a	40.6a	42.0a	24.8a
80 kg N ha <sup>-1</sup>	18.1a	28.6b	32.1b	18.6b
N+P	15.3a	41.3a	45.0a	26.0a
MSD	5.416	3.6249	7.9513	3.9013
Probability	0.2170	0.0003	<.0001	<.0001

<sup>1</sup> Week 0 to 8 represent sampling time after maize sowing.

<sup>2</sup> Means within a column followed by the same are not statistically different at  $p < 0.05$  according to Tukey's HSD test.

<sup>3</sup> MSD = Minimum significance difference.

Appendix 3. Concentration ( $\text{g kg}^{-1}$ ) of foliar nitrogen, phosphorus and potassium of 5-year old tree fallows during the 12-week decomposition period at Mkundi, Morogoro, Tanzania.

Tree species	Week 0 <sup>1</sup>	Week 2	Week 4	Week 6	Week 8	Week 12
Nitrogen						
<i>Acacia crassicarpa</i>	12.8c <sup>2</sup>	14.0ba	14.8ba	16.3b	16.5b	16.8b
<i>Acacia mangium</i>	20.1b	17.7ba	19.7a	25.4a	24.9a	26.0a
<i>Gliricidia sepium</i>	30.5a	12.5b	9.41b			
<i>Acacia polyacantha</i>	31.4a	19.8a	18.9a	15.5b	17.8ba	15.7b
MSD <sup>3</sup>	0.9038	7.2104	8.1945	4.7806	7.8497	5.6294
Probability	<.0001	0.0426	0.0165	0.0032	0.0367	0.0052
Phosphorus						
<i>Acacia crassicarpa</i>	0.51c	0.33b	0.31b	0.35b	0.36b	0.33b
<i>Acacia mangium</i>	0.71b	0.68ba	0.63ba	0.62a	0.64ba	0.61a
<i>Gliricidia sepium</i>	1.46a	0.83a	0.60ba			
<i>Acacia polyacantha</i>	1.39a	0.86a	0.86a	0.76a	0.81a	0.78a
MSD	0.1242	0.3926	0.4507	0.1866	0.3922	0.2511
Probability	<.0001	0.0118	0.0124	0.0105	0.0311	0.0060
Potassium						
<i>Acacia crassicarpa</i>	4.32d	1.66b	1.94b	1.37b	1.35a	1.47a
<i>Acacia mangium</i>	10.4c	6.43a	5.43a	4.75a	2.53a	2.38a
<i>Gliricidia sepium</i>	19.3a	6.92a	3.15ba			
<i>Acacia polyacantha</i>	12.0 b	7.58a	3.90ba	2.59b	2.99a	1.63a
MSD	0.7328	2.6853	1.5015	2.0430	2.3907	2.3796
Probability	<.0001	0.0339	0.0431	0.0158	0.1289	0.4267

<sup>1</sup> Week 0 to 12 represent sampling intervals during the decomposition periods.

<sup>2</sup> Means within a column followed by the same are not statistically different at  $p < 0.05$  according to Tukey's HSD test.

<sup>3</sup> MSD = Minimum significance difference.