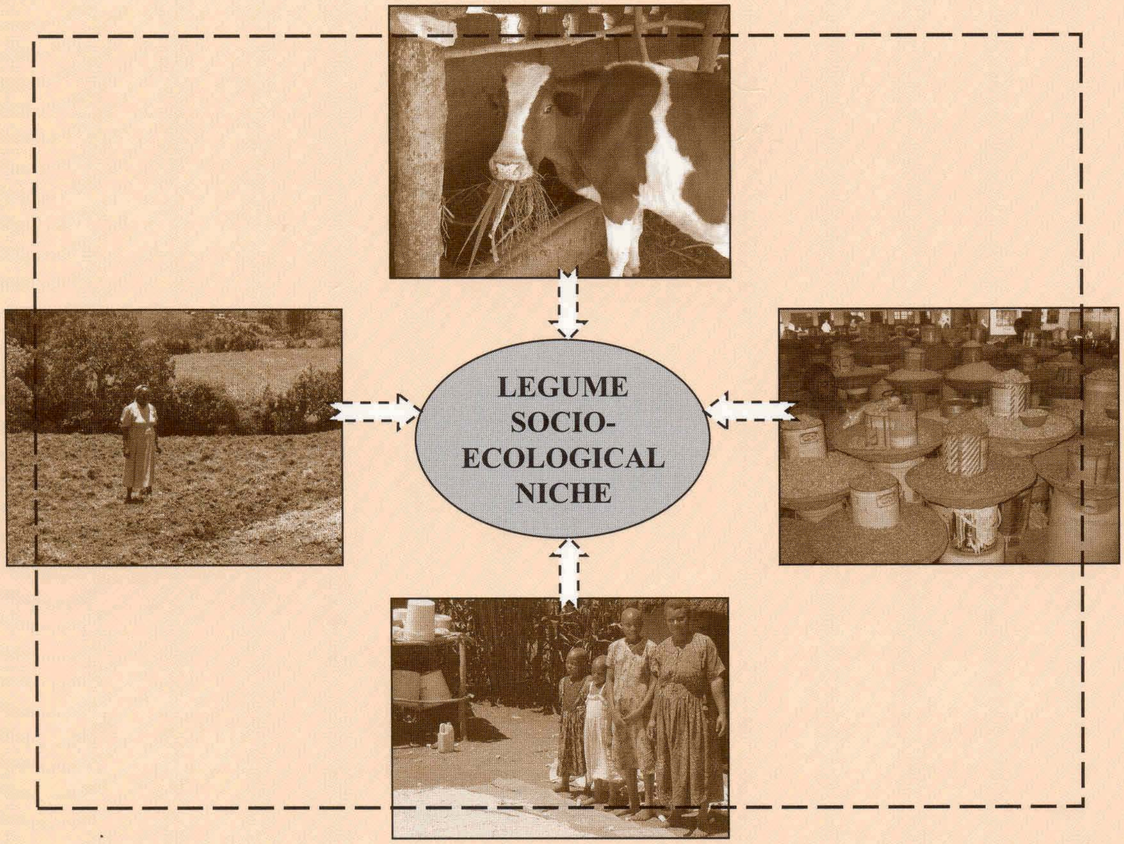
Exploring socio-ecological niches for legumes in western Kenya smallholder farming systems

John O. Ojiem



Tropical Resource Management Papers
Documents sur la Gestion des Ressources Tropicales
89

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Tropical Resource Management Papers,
ISSN 0926-9495

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Documents sur la Gestion des
Ressources Tropicales, ISSN 0926-9495

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ISBN: 90-8585-107-6.

Tropical Resource Management Papers, No. 74 (2006); ISSN 0926-9495
Also published as thesis (2006), Wageningen University ISBN 90-8504-513

Exploring socio-ecological niches for legumes in western Kenya smallholder farming systems

Dedicated to
Jerida, William, Valarie, Olivia and Robert

Abstract

This thesis explores the potential of using herbaceous and grain legume species to improve soil fertility and farm productivity in the heterogeneous smallholder farming systems of western Kenya. Poor soil fertility is responsible for the limited productivity of the western Kenya smallholder farming systems. Although legumes have the potential for improving productivity, their sustainable use is impeded by the high degree of biophysical and socio-economic heterogeneity that characterizes the farming systems. The socio-ecological niche concept was proposed as a framework for facilitating the identification and integrated assessment of biophysical and socio-economic factors with potential influence on the choice of sustainable legume technologies for smallholder farmers.

The utility of the socio-ecological niche concept was tested through on-farm experiments and socio-economic surveys in western Kenya. The on-farm experiments were conducted across three major agro-ecological zones (AEZ), and under different soil fertility conditions, to assess legume emergence, survival, nodulation, diseases tolerance, grain yield, biomass production, atmospheric N_2-fixation and net N contribution to soil N fertility. In addition, the economic benefits of growing grain and green manure legumes in rotation with maize were assessed to determine how they are influenced by agro-ecological conditions and within farm soil fertility heterogeneity. Socio-economic surveys characterized farmer legume production objectives, as well as socio-cultural, economic and institutional factors with potential impact on the use of legume technologies by western Kenya smallholder farmers. The biophysical and socio-economic factors were integrated and analysed to identify legume species for different farmer resource endowment groups, agro-ecological conditions and field typologies. Analysis of the alternative legume production scenario was undertaken, to test the utility of the socio-ecological niche concept.

Legume grain yield, total dry matter production (TDM) and atmospheric N_2-fixation increased with rainfall and soil fertility status. TDM ranged from 0.1 Mg ha^{-1} to 13.9 Mg ha^{-1}, and was generally less for the grain legumes, compared with the green manure and forage legumes. However, soyabean and groundnut showed greater potential among the grain legumes, producing up to 4.6 Mg ha^{-1} TDM. While the legume species and varieties showed capacity to form viable nodules with naturally occurring rhizobia, application of P was essential for good nodulation.

Generally, the species fixed 23-90% of their N requirements in AEZ 1 (Museno) and AEZ 2 (Majengo), compared to 7-77% of their N requirements in AEZ 3 (Ndori). However, N_2-fixation by the green manure species (29-232 kg N ha^{-1}) was greater than that by grain legume species (3-172 kg N ha^{-1}). Net N input by the grain legumes was negatively correlated with grain yield, and legume grain yields of above 1 Mg ha^{-1} resulted in negative net N inputs. Economic benefits of fitting legumes into the smallholder cropping systems in rotation with maize varied with rainfall, soil fertility and legume species. Yearly maize productivity of these rotations (short and long rains crops) decreased by 47%, from AEZ 1 to AEZ 3, and by 33%, from fertile fields to least fertile fields. Although continuous maize fertilized with both N and P had the largest total maize productivity, returns to land and labour were greatest with grain legume-maize cropping systems. In AEZ 2, where moisture was not limiting during the experimentation period, mean returns to land for grain legume-maize cropping systems were US$ 879 ha^{-1}, compared with US$ 533 for green manure-maize, and US$ 459 for continuous maize with N and P.

Rainfall, soil fertility, land, labour, and livestock ownership were identified as the most important factors influencing the choice of appropriate legumes for the smallholder socio-ecological niches. The analysis of the current legume production situation showed that the medium and the low resource endowed farmers were food insecure due to a combination of land and labour scarcity. However, when alternative legumes species selected according to the socio-ecological niche concept were used, maize self-sufficiency increased by 21-48%. This study demonstrated the utility of the socio-ecological niche concept as a useful tool for facilitating the integration of legumes into the western Kenya smallholder farming systems to improve soil fertility and farm productivity.

Keywords: a*daptability, agro-ecosystems, biophysical and socio-economic heterogeneity, economic benefits, N2-fixation, productivity.*

Preface

This thesis is a product of many years of dreaming, planning and searching for opportunities. My dreams were finally realised through a generous financial support from the Rockerfeller Foundation, which enabled me to join Wageningen University, as well as supporting my research activities in western Kenya. I am truly thankful for this financial support. In this connection, I am eternally grateful to Dr. John Lynam for showing interest in me and giving me the opportunity to realise this dream.

I consider myself fortunate to have had the honour of studying under the guidance of Prof. Ken Giller as my promoter. I first met Ken at a soil fertility workshop in Harare, Zimbabwe in 1997. This was the beginning of a fruitful and enlightening association. I learned a great deal from Ken and always felt challenged, whether it was in the classroom in Wageningen or in the farmers' fields in western Kenya, or eastern Uganda. I also had the privilege of working with Dr. Nico de Ridder as co-promoter. I met Nico for the first time in the little town of Bukoba, northern Tanzania- far away from The Netherlands. Little did I know he would play a major role in my success at Wageningen. I am indebted to him, not only for his excellent academic input, but also for his devoted assistance with the numerous and complex administrative details and procedure I had to go through. On the social side, I would like to thank Ken, Nico, and their families, for the many invitations to their homes and the wonderful meals we had together. Field experiments would not have been successful without the support of Dr. Bernard Vanlauwe, my other co-promoter. I gratefully acknowledge the help I received from him, especially in securing some of the legume seeds used in the experiments. But above all, I greatly benefited from his field visits to discuss the progress of the trials, and his thorough review of the manuscripts, which tremendously improved the quality.

Many people at the Plant Production Systems Group contributed, in one way or another, to my wellbeing and success at Wageningen and I thank them very much. I particularly would like to thank Ria van Dijk and Charlotte Schilt for always being ready to held with the logistics, especially travel and visa arrangements, which at times proved very challenging. The assistance and friendship of Dr. Shamie Zingore, Muhammed Shibu, Bongani Ncube, Trihn van Mai, Samuel Guto, Bob Douma and Benjamin Kibor, all with whom I shared workspace in the Attic, is greatly appreciated. Your company was always a great source of comfort. The friendship of the Kenyan students at Wageningen is greatly appreciated.

My career has greatly benefited from a number of people over the years. I must sincerely thank Dr. Joel K. Ransom for contributing a great deal to my early development in science through the many training opportunities that he provided. Dr. Cheryl A. Palm was a great source of encouragement for me as I struggled with ideas

for my PhD proposal, and my efforts would not have been completely successful without the input of Dr. Joseph G. Mureithi, who was always ready to assist in any way. I thank the Director, Kenya Agricultural Research Institute (KARI), for providing me with study leave, and the Director, KARI-Kakamega, for facilitation in many different ways.

Finally, the burden of writing this thesis would have been impossible to bear without the love and support of my family. I sincerely thank my wife Jerida for shouldering the responsibility of taking care of the family during my long absence, and William, Valarie, Olivia and Robert for inspiring me in their own unique ways.

John O. Ojiem
Wageningen, November 2006

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Chapter 1

General introduction

Chapter 1

General introduction

The low productivity of sub-Saharan smallholder farming systems

The smallholder farming systems of sub-Saharan Africa are characterized by poor productivity. Low soil fertility has been recognized as an important factor constraining agricultural productivity and farm income in sub-Saharan Africa (Sanchez et al., 1996; Stoorvogel et al., 1993). Soil nutrient balances have been widely used as sustainability indicators (Shepherd and Soule, 1998), and negative nutrient balances have been found in studies at national, regional and farm levels in sub-Saharan Africa (Smaling et al., 1993; Stoorvogel et al., 1993). However, soil fertility status is a function of social and economic processes associated with the household and its farm management (Ayuk, 2001).

A large degree of biophysical and socio-economic heterogeneity characterizes the sub-Saharan Africa smallholder farming systems. Variations in within-farm soil fertility (Tittonell et al., 2005b; Shepherd and Soule, 1998) are significantly influenced by farmers' soil fertility management. Most of the organic resources and mineral fertilizers are used on the home gardens and infields, at the expense of the outfields. This preferential application of nutrients leads to the development of gradients of declining soil fertility with distance from the homestead and is a reflection of limited availability of manure and other nutrient sources (Vanlauwe and Giller, 2006). Resource endowment, therefore, has an impact on the management and fertility of the soil. Model-based assessments (Shepherd and Soule, 1998) predicted negative soil C, N and P budgets for farmers with low and medium resource endowment and positive balances for those with high resource endowment.

Soil fertility management options

A complex combination of biophysical and socio-economic factors influences the capacity of smallholder farmers in sub-Saharan Africa to manage soil fertility. While mineral fertilizers can be used to improve soil fertility and boost food production, this option is constrained by a number of factors, such as unreliable markets (Anderson, 1992; Hassan et al., 1998) and limited access to capital (Hoekstra and Corbett, 1995). Animal manure (cow dung), compost manure, and crop residues are the major organic resources for soil fertility management in many smallholder farming systems in Africa. While animal manure is the most valuable resource in the region, its quality is often variable, depending on diet (Probert et al., 1995) and other factors, such as management (Rufino et al., 2006). Further more, the quantities of manure available on-farm are, quite often, insufficient to maintain soil fertility as the number of cattle are limited (Jama et al., 1997). Crop residues are frequently used as livestock feed, and in any case, have limited potential for soil improvement due to their limited capacity to supply N for crops (Giller and Cadisch, 1995).

The potential of legumes in smallholder productivity improvement

Grain and green manure legume species have the potential for improving the productivity of the smallholder farms in sub-Saharan Africa by providing food for human consumption and fodder for livestock. In addition, biological N_2-fixation is an important option for improving the soil N balance of the smallholder farming systems (Giller 2001). Beneficial effects of legumes on soil fertility as well as on subsequent cereal crops are well documented (Fujita et al., 1992; Peoples and Craswell, 1992; Wortmann et al., 1994). The potential of legumes to meet most, if not all, of the N requirements of succeeding crops has been demonstrated, for example by Lathwell (1990), and substantial yield increases in maize following legumes have been demonstrated, e.g. in Tanzania (Baijukya et al., 2006), Zimbabwe (Waddington et al., 1997) and Uganda (Fishler, 1996). According to Sanginga et al. (1992), inclusion of mucuna (*Mucuna pruriens*) in a rotation system, supplemented with low fertilizer rates, can maintain adequate maize yields, and improve soil physico-chemical properties (Lal et al., 1978; Wilson et al., 1982). However, for legumes to play an effective role in the improvement of productivity, the complexity of the smallholder systems, arising from biophysical and socio-economic heterogeneity, must be taken into consideration in the development and popularization of legume technologies.

The socio-ecological niche concept

The smallholder farming systems are highly variable in soil fertility status (Tittonell et al., 2005b). There are also large variations in farm size, quantity and quality of livestock, soil and plant management, food consumption patterns, and sources of income, among the different resource endowment groups (Shepherd and Soule, 1998; Tittonell et al., 2005a). Farmer production objectives also vary and may include production of food and fodder and maintaining soil fertility, or various combinations of these. All these factors have significant influence on the choice of appropriate legume technologies for the smallholder farmers. This means that efforts should be focused on understanding the biophysical (climate, soil type) and socio-economic variables (land and labour constraints, livestock ownership) that shape the smallholder environment, as well as the farmers' goals and aspirations. This would lead to an appreciation of how the social, economic and biophysical environmental conditions are likely to affect a given legume technology, and eventually, to some rationalization of legume options and conditions necessary for their effective functioning and impact. These conditions constitute the window of opportunity (or *socio-ecological niche*) for the technology in the system.

Rationale for the study

For legumes to play a significant role in the improvement of smallholder farming systems, sustainable incorporation of appropriate species is required. The use of the species in soil fertility management is beset by a number of ecological and socio-economic constraints. Important biophysical constraints include soil nutrient deficiencies, especially phosphorus (P), soil acidity, and moisture availability (Giller and Cadisch, 1995). These variables have significant influence on the productivity of legumes. Similarly, a number of socio-economic constraints exist. Non-food legumes, e.g. green manures grown for soil fertility sacrifice land normally devoted to food production. In addition, labour requirements for planting and incorporation of legumes into the soil may be high (Ruhigwa et al., 1995). Farmer production objectives and preferences also vary. Legume species differ significantly in market value, and there are large seasonal fluctuations in prices. These biophysical and socio-economic factors have considerable influence on the choice of legume technologies in smallholder farming systems, and should be addressed in an integrated manner, to achieve sustainable incorporation of legumes into smallholder farming systems to improve productivity.

The socio-ecological niche concept is proposed as a useful framework for integrating and analysing the biophysical and socio-economic factors likely to influence the sustainable incorporation of legumes into smallholder systems, to facilitate the development of legume technologies better tailored to the broad heterogeneity of smallholder farming systems. This study explores the utility of the socio-ecological niche concept as a tool for facilitating legume technology development and targeting within the heterogeneous smallholder farming systems, using some selected promising legume species and varieties, and western Kenya smallholder farming systems as an example.

Objectives of the study

The overall objective of the study was to test the utility of the socio-ecological niche concept as a tool for integrating and analysing the biophysical and socio-economic heterogeneity that influences the choice of legumes, to achieve better targeting of legume technologies for smallholder farmers. The specific objectives, which involved on-farm experimentation and farm surveys, were:

i) To screen a range of green manure, grain and forage legume species and varieties for adaptability and productivity under differing rainfall and soil fertility conditions in western Kenya.

ii) To assess the contribution of the green manure, grain and fodder legume species, through biological N_2-fixation, to the nitrogen economy of the smallholder systems of western Kenya.

iii) To assess the economic benefits of the green manure and grain legumes grown in rotation with maize under variable rainfall and soil fertility conditions in western Kenya.

iv) To identify, through on-farm surveys, the major legume production objectives of the farmers, as well as the principal socio-cultural, economic and institutional factors that have significant potential influence on the of choice of legume technologies within the heterogeneous smallholder farming systems in western Kenya.

v) To provide an illustration of how the socio-ecological niche concept can be used to integrate the biophysical and socio-economic factors, to delineate a niche and select appropriate legume technologies that match the niche.

Outline of the thesis

Chapter 2 is a theoretical treatment of socio-ecological niche concept. The concept is introduced, defined and discussed as a framework for legume technology innovation and popularization under smallholder production systems. In Chapter 3, the performance of promising grain, green manure and forage legumes in response to variations in agro-ecological and soil fertility conditions is reported. Emergence, survival, response to diseases, nodulation capacity, biomass production, and grain yield of the species are discussed. Chapter 4 reports on the influence of biophysical heterogeneity on the contributions of grain and non-grain legume species to the nitrogen economy of smallholder systems of western Kenya. The capacity of the legume species to fix atmospheric nitrogen under non-ideal smallholder conditions is reported, as well as the net N contributions by the grain legumes to the farming systems. In Chapter 5, the economic benefits of incorporating green manure and grain legumes into the smallholder cropping systems are assessed. Net benefits (returns to land and labour) of green manure-maize and grain legume-maize rotations are compared to continuous maize cropping, under different rainfall and soil fertility conditions. Chapter 6, which also incorporates the general discussion section of the thesis, synthesizes the results of different chapters of the thesis. The utility of the socio-ecological niche concept as a framework for facilitating sustainable incorporation of legume technologies into the heterogeneous smallholder farming systems is discussed. The notion of socio-ecological niche typology is formulated and presented as a means for integrating the biophysical and socio-economic dimensions of the socio-ecological niche concept, in the investigation of appropriate legume technologies for the heterogeneous smallholder farming systems. Lastly, the application of the socio-ecological niche concept by research and development agents is discussed, and the major conclusions drawn from the study given, including suggestion for the use of models to refine the application of the socio-ecological niche concept in targeting legume technologies in smallholder farming systems.

Chapter 2

Socio-ecological niche: A conceptual framework for integration of legumes in smallholder farming systems

This Chapter is in press as:

Ojiem, J.O., Ridder, N. de, Vanlauwe, B. and Giller, K.E. Socio-ecological: A conceptual framework for integration of legumes in smallholder farming systems. *International Journal of Agricultural Sustainability.*

Chapter 2

Socio-ecological niche: A conceptual framework for integration of legumes in smallholder farming systems

Abstract

There are numerous examples of technologies with great potential that have not been accepted by smallholder farmers. Quite often, these technologies do not fit well into smallholder systems due to the inherent high level of heterogeneity of these systems. For example, despite their great potential, the adoption of legumes by smallholder farmers in many parts of sub-Saharan Africa has remained poor. A wide range of biophysical (e.g. climate, soil fertility, etc.) and socio-economic (e.g. preferences, prices, production objectives, etc.) variables influence the use of legumes in smallholder farming systems. While some of these variables constrain the adoption of some legumes, others offer opportunities for beneficial use of other legumes in the same system. Therefore, widespread adoption of legumes in smallholder systems can only be achieved if all of the major biophysical and socio-economic constraints are simultaneously identified and addressed. The "socio-ecological niche" concept proposed in this paper provides the framework through which this might be achieved. The socio-ecological niche, in any given region of agricultural activity, is created by the convergence of agro-ecological, socio-cultural, economic, and ecological factors, to describe a multi-dimensional environment for which compatible technologies can be predicted. The socio-ecological niche concept can be applied in many different contexts in technology development. However, this paper discusses its use with respect to the development of legume technologies. Two case studies are presented to illustrate the concept and to demonstrate its practical significance. The concept is being used in on-going, participatory research on legumes in western Kenya smallholder systems.

Key words: Biophysical, heterogeneity, smallholder systems, socio-economic, technology.

Introduction

Legumes have traditionally been grown in many smallholder farming systems in sub-Saharan Africa (e.g. Masefield, 1949; Sturdy, 1939). Attempts to integrate new legumes into smallholder agriculture can be traced to the early colonial period. For example, the first legume introductions into East Africa were in Uganda in 1906 (Byenkya, 1988). Considerable emphasis in the early colonial period was placed on the use of legumes as green manures for soil fertility improvement (e.g. Davy, 1925; Doyne, 1937; International Institute of Agriculture, 1936; Gethin-Jones, 1942). Attempts to introduce legume cultivation on a wide scale included some spectacular failures such as the 'groundnut affair' in Tanzania (Wood, 1950). During this era, mixed farming, modelled after the European mixed-farming system, was becoming established and legumes were seen as important component of this system (Sumberg, 2002). Research emphasis was placed heavily on screening for environmental adaptation, with key initial indicators being the legume's ability to establish, grow and survive (Sumberg, 2002). Obviously, significant changes have taken place in smallholder farming systems since the colonial period. Farmers have evolved new farming systems and the increased population density and pressure on land has led to emergence of numerous constraints beyond purely biophysical factors, greatly increasing the degree of complexity and diversity of the farming systems (e.g. Scoones, 2001). In the light of this new reality, it is evident that addressing environmental factors alone cannot be considered adequate for fitting legumes into smallholder farming systems. Despite this, agronomic research has remained focused on growth and performance of legumes at plot scale.

The potential benefits of technologies incorporating the use of legumes are widely acknowledged (Vanlauwe and Giller, 2006). Legumes have the ability to contribute to sustainable production systems through provision of food (and cash), fodder and fuelwood, in addition to the benefits that arise in terms of maintenance of soil fertility due to their ability to fix N_2 from the atmosphere (Giller, 2001). Beneficial effects of green manure, grain and fodder legumes have been reported in numerous publications (e.g. Fujita et al., 1992; Peoples and Craswell, 1992; Sanginga et al., 2001; Wortmann et al., 1994). However, despite this great potential, there has been relatively little success in achieving widespread adoption of legumes by smallholders in sub-Saharan Africa (Sumberg, 2002; Thomas and Sumberg, 1995), particularly those species meant to improve soil fertility (Mapfumo et al., 2005; Wortmann et al., 1994). A similar situation exists with respect to forage legumes. Cultivation of forage legumes remains limited in sub-Saharan Africa despite intensive research over a period of many decades (Thomas and Sumberg, 1995). As a consequence of this, the contribution of food, fodder and soil-fertility-improving legumes to smallholder farming systems has remained far below the potential (Giller, 2001).

Besides the traditionally grown food legumes, for example cowpea (*Vigna unguiculata* (L.) Walp); common bean (*Phaseolus vulgaris* L.), a number of successful but isolated cases exist where non-traditional legume species have been adopted, e.g. improved soyabean germplasm in southern Africa (Mpepereki et al., 2000) and West Africa (Sanginga et al., 2003). Stylo (*Stylosanthes guianensis* L.) fodder banks have been widely-adopted by West African livestock farmers (Elbasha et al., 1999; Tarawali, 1999). However, despite these successes, it is evident that the potential of legumes demonstrated on experimental research farms remains largely unexploited by smallholders in sub-Saharan Africa (Mapfumo and Giller, 2001) and the contribution of food, fodder and soil fertility improving legumes to smallholder farming systems has remained small (Giller 2001). The modest success of legumes can be attributed partly to lack of appropriate methodologies and tools to stimulate adoption (Amede, 2004), and the need for new and more innovative approaches to identify potential niches for legumes and to facilitate the integration of legumes into complex smallholder farming systems. A further, at least equally important reason for the lack of uptake of legumes can be attributed to the mode of research employed: in the past research has not involved the farmer as an equal partner at an early stage in the evaluation of technologies. This has led to 'top-down' recommendations being developed from research stations without recognition of the farmers' knowledge or a proper understanding of farmers' objectives.

Sumberg (2002) suggests that the required characteristics of the legume plant and its associated management can be defined by three sequential contextual levels: i) socio-cultural, political and economic factors; ii) agro-ecological factors; and iii) the production system. These sequential contextual levels form a funnel and technologies emerging from the bottom of the funnel are expected to 'fit well within the larger picture'. While the need for putting technologies in appropriate local context may be generally appreciated, the problem remains as to how this can be achieved in practice.

African smallholder farming systems are highly-variable in terms of soil fertility status, labour availability, livestock ownership, cash income, farmer objectives, and cultural aspects (e.g. preferences) etc. While these variables constrain the adoption of certain categories of legumes or certain legume species, they also offer opportunities for other legumes to be used beneficially in the same system. This means that it is not useful to give fixed or 'blanket' recommendations for a particular legume technology in a smallholder situation. Instead, efforts should be focused on understanding the biophysical and socio-economic variables, processes and interactions that shape the complex smallholder environment so that these can be factored into the technology development process. This would lead to an appreciation of how the environmental conditions are likely to affect a given legume technology, and eventually, to some rationalization of legume options and conditions necessary for their effective functioning and impact. These environmental conditions constitute the window of opportunity (or *socio-ecological niche*) for the technology in the system.

Our aim is not to develop a rigid, prescriptive or predictive procedure or approach. In discussions with agronomists (including crop, soil and livestock scientists) we have found the concept of the socio-ecological niche very useful in discussing how both research and technologies for development can be better tailored to the broad heterogeneity of smallholders and farming systems. This has led us to explore some ideas of how the concept of the socio-ecological niche can be used to aid research and development. We do not include detailed discussion of how these concepts can be combined with participatory approaches here. Our goal is to provide insights for researchers and other actors in development (from NGOs, extension etc.) to evaluate technical (or social) options critically before introducing them into the iterative cycle of participatory research – essentially to challenge the thinking and sharpen the role of researchers and development actors. In this paper, therefore, we: (i) propose the socio-ecological niche concept as a suitable framework for integration of legume technologies into smallholder farming systems; (ii) define the concept and discuss the factors operating at various levels to delineate the socio-ecological niche; (iii) outline a procedure that could be followed in niche delineation and identification of compatible legume technologies; (iv) illustrate the practical significance of the socio-ecological niche concept in technology development, using appropriate case studies; and (v) suggest the way forward.

The socio-ecological niche concept

Our conception of the socio-ecological niche is analogous to that of the "ecological niche" of an organism in classical ecological theory. Hutchinson (1957) defines a niche as a region (an *n*-dimensional hyper-volume) in a multi-dimensional space of environmental factors that affect the welfare of a species (Figure 1a). The ecological niche denotes a habitat where organisms of a species can live (where conditions are suitable for life) and the functions of that organism within the ecosystem. Such ecological models attempt to explain response of biological species to gradients in environmental variables. The variables exert an influence by creating environmental stresses, which together determine an organism's ecological niche (Sibly and Hone, 2002). We simply extend this concept to include a range of other socio-economic (including cultural and institutional) factors that recognise the role of human interest and agency in determining the socio-ecological niche.

This concept can also be depicted by visualizing, within a given region of agricultural activity, a series of hierarchical factors (acting as sieves) whose interplay ultimately creates the desired environment for a legume technology (see Figure 1b). Starting from the top, agro-ecological factors influence adaptation of the legume to broad level environmental conditions. The next layer consists of socio-cultural factors, e.g. community restrictions and incentives. These have significant influence on technology adoption. Economic factors influence farmer behaviour with respect to technology adoption decisions, while ecological factors operate at the local level and influence adaptation to the local environmental conditions. Institutional support services e.g. input sources, credit facilities, extension services, etc. are crucial to technology innovation and therefore form an integral part of the socio-ecological niche. However, these services are cross-cutting and are therefore not shown as separate layer. All these factors combine to define the niche for a legume technology and are discussed in more detail below.

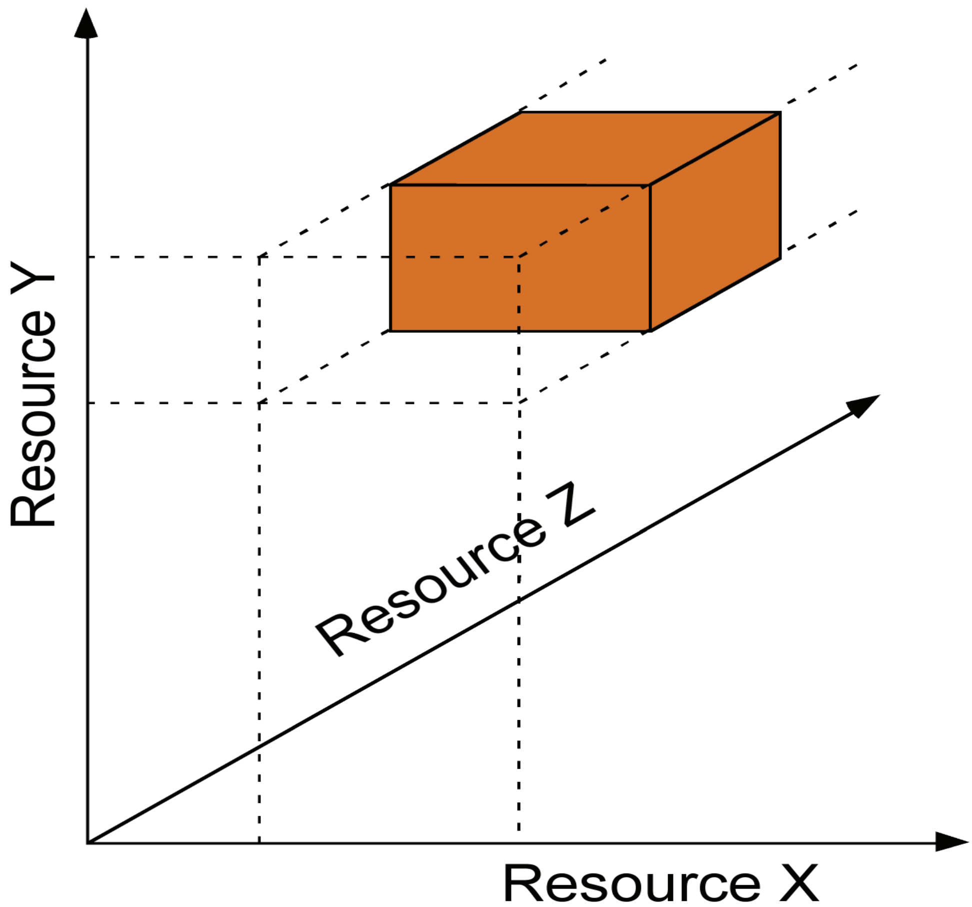


Figure 1a. The niche as an *n*-dimensional hyperspace (after Hutchinson, 1957).

Agro-ecological factors

Agro-ecosystems are communities of plants and animals interacting with their physical and chemical environment that have been modified by people to produce food, fibre, fuel, and other products for human consumption and processing (Altieri, 2002). The main idea implicit in agro-ecological research is that these ecological relationships and processes can be manipulated to improve production and produce in a more sustainable manner (Gliessman, 1998). Agro-ecosystems operate at different scales. However, in the context of the socio-ecological niche concept, we discuss agro-ecological factors at two scales: (i) the broad scale biophysical conditions to which the legumes must be well adapted (we refer to these as agro-ecological factors); and (ii) the biophysical factors that influence the productivity of legumes at the farm level (we refer to these as local ecological factors). Major agro-ecological factors include precipitation, temperature, solar radiation, photoperiod, soil type, etc. An understanding of these factors allows adapted germplasm to be selected. For example, Keatinge et al. (1996; 1998) demonstrated the close linkage between temperature and photoperiod and legume phenology and how these could be used as selection criteria for grain and green manure legumes. Local ecological factors are discussed below.

Socio-cultural factors

Although it is widely accepted that the behaviour of smallholder farmers can be understood in essentially economic terms, “economic man always operates within a cultural framework which defines the values in terms of which he economizes” (Cancian, 1972). There is, therefore, a fundamental link between the economic and socio-cultural factors, in the manner in which they affect technology development. The socio-cultural factors likely to have greater significance in the determination of socio-ecological niche include group values, attitudes and norms, land tenure, labour allocation to household and community tasks, organization of labour and marketing, off-farm livelihood strategies, household food demand and supply, and food habits and preferences. There are many definitions of culture. However, with respect to the relationship between culture and development, Harrison (1992) defined culture as a coherent system of values, attitudes, and institutions that influences individual and social behaviour in all dimensions of human experience. The value systems, attitudes, and institutions affect the manner in which any new technology is viewed by a given community and must therefore be seen as independent and causally substantive variables in the process of technology development. It would be wrong to assume that any introduced technology would function effectively and lead to economic prosperity irrespective of cultural setting. Rationalization on the basis of socio-cultural factors provides the appropriate socio-cultural context for the technology. Significant characteristics, requirements, and perceptions can be identified and socio-cultural barriers to the use of the technology addressed. The potential role of these cultural factors as causal variables affecting the path of economic growth and development has become a subject of considerable debate (Altman, 2001).

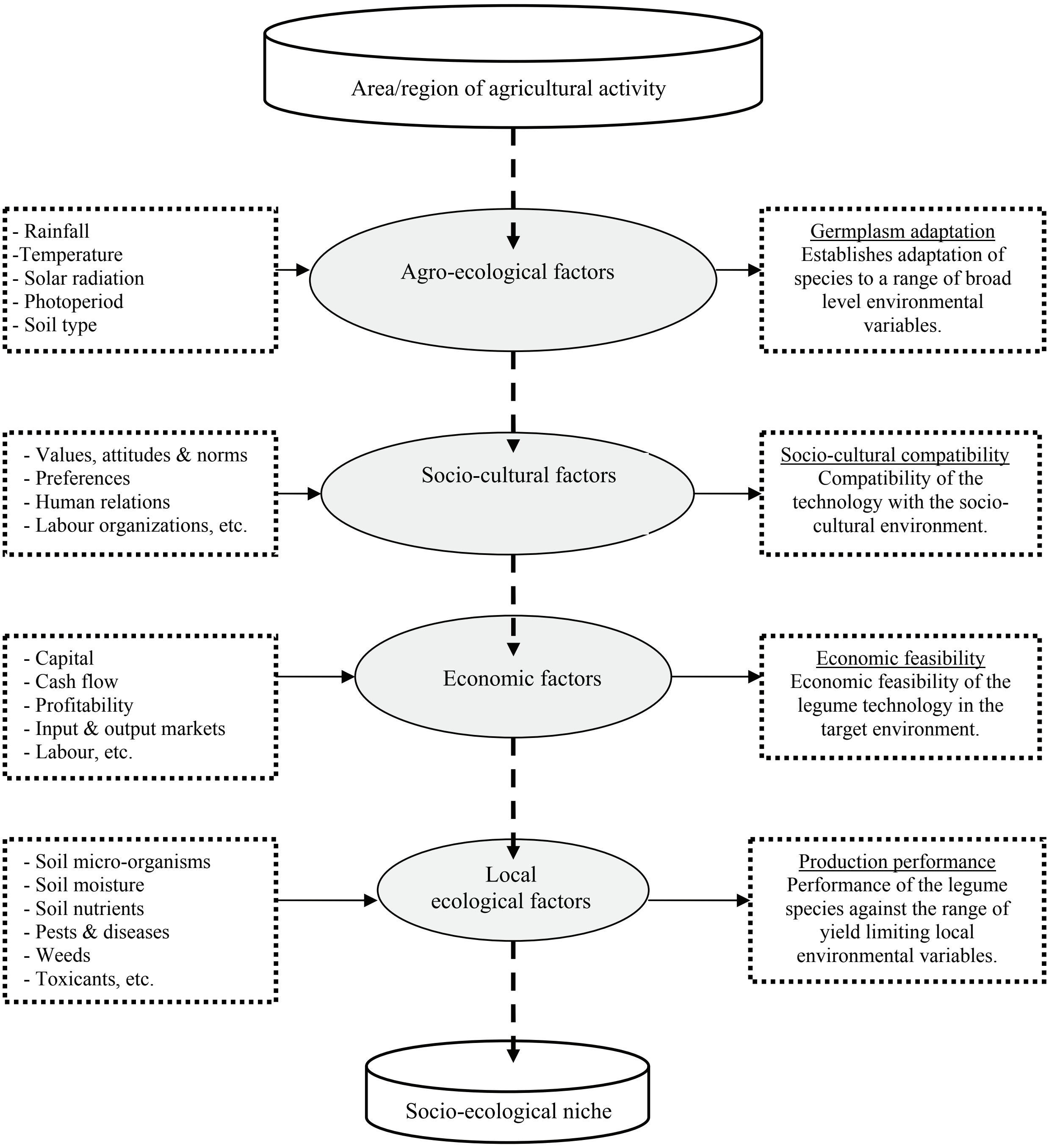


Figure 1b: Schematic diagram depicting the concept of the socio-ecological niche, the hierarchical arrangement of factors that influence the delineation of the niche, and the functions and outputs of the factors.

Economic factors

Farmers' decision making about technology adoption are determined largely by biological and economic factors (Winklemann, 1976). Factors such as land, financial capital, labour, and input and output markets, are major variables that can exert significant effects on the process of technological change. These are the variables that co-determine the niche for a legume technology. By shaping farmer perceptions and behaviour, the interplay of these variables produces a unique application domain for the new technology. Levinthal (1998) in a paper on the slow pace of technological change suggests that a new technology is most likely to be commercially viable and profitable in its niche. However, to achieve commercial viability and profitability, the technology must first go through a process of economic rationalization, on the basis of the prevailing constraints, opportunities, goals and interests. In agriculture, this process allows farmers to gain some insight of how the technology might yield returns in future, and goes on in spite of the positive expectations communicated by change agents.

Local ecological factors

Local ecological factors operate at the local level to contribute to the delineation of the socio-ecological niche. In the context of the socio-ecological niche concept, local ecological factors are biophysical variables at the local (or farm) level that constraint legume productivity. Giller and Cadisch (1995) identified the main biophysical factors that limit biological nitrogen fixation (BNF) in legumes as soil nutrient deficiencies, or factors associated with soil acidity, large concentrations of plant-available N in the soil and moisture deficiency. These are good examples of local ecological factors that co-determine the socio-ecological niche for a legume. Other important local ecological factors that have significant effects on the productivity of legumes are pest and diseases, and noxious weeds.

Institutional support services

Access to institutional support services, such as input dealers who would sell to farmers the requisite legume seeds, suitable blends of fertilizer, pesticides, etc, is important for legume technologies to function. Effective seed systems are of particular importance for legumes. Legume technologies are often information-intensive therefore access by farmers to appropriate technical information, when and where required, is essential. This implies that farmers should not only have access to extension agents but the agents should also be well equipped with correct information. Meeting household cash needs is a major objective of the farmers that legumes satisfy.

Access to functional produce markets is therefore an important aspect of the institutional services environment. A well established institutional environment would be supportive to the use of legume technologies by farmers, leading to multiple benefits of food security, soil fertility, forage for livestock, and cash for households. By their nature, these services are cross-cutting and are therefore not presented separately in Figure 1b.

Towards a definition of the socio-ecological niche

The factors described above, in combination, and including their interactions, delineate the socio-ecological niche for a legume technology. The concept of socio-ecological niche can be adapted and applied in many different contexts, such as in agriculture, manufacturing, and marketing. While a contextual and slightly variable definition of the concept is expected in each of these cases, the general principle remains the same. In the context of agriculture, and particularly in smallholder farming, the socio-ecological niche can be defined as "*A smallholder farmer environment fashioned by the interactions between assortments of biophysical and socio-economic factors and processes that facilitate functionality and presents to the smallholder the potential to attain desired production objectives*". Applying this concept, the technology and its products would be rationalized not only on the basis of biophysical performance but also on relevant socio-cultural and economic issues, which form part of the socio-ecological niche. Such a rationalization would increase the chances of legume options fitting well in smallholder systems. The socio-ecological niche thus defines the boundaries for legumes within existing farming systems and under existing biophysical and socio-economic conditions. The niche may be dynamic, as changes in, for example, policies and prices can alter the boundaries, increasing or decreasing its size.

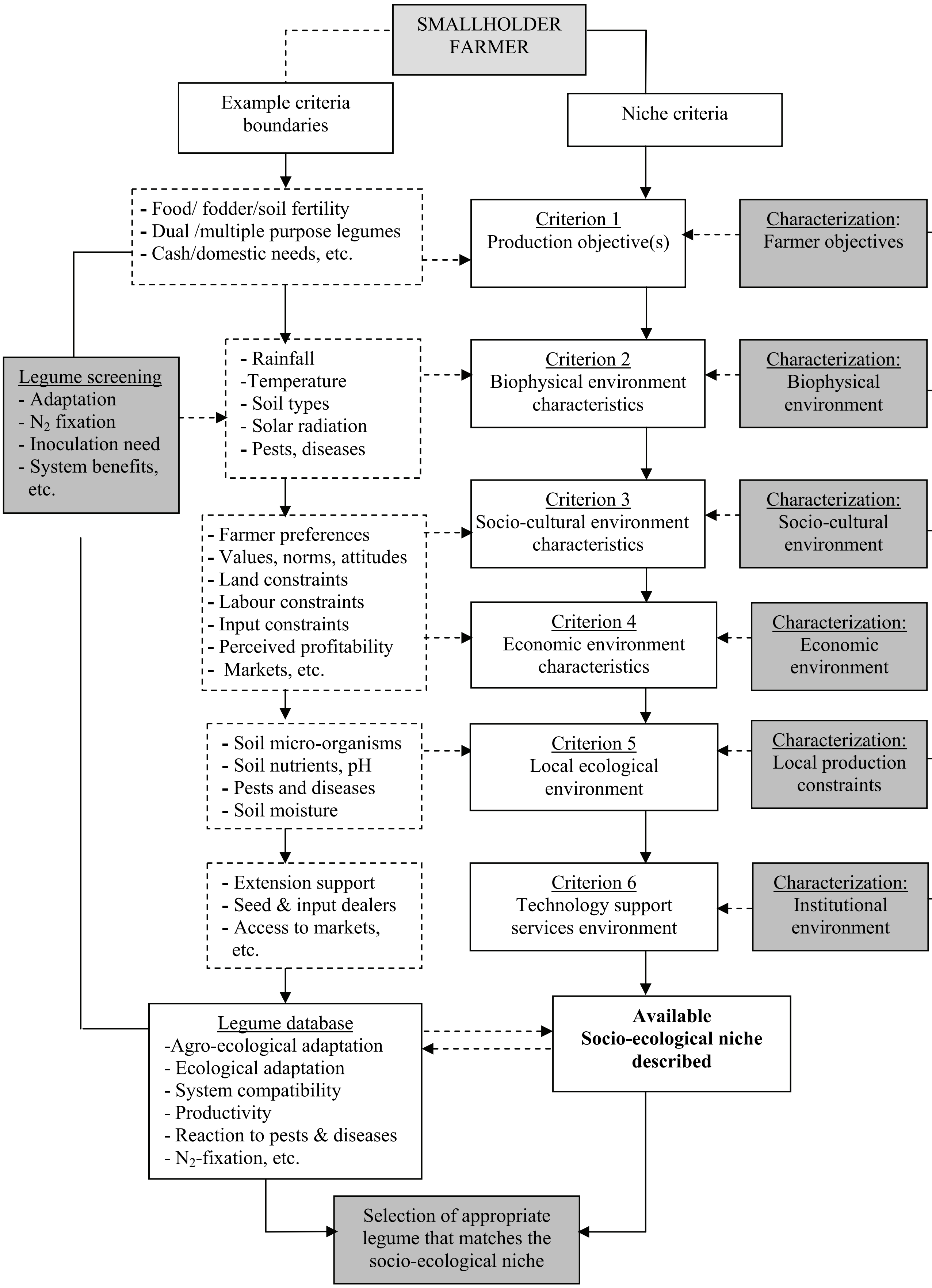


Figure 2: Legume niche criteria, criteria boundaries, the process for delineation of socio-ecological niche(s), and the selection of potential legumes for the niche(s).

The role of the farmer in the socio-ecological niche concept

The farmer is central in defining the socio-ecological niche, since it is the farmer's production objective, biophysical, socio-economic, and institutional environments that determine the nature of the niche. Therefore, the socio-ecological niche can only be described effectively with reference to the farmer, i.e. the type of legume the farmer wants to grow to meet his/her production objectives and whether the prevailing biophysical and socio-economic environments and the existing institutional framework can support that choice. Thus, legumes that have been adopted by farmers and are found to fulfil farmers' needs must have found their suitable socio-ecological niches on-farm. In this sense our concept of the socio-ecological niche shares similarities with the definition of an 'innovation' according to Leeuwis and van den Ban (2004), who suggest that a true innovation or 'complete' technology exists only if there is an appropriate mix and balance between technical devices and socio-organizational arrangements. The approach we advocate is also in line with thinking associated with an 'innovation systems framework' (Hall et al., 2003). Since the farmer is central in defining the socio-ecological niche, and given the differences that normally exist between farmers, there can be numerous socio-ecological niches.

Determining available socio-ecological niches

The four groups of niche-defining factors (see Figure 1b) and the cross-cutting institutional factors form the major criteria essential for determining the available socio-ecological niches for legumes in any given region. When the target farmers have been identified, a sixth criterion, the legume production objective, can be added. A procedure that could be followed in matching legumes to appropriate socio-ecological niches is elaborated in Figure 2. In this procedure, which may target individual smallholder farmers or common objective farmer groups, niche screening can be performed in a series of steps. For each niche criterion, several criteria boundaries can be established and used to set the limits for the niche. Information gaps with respect to any niche criterion can be handled by performing an appropriate biophysical or socio-economic characterization. Once all the niche criteria have been examined and criteria boundaries established, the socio-ecological niche can be fully described. It is the limits imposed on the farmer by these different criteria boundaries that define the available socio-ecological niche(s) and set the stage for the selection of an appropriate legume type(s) for the identified niche(s). Available legume databases can then be consulted to select a legume that matches the identified socio-ecological niche. It is important to emphasize that the entire procedure should involve active participation of farmers. Some examples of how the niche criteria can be used to stratify farmers and assemble the information needed for niche description are discussed below.

Legume production objective (Niche Criterion 1)

The reason farmers want to incorporate a given legume species in their cropping system is often to meet particular, well-defined production objectives. Having knowledge of these objectives is therefore crucial as it can inform the choice of legume options to be made available to the farmers. The major legume production objectives (Figure 3a) would normally include the need to satisfy household food needs (A_1), to improve soil fertility (B_1), and to improve the quantity and quality of fodder for livestock (C_1). Another important legume production objective is to improve family cash income situation. However, this objective is cross-cutting and is achievable via A_1, B_1, and C_1. In most circumstances, however, farmers seek to satisfy two or more objectives at the same time. These could be food and soil fertility improvement (A_1 B_1), soil improvement and livestock feed (B_1 C_1), food and livestock feed (A_1 C_1), or all the three (A_1 B_1 C_1). In such cases, dual or multi-purpose legume types, or different legumes on different fields on the farm, would be the most appropriate options.

Socio-cultural environment (Niche criterion 3)

Rural areas, where most smallholders operate, are not as homogeneous as often portrayed. Wiggins and Proctor (2001) view rural areas as consisting of ‘peri-urban zones’, ‘the (middle) countryside’, and ‘remote rural areas’. Each of these categories has its own unique constraints and opportunities. For example, the peri-urban zones, due to their proximity to the cities, offer opportunities for market gardening and dairying, while subsistence farming is likely to be a major activity in the remote rural areas. Any surplus production in the remote rural areas has to be of high value to bear transport costs. This means that the role, and by implication, the suitable legume type, will be different in each of these rural area zones.

A wide degree of heterogeneity also exists at farm level. For example, Tittonell et al. (2005a) distinguished five farm types in western Kenya, based on farmers’ resource endowment and production criteria. Therefore, based on resource endowment or constraints, farmers constituting an ideal target group for a certain technology can be identified. A variety of distinguishing (socio-cultural and economic factors) characteristics may be used, depending on purpose and relevance. Demographic characteristics, e.g. age, gender, household composition (for labour) can be used. Other characteristics of value are those related to attitudes and values (Senauer et al., 1991) of the individuals or the community concerned. Access to on-farm and off-farm sources of income and functional markets may be additional characteristics in this respect. It is also important to establish other aspects of resource endowment, particularly land availability, access to labour, and household income. In the example given in Figure 3b, a smallholder farmer may have land scarcity (A_3), as an important constraint, labour scarcity (B_3), or input scarcity (C_3). These constraints may also be experienced in combination, thus land and labour scarcity (A_3 B_3), labour and input scarcity (B_3 C_3), land and input scarcity (A_3 C_3), or all the constraints together (A_3 B_3 C_3).

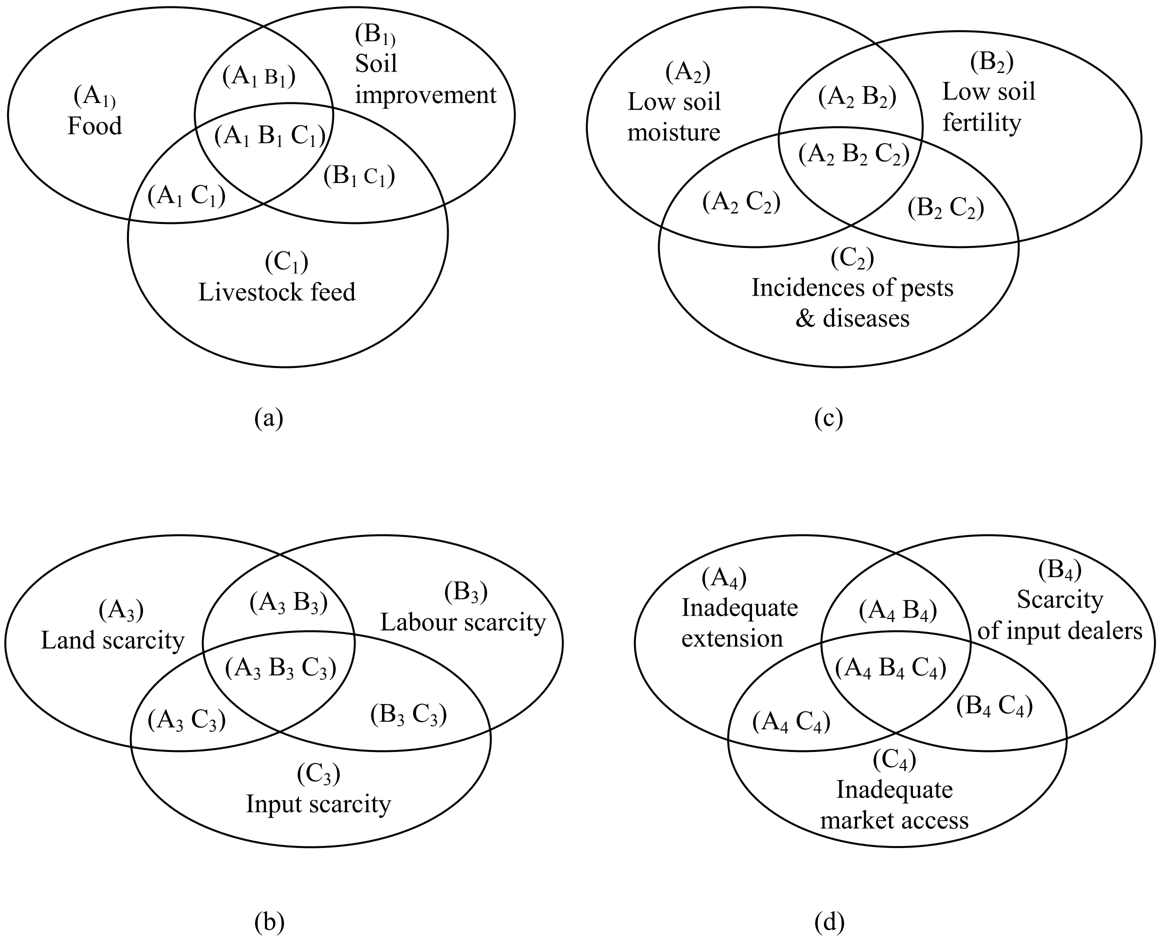


Figure 3. Classification of farmers according to: (a) Legume production objectives; (b) Scarcity of resources for legume production; (c) Local environmental constraints and; (d) Access to essential technology support services.

Intercropping and relaying practices enhance the efficiency of land use and are normally embraced by farmers facing land scarcity. Legumes that grow well in association with other crops are likely to be the choice under such circumstances. Labour scarcity is becoming more acute in many smallholder systems. In western Kenya, for example, discussions with farmers revealed a number of factors responsible for this. Firstly, many children can no longer supplement household labour because they now attend school and have to report to school much earlier than they used to. Secondly, many social organizations, such as labour groups, are no longer active, and community members are becoming increasingly individualistic and commercially-minded and expect cash payment for any work done. Thirdly, a majority of smallholder farmers sell their labour to earn cash for household needs. This may lead to delays in farming operations on their own land. There is a high dependency rate which leads to shortage of cash for farm inputs, among others. High incidence of diseases (HIV/AIDS and malaria) and death among family members puts further strain on the meagre cash incomes. Other important socio-cultural issues are those related to farmer preferences, e.g. for grain colour, grain size, and taste, especially for legumes grown primarily for household consumption. Although we focus in our examples on western Kenya, where the author is based for his research, these lessons are relevant to many intensive smallholder farming systems in sub-Saharan Africa.

Local ecological factors (Niche criterion 5)

The biophysical environment of the farmer is important in determining legume niches. Figure 3c shows some of the important local ecological constraints. Legume species react in different ways to environmental stress factors such as soil moisture, soil nutrient deficiencies, and incidences of pests and diseases. Farmers also experience different combinations of these constraints, e.g. low soil moisture (A_2), low soil fertility (B_2), high incidences of pests and diseases (C_2). In reality, however, farmers are faced with multiple, interacting constraints, e.g. low soil moisture coupled with low soil fertility (A_2 B_2), low soil fertility and high incidences of pests and diseases (B_2 C_2), low soil moisture and high incidences of pests and diseases (A_2 C_2), or all the factors (A_2 B_2 C_2).

It is necessary to establish the variability in these environmental factors since they contribute to the creation of the niche. For example, in the marginal rainfall Bondo District of western Kenya, a group of farmers narrated how their environmental conditions have changed over the last few decades. They believe that not only has the rainfall declined significantly over the last 20-30 years, but the reliability of rainfall has also decreased considerably over the same period. These changes are attributed to environmental degradation, especially the cutting of trees, which they strongly believe has left their region more vulnerable to drought. Their choice of plant species and varieties to plant is therefore more critical than before. Some of the legume species they used to plant no longer fit well in their cropping system. They gave an example of cowpea, which they used to plant in maize, delayed by a few weeks to reduce competition. This can no longer be done because the rainfall has become so unreliable that delaying cowpea planting by even a week dramatically increases the chances of crop failure. This may explain the disappearance of such legumes in such farming systems.

Soil pH, drainage toxicants, availability of nutrients, especially phosphorus, and other fertility indicators, such as soil depth and organic carbon content, are important aspects of the biophysical environment. For legumes particularly, effects of soil conditions on survival of large populations of effective rhizobia is essential since the host legume-rhizobium association is required for N_2-fixation to occur (Giller, 2001). Presence or absence of particular plant pests and diseases also help to shape the biophysical environment of the farmer.

Institutional support services environment (Niche criterion 6)

The institutional support environment of the farmer would either facilitate or impede the selection and adoption of a particular technology. Figure 3d details some of the possible constraints with respect to institutional support services environment of the farmer. Farmers may lack adequate information through scarcity of government extension agents or non-governmental organizations (NGOs) in their locality (A_4), have scarcity of input dealers (B_4), and have inadequate market access (C_4). Similarly, (A_4 B_4), (B_4 C_4), (A_4 C_4), and (A_4 B_4 C_4) represent dual and multiple constraint circumstances that farmers may be facing, with respect to institutional services environment. Access to technical information through extension agents, availability of input dealers in the locality, and whether or not farmers have access to markets for produce, will not only strongly influence their decision to grow legumes in general but also the types or species of legumes they may grow.

The case of western Kenya serves as a good example of the importance of the role of the institutional services in this matter. Although there are few government extension agents in western Kenya, as is the case in the other parts of the country, a fair number of farmers have access to extension services due to a relatively large number of NGOs in the region. However, farm input dealers are still scarce, especially in remote places, so many farmers who may be keen to grow legumes have no access to seeds and fertilizer. Discussions revealed that many also lack knowledge on seed preservation and storage, a fact they believe is responsible for the disappearance of many legume species that used to be grown in the region. With the exception of bean, which is normally intercropped with maize, currently less than 10% of farm areas are devoted to legume cultivation in this region. Seeds of many useful legumes, e.g. groundnut and soyabean, do not store for long and farmers need to purchase fresh seed when required. Alternatively, farmers can organize themselves and set up their own seed production units. This requires information and other necessary technical support that can only be available when the institutional support environment is well developed.

Selecting legumes for a niche

Once the ranges of factors influencing potential legume use are established, the next step is to determine which legume species and varieties fit the niche criteria boundaries defined. It is the niche criteria and the criteria boundaries that combine to define the conditions of a particular socio-ecological niche, which in turn, impose limits on legume choice for the niche. In order to properly select legumes that fit socio-ecological niche conditions, a database on legumes is essential. Several legume databases that can serve this purpose are available, e.g. LEXSYS, a decision support tool for integration of legumes into tropical farming systems developed by the International Institute for Tropical Agriculture (IITA) and a legume screening database (LSD) developed by the Kenya Agricultural Research Institute (KARI). Researchers and extension agents can help in gathering and synthesizing the information available in these legume databases and sharing it with farmers, to facilitate the choice of an appropriate legume for an identified socio-ecological niche. Critical information available in these databases include: (i) ecological adaptation; (ii) potential adaptability in target cropping system; (iii) contribution of the legume (e.g. food, fodder or soil fertility); (iv) productivity (e.g. biomass and grain yields); (v) reaction to pests and diseases; (vi) nodulation; and (vii) N_2-fixation capacity, etc.

Case studies illustrating the socio-ecological niche concept

We illustrate the concept of socio-ecological niche by using two case studies derived from western Kenya. The first case study (the black bean) emphasizes the importance of the biophysical component of the socio-ecological niche concept, while the second case study (improved fallows) underscores the importance of the socio-economic (socio-cultural and economic) component of the concept.

Case study 1: The black bean in western Kenya

In most parts of western Kenya, the common bean is an important crop, both for food and cash income. However, the production of this crop was threatened by a number of constraints, including bean stem maggot and bean root rot, whose incidence was quite severe due to low soil fertility status of the smallholder farms in the region. An investigation by Nderitu et al. (1997) identified *Pythium* spp. and *Fusarium solani* as the most important root rot pathogens in the farmers' fields. *Pythium* root rot attacked bean seedlings early in the season and caused high plant mortalities, while *Fusarium* attacked later in the season and caused stunting and poor seed formation. The local varieties grown by farmers (*Alulu, Lipala, Wairimu, Punda* and *Rosecoco*) were highly susceptible to bean root rot pathogens and farmers could no longer produce this crop.

To address this problem, farmers were introduced to an IPM package, which included the use of bean root rot resistant/tolerant varieties from the Kenya Agricultural Research Institute (KARI) – GLP X-92, KK 22, KK 20, KK 15, KK 14, and KK 8. Since KK 15 has black seeds, researchers did not expect it to generate much interest as black seed colour is less preferred by farmers and no varieties with this seed type were grown traditionally. Nevertheless, they included it because it had shown strong resistance to bean root rot pathogens, recording high grain yields in field trials.

A survey of the impact of the new bean varieties was conducted in June 2001, five years after introduction (Odendo et al., 2002). Survey results (Table 1) showed that there was strong farmer awareness of variety KK 15, the black bean, in the two districts: 84% in Kakamega and 98% in Vihiga. Contrary to researchers' expectations, KK 15 was the most widely-adopted improved bean variety in Vihiga (80%). In Kakamega, the variety was adopted by an impressive 42% of the farmers, coming a close second to KK 22, the favourite small red seeded variety, which had 62% adoption rate. In addition, the mean area allocated to variety KK 15 was the second largest in both districts, indicating the general acceptance of this black seeded bean variety. Farmers were able to sell appreciable quantities of KK 15, suggesting that the variety was not only contributing significantly to farmers' food needs but also to their household income.

This case study illustrates the importance of the biophysical *(agro-ecological* and *local ecological factors)* component of the socio-ecological niche concept. The black bean variety met the biophysical criteria (high yield, bean root rot resistant, and early maturing) and even though the socio-economic criteria were not immediately met, researchers gambled with it because they believed it stood the best chance of succeeding against the severe onslaught of been root rot diseases, which had previously rendered bean production impossible in the region. Given the seriousness of the problem, farmers were able to downplay their socio-cultural and economic concerns and rationalize adoption mainly on the basis of biophysical attributes of the variety. Indeed, the black seed colour led to a 'novelty' value of this variety and early-adopters earned considerable income from selling seed of the variety to other farmers in the area. The fact that no black seeded bean variety had been accepted before indicates that technologies that do not satisfy the socio-economic aspects of the socio-ecological niche concept might be accepted only in extreme situations, e.g. when the very survival of the farmers is threatened, as in this case. Earliness of the variety (74 days to maturity) was particularly important because it meant it is ready for consumption during the February-May hunger period, before the main crop is harvested.

Table 1. Awareness, adoption, and marketability of new root rot tolerant bush bean varieties by farmers in western Kenya

Improved bean variety	% awareness		% adoption		Area sown to variety by sampled households (hectares) ψ		Mean quantities sold by sampled farmers (kg) *	
	Kakamega	Vihiga	Kakamega	Vihiga	Kakamega	Vihiga	Kakamega	Vihiga
KK 8	63	74	34	35	2.0	1.6	21(2-80)	14 (4-50)
KK 14	20	38	4	5	0.5	0.1	20	5
KK 15	84	98	42	80	2.75	4.2	30 (2-100)	23 (2-160)
KK 20	13	34	2	5	0.05	0.2	4	NA
KK 22	84	92	69	69	12.3	8.3	45 (3-360)	34 (5-200)

Modified from Odendo et al., 2002.
ψ : Area mean of long and short rain growing seasons.
* Range in parenthesis.

Case study 2: The improved fallow technology in western Kenya

Natural fallow is land left to rest from cultivation for a long period in order to restore soil fertility lost from cropping. Improved fallow, on the other hand, is land resting from cultivation but the vegetation is not natural but managed and planted with species of leguminous trees, shrubs, and herbaceous cover crops (Amadalo et al., 2003). The cover crops improve soil fertility in six- month (one to two seasons), although studies by Niang et al. (2002) concluded that a 6-month fallow can yield as much recyclable nutrients as 12- month fallow. The legumes accumulate nitrogen via atmospheric fixation and in tree and shrub species, the roots access and recycle nitrogen that is at depths otherwise inaccessible to crop roots. The use of improved fallow technology can result in yield increases of between 100-200% (Amadalo et al., 2003). However, the technology requires additional labour for sowing of the tree seeds, cutting the fallows, and in preparing the land following a fallow.

The technology, using the fast-growing legume trees *Sesbania sesban* (L.) Merr., *Tephrosia candida* (Roxb.) DC. and *Crotalaria grahamiana* Wight and Arn., was introduced to farmers in 1994 through a collaborative project between the Kenyan Forestry Research Institute (KEFRI) and the World Agroforestry Centre (ICRAF). This pilot project initially covered 17 villages spread in three districts (Kakamega, Vihiga and Siaya) in western Kenya and later on extended to cover some non-pilot villages as well. A detailed study was carried out on the impact of improved fallows on livelihoods by Place et al. (2005). Interesting and distinctive adoption patterns emerged inside and outside the pilot area (Figure 4). Inside the pilot villages, the use of improved fallow technology surged rapidly from 1997, reaching about 25% of the households in 1999. This rapid surge was followed by a steep decline in use to only about 13% of the households, after which the pattern appeared to level off at around this figure. In contrast, the use of the technology outside the pilot villages rose steadily from 4.1% in 1997 to 13.7% in 1999, and thereafter levelled somewhat at about 13%. The size of the fallow plots was extremely small, averaging 0.04 ha per farm in 2001. Place et al. (2005) attribute the adoption patterns in pilot villages to high degree of technical support, which may have led to early high rates of testing by farmers. This rise was followed by dis-adoption by those who did not receive sufficient benefits or were unable to manage the technology after ICRAF and partners reduced backstopping efforts. Since 2001, the improved fallows have largely disappeared from farmers' fields in western Kenya. Mango (2002) enumerates a number of factors which may have caused dis-adoption of improved fallow technology by farmers in the pilot villages. A summary of these include: (1) rock phosphate, which was needed to correct P deficiency, and was supplied through ICRAF support, became unavailable when ICRAF withdrew; (2) women, who generally have many chores, could not successfully manage such a labour-intensive technology; (3) ICRAF and partners provided much technical and material support which ensured the success of the project but not its sustainability; and (4) ICRAF bought improved fallow seeds from farmers at generous prices. Farmers therefore saw improved fallows as a money-making venture and the soil improvement objective became secondary. When ICRAF stopped buying seed, the market collapsed and they saw no compelling reason to continue with the fallows.

This case study illustrates the importance of the socio-economic (*socio-cultural* and *economic* factors) component of the socio-ecological niche concept. The differences in the adoption behaviour between pilot and non-pilot villages can be explained by the way farmers rationalize decisions about new practices. Leeuwis and van den Ban (2004) term this the 'evaluative frame of reference', which relates to knowledge and mode of reasoning about the natural, economic and the social world. The evaluative frame of reference incorporates perceptions of technical and socio-economic consequences, perceptions of likelihood and risk, and valuation of consequences and risks *vis-à-vis* aspirations. Applying this analytical framework to this case study, it becomes clear that farmers in the pilot villages, because of the technical and material support offered, did not find it necessary to go through this process. When later on support was withdrawn and they started rationalizing the practice, the percentage of households using the technology fell rapidly.

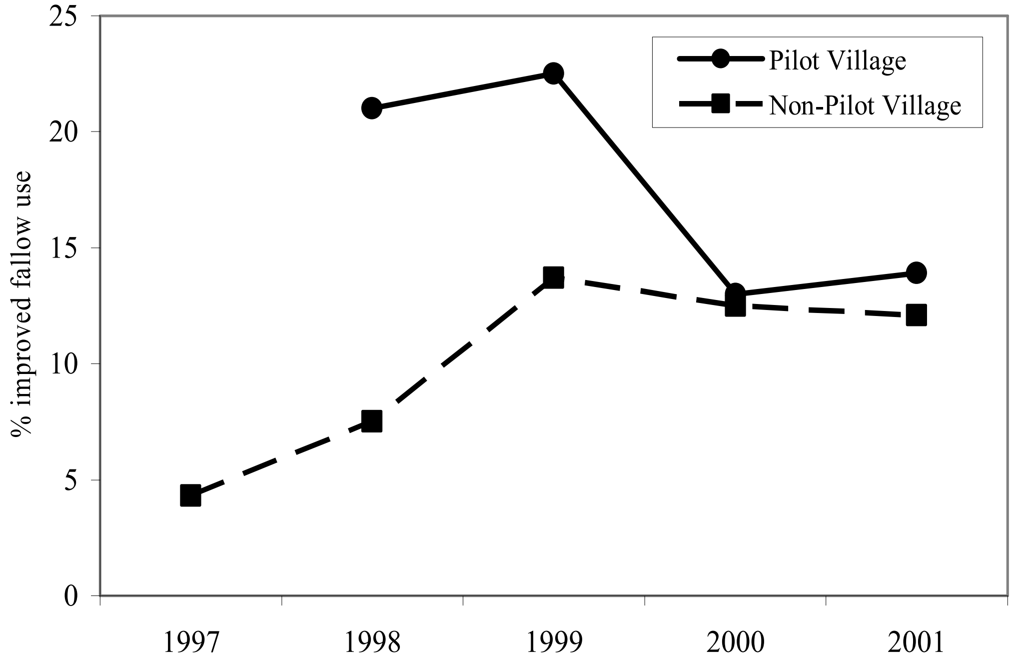


Figure 4. Adoption patterns of improved fallow species by target farmers in western Kenya between 1998 and 2001. Modified from Place et al., 2005.

Conclusions

Strategies for improving the adoption of legume technologies by smallholder farmers should take into account the large degree of heterogeneity in smallholder systems. Due to this heterogeneity, numerous biophysical and socio-economic constraints have to be addressed in order for a technology (e.g. legumes) to fit into the system and generate impact. The necessity for developing technologies that address the realities on the ground is generally appreciated and often the major objective of many projects. However, the fact that many technologies have not been accepted in smallholder systems suggests there are difficulties in practically achieving this objective. The socio-ecological niche concept offers a useful conceptual and practical framework for achieving this. The idea of the niche as being defined by multiple dimensions with which technologies must be compatible, and the procedure of niche screening elaborated here, offer useful approaches. The two case studies presented demonstrate the practical significance of the concept and the need for giving sufficient attention to all the dimensions (biophysical and socio-economic) of the niche so that technologies emerging from the process may fit in well in heterogeneous smallholder systems and be accepted by farmers. An extra dimension, not directly addressed in this paper, is to work closely together in partnership with farmers from the start of the research cycle. Of course, the scientists' role in participatory research, in addition to learning from the farmers, is to suggest potential interventions and improvements from their own experience, harnessing the most useful inputs from outside the local knowledge system. We are confident that the concept of the 'socioecological niche' can assist researchers in their understanding so that they think twice before introducing inappropriate technologies at the expense of farmers' time and confidence. We are currently using the 'socioecological niche' in experimental research evaluating a wide-variety of legumes together with farmers in western Kenya, and we believe the concept to be applicable to a wide range of technologies in tropical smallholder agriculture.

Chapter 3

Testing the socio-ecological niche concept: Adaptability of legumes in major western Kenya agro-ecosystems

This Chapter has been submitted for publication as:

Ojiem, J.O., Ridder, N. de, Vanlauwe, B. and Giller, K.E. Testing the socio-ecological niche concept: Adaptability of legumes in major western Kenya agro-ecosystems. *Field Crops Research.*

Chapter 3

Testing the socio-ecological niche concept: Adaptability of legumes in major western Kenya agro-ecosystems

Abstract

Smallholder farming systems in sub-Saharan Africa are often poorly productive. Although legumes have the potential for improving system productivity, their use by farmers is limited. Smallholder farmers operate under diverse agro-ecological conditions, with variations in precipitation, temperature, solar radiation, soil type, etc, to which legumes must be adapted. At the farm level, variations exist in soil fertility and incidence of pests and diseases between fields and farms. These agro-ecological factors limit the productivity of legumes in smallholder systems. Similarly, socio-economic constraints, e.g. scarcity of land, labour and production inputs, and individual farmer preferences limit the potential adoption of different legumes. Smallholder production environments therefore consist of niches with ecological and socio-economic dimensions (or socio-ecological niches) to which legumes must fit into in order to achieve wider acceptance. This study assessed the impact of the agro-ecological factors on legume productivity, as part of determining the fitness of legumes in farmers' socio-ecological niches. A range of green manure, forage and grain legume species were screened in three major agro-ecological zones (AEZ) in western Kenya: high rainfall zone (AEZ 1); medium rainfall zone (AEZ 2); and low rainfall zone (AEZ 3) to determine adaptation to varied agro-ecological conditions, and at farm level, to variations in soil fertility status and phosphorus (P) fertilization. Farmer preference was also assessed. Productivity varied significantly ($P<0.01$) between the AEZs, with total dry matter (TDM) accumulation ranging from 0.1 Mg ha^{-1} to 13.9 Mg ha^{-1}. These variations indicated differential performance of the legume species in the AEZs. Soyabean and groundnut were the best performing grain legumes in all AEZs. Averaged across high and low fertility fields and P treatments, TDM of soyabean decreased from 4.09 Mg ha^{-1} in AEZ 1 to 0.80 Mg ha^{-1} in AEZ 3, while that of groundnut decreased from 3.39 Mg ha^{-1} in AEZ 1 to 1.15 Mg ha^{-1} in AEZ 3. Groundnut variety ICGV-12988 had the best productivity in AEZs 1 and 3, while CG 7 had the best productivity in AEZ 2. However, the productivity of soyabean variety SB20 was consistently good across all zones. Although common bean is the most widely grown legume by farmers in western Kenya, it had the poorest productivity in all the zones, ranging from 0.44 Mg ha^{-1}, in AEZ 1, to 0.28 Mg ha^{-1} in AEZ 3. The TDM production of lablab decreased sharply with rainfall, from 9.53 Mg ha^{-1} in AEZ

1 to 1.01 Mg ha^{-1} in AEZ 3. Addition of P fertilizer significantly ($P<0.01$) increased legume productivity. The TDM production of soyabean varieties SB20 and SB17 and groundnut varieties ICGV-12988 and CG7 was significantly increased with P. Averaged across high and low fertility fields and P treatments, the green manure and forage legumes accumulated between 60 and 80% greater TDM than grain legumes. Velvet bean (8.37 Mg ha^{-1}), siratro (7.82 Mg ha^{-1}) and sunnhemp (7.01 Mg ha^{-1}) were the best species in AEZs 1, 2 and 3, respectively. Siratro and velvet bean showed more sensitivity to poor soil fertility than sunnhemp and desmodium. Farmer assessments were not in full agreement with agronomic evaluation in all cases. Our results demonstrate the potential of legume species for improving western Kenya smallholder productivity, so long as careful selection is made to match legumes to agro-ecological conditions and farmer needs.

Key words: Grain legumes, green manures, forage legumes, phosphorus deficiency, farmer evaluation, soil fertility heterogeneity.

Introduction

Smallholder systems of sub-Saharan Africa are poorly productive, partly due to fertility depletion arising from continuous cropping with few purchased inputs. Nitrogen is the nutrient taken up in the greatest quantities by crops, leading to universal deficiency in most agricultural systems (Giller, 2001). Use of leguminous plant species offers promise for improvement of the systems. Benefits of incorporating legumes into smallholder systems include improvements in soil structure (Gliessman, 2000), weed control (Bradshaw and Lanini, 1995; Hedge and Miller, 1990) and restoration of soil fertility through inputs of fixed atmospheric nitrogen (Smithson and Giller, 2002). By biologically fixing atmospheric nitrogen, legumes provide opportunity for the reclamation of degraded lands (Peoples and Craswell, 1992; Thomas et al., 1997) and protection of the soil against erosion (Busscher et al., 1996).

Smallholder farmers in western Kenya, as in many parts of sub-Saharan Africa, operate in very diverse agro-ecological conditions, which influence the growth and production of legumes. At the farm level, the systems are characterized by biophysical and socio-economic heterogeneity (Tittonell et al., 2005a,b), which not only constrains the use of legumes, but also limits their potential. Differences exist in soil fertility between fields of the same farm, arising from inherent soil properties and management regimes. Other agro-ecological factors limiting the productivity of legumes in the smallholder systems include precipitation, temperature, soil type, pests and diseases, and nutrient deficiencies, particularly phosphorus (P). N_2-fixation by legumes in P-deficient soils may not be sufficient to maintain productivity (Giller et al., 1997).

Due to the heterogeneity between farms, the choice of legume types for incorporation into smallholder farming systems is important since different legumes, e.g. grain, green manure and forage species may be preferred by different farmers, with different impacts on soil fertility. Net N additions to the soil are likely to be small or even negative for grain and fodder legumes, where substantial N is removed at harvest (Giller, 2001; Smithson and Giller, 2002). Under these variable conditions, the proportion of N in a legume crop derived from N_2-fixation may vary widely (Giller, 2001). Similarly, socio-economic constraints, e.g. scarcity of land, labour and production inputs, taste preferences and production objectives limit the legume options in smallholder farming systems. Multipurpose grain and fodder legumes, with benefits of producing grain and fodder, but which are traded off for a reduced contribution to soil fertility, are likely to be more readily accepted by farmers. Due to these constraints, the smallholder production environment can be viewed as consisting of niches that have agro-ecological and socio-economic dimensions (or socio-ecological niches) into which legumes must fit to enhance productivity (Chapter 2).

The agro-ecological factors that determine the socio-ecological niche are distinguishable at two scales: (i) the broad level environmental conditions, e.g. precipitation, temperature, solar radiation, soil type, etc, which influence the adaptability of legumes at agro-ecosystem level; and (ii) the local level variations, e.g. in soil fertility status and incidence of pests and diseases, etc., which influence the productivity of legumes at farm level. However, it is acknowledged that widespread incidence of some pests and diseases can be considered to operate at agro-ecosystem and local levels. The objective of this study was to test the socio-ecological niche concept by determining: (i) legume adaptability to broad level agro-ecological conditions; and (ii) legume productivity in response to variations in soil fertility status and P fertilization, at the farm level. A range of green manure, forage and grain legume species were therefore screened in three major agro-ecological zones (AEZ) in western Kenya: (i) high rainfall zone (AEZ 1); (ii) medium rainfall zone (AEZ 2); and (iii) low rainfall zone (AEZ 3).

Materials and methods

Sites selection and characterization

The experiments were conducted at three sites chosen to represent three major agro-ecological zones in western Kenya: Museno (AEZ 1), located at 00^{o} 14' N and 34^{o} 44' E (high rainfall); Majengo (AEZ 2), located at 00^{o} 00' N and 34^{o} 41' E (medium rainfall); and Ndori (AEZ 3), located at 00^{o} 02' S and 34^{o} 20' E (low rainfall). All of the sites have bimodal rainfall patterns, with first (the long rains) growing season extending from March to August and the second (the short rains) from September to January. The sites are described in more detail in Table 1.

In order to address the heterogeneity in soil fertility, which is a common feature in smallholder farms in western Kenya (Tittonell et al., 2005a), two fields (a high fertility (HF) field and low fertility (LF) field) were selected in each experimental farm and in all the AEZs. The fertility ratings of the two fields were based entirely on the soil fertility perceptions of the participating farmers. However, in each field, composite soil samples (0-20 cm depth) were taken from nine spots and bulked. From each bulked sample, a sub-sample of about 1 kg was then taken for chemical and physical analysis (Table 1). In AEZ 1, there were large differences between high and

Table 1. Soil and agro-climatic characteristics of the study sites in Western Kenya where the experiments were conducted.

Site/Field & fertility status	Location (coordinates)	Agro-ecological classification	Altitude (masl)	Mean Annual Rainfall (mm)	Mean Annual Temp. (°C)	Soil type[a]	pH (H_2O)	Total C (g kg^{-1})	Total N (g kg^{-1})	C:N ratio	Extractable P (mg kg^{-1})	Particle size (%)		
												Sand	Silt	Clay
Museno	Latitude: 00° 14′ N Longitude: 34° 44′ E	Upper Midland Zone 1 (AEZ 1)	1500	2000	18									
High fertility	-	-	-	-	-	Nitisol	5.59	11.5	1.34	9:1	15.8	37	26	37
Low fertility	-	-	-	-	-	Nitisol	5.13	8.00	0.85	9:1	4.4	45	21	34
Majengo	Latitude: 00° 00′ N Longitude: 34° 41′ E	Upper Midland Zone 2 (AEZ 2)	1385	1600	19									
High fertility	-	-	-	-	-	Acrisol	5.82	16.9	1.77	10:1	2.5	36	33	31
Low fertility	-	-	-	-	-	Acrisol	5.79	14.7	1.77	8:1	1.5	35	35	30
Ndori	Latitude: 00° 02′ N Longitude: 34° 20′ E	Transitional Lower Midland Zone 2/3 (AEZ 3)	1270	1200	22									
High fertility	-	-	-	-	-	Ferralsol	5.88	15.0	1.77	8:1	2.4	29	33	38
Low fertility	-	-	-	-	-	Ferralsol	5.82	12.4	1.30	10:1	1.8	33	33	34

masl = metres above sea level, [a]Jaetzold and Schmidt, (1983).

Table 2. Description of legume species screened at the three agro-ecological zones in western Kenya, long rain 2003 season

Species name	Common name	Source/Variety/Description	Plant spacing	
Grain legumes:			Inter-row	Intra-row
Glycine max (L.) Merr.	Soyabean	[a]IITA /Code TXG1831-32E (SB2)/ early maturity	50 cm	5 cm
		IITA /Code TXG1835-10E (SB3)/ early maturity	50 cm	5 cm
		IITA /Code TXG1893-10F (SB17)/ medium-late maturity	50 cm	5 cm
		IITA /Code TXG1448-2E (SB20)/ medium-late maturity	50 cm	5 cm
Arachis hypogaea L.	Groundnut	*Nyahela*/ farmers' local landrace, early maturity	50 cm	10 cm
		[b]ICRISAT/Code ICGV-12911/ early maturity	50 cm	10 cm
		ICRISAT/Code ICGV-12988/ early maturity	50 cm	10 cm
		ICRISAT/CG7/ medium maturity	50 cm	10 cm
Phaseolus vulgaris L.	Common bean	western Kenya/*Okwuodo* (land race)/ early maturity	50 cm	10 cm
		[c]KARI/Code KK8/ medium late maturity	50 cm	10 cm
		KARI/Code KK15/ early maturity	50 cm	10 cm
		KARI/Code KK20/ early maturity	50 cm	10 cm
Vigna radiata (L.) R. Wilczek	Green gram (LG)	Farmers' landrace/ long grained, early maturity	25 cm	15 cm
	Green gram (RG)	Farmers'landrace/ round grained, early maturity	25 cm	15 cm
Phaseolus lunatus L.	Lima bean	KARI	25 cm	15 cm
Lablab purpureus (L.) Sweet	Lablab	KARI	60 cm	30 cm
Vigna unguiculata (L.) Walp	Cowpea	KARI (M66)	25 cm	15 cm
Green manure legumes:				
Crotalaria juncea L.	Sunnhemp	KARI	30 cm	Drill
Crotalaria ochroleuca (G.) Don	Crotalaria	KARI	30 cm	Drill
Mucuna pruriens (L.) DC.	Velvet bean	KARI	60 cm	30 cm
Canavalia ensiformis (L.) DC.	Jackbean	KARI	60 cm	30 cm
Forage legumes:				
Desmodium uncinatum (Jacq.) DC.	Silver leaf desmodium	KARI	30 cm	Drill
Macroptilium atropurpureum (DC.) Urban	Siratro	KARI	30 cm	Drill
Stylosanthes guianensis (Aublet) Sw.	Stylo	KARI	30 cm	Drill

[a]IITA = International Institute for Tropical Agriculture. [b]ICRISAT = International Crops Research Institute for the Semi-Arid Tropics. [c]KARI = Kenya Agricultural Research Institute

low soil fertility fields in total N and extractable P, while in AEZ 2 and 3 the differences in soil fertility parameters were small.

Experimental design and treatments

The experiments were established in a split-plot design, replicated in two blocks. The main plots consisted of two P rates, 0 kg P ha^{-1} and 30 kg of P ha^{-1}, using triple super phosphate (TSP) fertilizer (0:46:0 N:P:K), while the sub-plots were the grain, green manure and forage legume species and varieties listed in Table 2. The legume plots were established in both HF and LF fields in all the experimental farms at the beginning of the long rain season in April 2003 in plots measuring 2 m by 2 m. Prior to planting, germination tests were conducted to ensure at least 95% seed viability. TSP was applied at planting at 30 kg P ha^{-1} to main plots receiving P, placed in planting holes, and for drilled species, in furrows (See Table 2). No inoculation of the seeds was done and the species relied solely on naturally occurring rhizobia for nodulation. Four weeding operations were done in AEZs 1 and 2 sites at 22, 45, 62 and 80 days after planting (DAP), due to relatively high weed growth rate, while in AEZ 3 site, three weeding operations were done at 22, 45 and 62 DAP.

Legume emergence and establishment

Plant emergence and survival were assessed in all plots in each AEZ. The number of plants emerged in each plot was recorded at 21 DAP, except velvet bean and jackbean, which were relatively slow in emergence and were assessed between 21 and 35 DAP. Plant survival was assessed at mid-pod filling stage for each species. The number of plants surviving at this stage was counted and expressed as percentage of emerged. It proved difficult to accurately count plants in cowpea, desmodium and stylo plots due to non-erect growth habit of these species. Consequently, survival data for these legumes is not reported.

Reaction of species to diseases

Reaction of the legume species to diseases was assessed in all farms between 45 and 55 DAP, depending on the speed of establishment of the species. In all the species studied, incidence of diseases reached the peak within the first two months of growth. Reaction to diseases was scored on a scale of 1 to 5 as follows: (1) most plants in the plot show severe disease symptoms, high death rate; (2) same as (1) but low death rate; (3) many plants in the plot show mild disease symptoms; (4) few plants in the plot show mild disease symptoms; and (5) all plants in the plot are healthy, no observable disease symptoms. Due to the impracticality of scoring for individual diseases (symptoms often similar and confusing), scoring was done for a complex of diseases. Disease symptoms were mainly observed on the leaves and stems. Pest incidence was minor in all the agro-ecological zones and was therefore not scored.

Species nodulation and N_2-fixation potential

Assessment of the capacity to form viable nodules with native rhizobia was done in all legume plots at around mid-flowering stage. A visual ranking was made based on a methodology described by Peoples et al. (1997) and Corbin et al. (1977). N_2-fixation potential was based on: (1) the relative number of nodules on the crown root; (2) the size of nodules; and (3) whether or not the nodules were active (assessed by red colouration). These parameters were used to rank N_2-fixation potential on a scale of 1 to 5, where: (1) little or no nodulation and N_2-fixation potential; (2) poor nodulation and N_2-fixation potential; (3) fair nodulation and N_2-fixation potential; (4) good nodulation and good potential for N_2-fixation; and (5) excellent nodulation and high potential for N_2-fixation. Ranking was done on 10 plants sampled in the middle two rows of the plot.

Biomass and grain production

The above ground biomass was determined at peak flowering, while grain yield was determined at harvest. The species matured at different times and grain was harvested between June and August, 2003. The above ground biomass and grain production were determined by harvesting all the plants in the plot after discarding one border row on each side of the plot and one plant at each end of the rows. Biomass samples were taken from each plot and immediately weighed with an electronic balance to determine fresh weight then oven-dried at 65^oC for 4 days to determine dry weight. Grain moisture content was determined using an electronic moisture meter and yield expressed at 12% moisture content.

Farmer evaluation

A participatory evaluation exercise was conducted to determine farmers' opinion on the performance of the species and to gain insight into the major criteria they use for selecting legumes. A separate exercise was conducted in each AEZ in order to capture differences between the locations. In each AEZ, a group of between 35 and 50 farmers, constituting trial hosts and their neighbours, participated in the evaluation exercises. Farmers in each AEZ separately agreed on important evaluation criteria to be used. However, due to similarities in proposed criteria across the locations, seven principal evaluation criteria were generalized for use in all the AEZs. These were: (1) ability of the legume to emerge well; (2) early maturity; (3) good flowering and leafiness; (4) disease and pest tolerance; (5) ability of the legume to grow well in low fertility soil; (6) drought tolerance; and (7) general productivity (grain and biomass). These criteria were used by farmers in each site to evaluate each legume species and variety. On each evaluation criteria, farmers scored for performance on a scale of 1 to 10: where 1= worst performance and 10 = best performance.

Data analysis

The data for the legumes species and varieties given in Table 2 were subjected to analysis of variance (ANOVA) using SAS statistical software, release 8.2 (SAS Institute Inc., Cary, NC, U.S.A.). The experimental factors were AEZ, legumes, varieties and phosphorus. Plant emergence, survival, reaction to diseases, nodulation and N_2-fixation, and grain yield and total dry matter production were analysed. Where significant differences were detected, comparisons of means were made by standard error of difference (SED). Since the number of observations was not equal for all legume species means, appropriate SED values were calculated and used in the comparison of legume means.

Results

Legume species emergence

Emergence of the legume species (Table 3) declined significantly ($P<0.01$) with AEZ potential. Mean emergence rate was 83% in AEZ 1, 76% in AEZ 2 and 64% in AEZ 3. Significant ($P<0.01$) differences in emergence were detected among legume species. In AEZ 1, soyabean (90%) and groundnut (88%) had the best emergence among the grain legumes. Emergence of common bean (bean) and lablab were significantly poorer than the rest of the grain legume species. Soyabean variety SB20 (92%) and groundnut variety ICGV-12988 (91%) had the best emergence,

Table 3. Emergence of legume species and varieties in three agro-ecological zones in western Kenya, long rains 2003 season.

	% emergence									
	AEZ 1			AEZ 2			AEZ 3			Mean
	HF field	LF field	Mean	HF field	LF field	Mean	HF field	LF field	Mean	
Soyabean[1] mean	**94**	**86**	**90**	**74**	**85**	**80**	**60**	**65**	**63**	**77**
Var. T XG1831-32E (SB 2)	90	83	87	71	86	79	58	53	56	74
Var. TXG1835-10E (SB 3)	88	88	88	81	80	81	70	74	72	80
Var. TXG1893-10F (SB 17)	83	87	85	71	88	80	50	64	57	74
Var. TXG1448-2E (SB 20)	95	88	92	73	85	79	62	72	67	79
Groundnut[1] mean	**89**	**86**	**88**	**62**	**75**	**69**	**52**	**55**	**54**	**70**
Var. *Nyahela*	94	80	87	61	63	62	44	51	48	66
Var. ICGV-12911	88	87	88	72	80	76	45	63	54	73
Var. ICGV-12988	89	92	91	67	77	72	68	57	63	75
Var. CG7	86	85	86	73	79	76	50	49	50	70
Bean[1] mean	**79**	**72**	**76**	**69**	**72**	**71**	**64**	**61**	**63**	**70**
Var. *Okwuodo*	73	75	74	70	69	70	72	59	66	69
Var. KK 8	84	69	77	61	78	70	64	63	64	70
Var. KK 15	84	72	78	73	65	69	63	62	63	68
Var. KK 20	73	72	73	81	75	78	57	62	60	66
Green gram[2] mean	**83**	**83**	**83**	**75**	**79**	**77**	**50**	**69**	**60**	**73**
Var. LG	87	84	86	73	83	78	50	72	61	75
Var. RG	80	81	81	77	74	76	50	70	60	72
Lima[3]	88	84	86	57	80	69	63	48	56	70
Lablab[3]	63	67	65	62	59	61	87	32	60	62
Cowpea[3]	80	84	82	64	74	69	70	36	53	68
Sunnhemp[3]	92	91	92	89	89	87	86	85	86	89
Crotalaria[3]	93	92	93	91	92	90	89	87	88	91
Velvet bean[3]	75	76	76	70	71	70	66	63	65	71
Jackbean[3]	77	78	78	74	75	74	65	66	66	72
Desmodium[3]	84	85	85	81	83	82	77	74	76	81
Siratro[3]	87	88	88	86	86	85	81	76	79	84
Stylo[3]	84	85	85	81	80	81	78	84	81	82
Mean (varieties)	85	82	84	72	77	75	57	62	60	-
SED for varieties/legume[3] means	8.5**	8.5**	6.0**	8.5**	8.5**	6.0**	8.5**	8.5**	6.0**	3.5**
Mean (legumes)	83	83	83	74	78	76	64	63	64	-
SED[1]	4.3**	4.3**	3.0**	4.3**	4.3**	3.0**	4.3**	4.3**	3.0**	1.8**
SED[2]	5.3**	5.3**	3.7**	5.3**	5.3**	3.7**	5.3**	5.3**	3.7**	2.1**
SED[3]	6.8**	6.8**	4.8**	6.8**	6.8**	4.8**	6.8**	6.8**	4.8**	2.8**

SED[1] = for comparing among legume[1] means. SED for varieties x fertility interaction means = 8.5 SED for legume[3] x fertility interaction means = 8.6
SED[2] = for comparing legume[1] means with legume[2] mean. SED for legume[1] x fertility interaction means = 4.3
SED[3] = for comparing legume[1] means with legume[3] means. SED for legume[2] x fertility interaction means = 6.1
SED =Standard error of differences between means, ** = significant at $P<0.01$.

which were significantly (*P*<0.01) better than those of the bean varieties. Among green manure and forage legume species, crotalaria (93%) and sunnhemp (92%) had the best emergence, which were significantly (*P*<0.01) different from jackbean (78%) and velvetbean (76%).

There was a reduction in emergence by up to 31% in AEZ 2. Soyabean (80%) and green gram (77%) had significantly (*P*<0.01) better emergence than lablab (61%). Among the green manure legumes, crotalaria and sunnhemp had emergence rates of 90% and 87%, respectively, which were significantly better than those of jackbean (74%) and velvet bean (70%). Mean emergence was 17% lower in AEZ 3 compared with AEZ 2. Soyabean and bean had the best mean emergence of 63% each. Like in AEZs 1 and 2, groundnut had poorer emergence in AEZ 3 compared with soyabean. However, the emergence of the green manure and forage legume species was generally consistent with those in AEZ 1 and AEZ 2. Crotalaria (88%) and sunnhemp (86%) had the best emergence, which were significantly (*P*<0.01) higher than those of jackbean (66%) and velvet bean (65%).

Species reaction to diseases

The climate during the long rains 2003 growing season was conducive for a build up of high disease pressure because of high rainfall received during the season, especially in AEZs 1 and 2 (Figure 1). Due to this, incidence of diseases was high and effective screening of legume species for disease infestation was feasible. The major diseases encountered included angular leaf spot, anthracnose, rusts and bacterial blights, which were especially severe in bean and cowpea. The infestation of the legume species by diseases differed significantly (*P*<0.01) between AEZs (Table 4). Contrary to emergence trends, disease infestation increased with decreasing rainfall. Species showed significantly (*P*<0.01) lower disease infestation in AEZ 3, with mean scores of 3.9, 3.4 and 3.2, for AEZ 3, AEZ 2 and AEZ 1, respectively.

In AEZ 1, soyabean had a disease score of 3.7, indicating significantly (*P*<0.01) greater disease tolerance than the rest of the grain legume species, while bean (with a score of 1.2) was more susceptible to diseases than the rest of the grain legumes. Among the grain legume varieties, soyabean SB17, and SB20 had the best scores of 4.0 each, showing significantly (*P*<0.01) greater disease tolerance than the rest. Bean varieties had the least tolerance scores of between 1.0 and 1.6. Similar to plant emergence, the disease tolerance of the green manure and forage legume species was significantly (*P*<0.01) better than the rest, with scores ranging from 4.6 to 4.3. However, the disease tolerance of lablab, a dual purpose species, was comparable to green manure and forage legumes.

Table 4. Reaction of legume species and varieties to diseases in three agro-ecological zones in western Kenya, long rains 2003 season.

Legume/variety		Disease scores			
		AEZ1	AEZ2	AEZ3	Mean
Soyabean[1] mean		**3.7**	**4.0**	**4.1**	**3.9**
	Var. TXG1831-32E (SB 2)	3.5	4.0	4.3	3.9
	Var. TXG1835-10E (SB 3)	3.3	3.9	4.1	3.7
	Var. TXG1893-10F (SB 17)	4.0	4.3	4.2	4.1
	Var. TXG1448-2E (SB 20)	4.0	4.4	3.9	4.1
Groundnut[1] mean		**2.9**	**2.9**	**3.7**	**3.2**
	Var. *Nyahela*	2.7	2.7	3.6	3.0
	Var. ICGV-12911	2.9	3.0	3.7	3.2
	Var. ICGV-12988	3.3	3.0	3.7	3.3
	Var. CG7	2.9	2.8	4.2	3.3
Bean[1] mean		**1.2**	**1.6**	**3.3**	**2.0**
	Var. *Okwuodo*	1.0	1.9	3.0	2.0
	Var. KK 8	1.0	1.4	3.4	1.9
	Var. KK 15	1.6	1.3	3.4	2.1
	Var. KK 20	1.3	1.8	3.4	2.2
Green gram[2] mean		**2.9**	**3.2**	**3.5**	**3.2**
	Var. LG	3.0	3.2	3.3	3.1
	Var. RG	2.7	3.2	4.2	3.3
Lima[3]		3.0	3.4	4.3	3.6
Lablab[3]		4.5	4.7	4.4	4.5
Cowpea[3]		2.8	2.4	3.7	2.9
Sunnhemp[3]		4.3	4.3	4.5	4.3
Crotalaria[3]		4.3	4.3	4.3	4.3
Velvet bean[3]		4.4	4.3	4.5	4.4
Jackbean[3]		4.5	4.3	4.5	4.4
Desmodium[3]		4.3	4.6	4.6	4.5
Siratro[3]		4.3	4.3	4.6	4.4
Stylo[3]		4.3	4.5	4.6	4.4
Mean (varieties)		2.9	2.9	3.7	3.1
SED for varieties/legume[3] means		0.3**	0.3**	0.3**	0.03**
Mean (legumes)		3.2	3.4	3.9	-
SED[1]		1.15**	1.15**	0.15**	0.09**
SED[2]		0.19**	0.19**	0.19**	0.11**
SED[3]		0.35**	0.35**	0.35**	0.14**

SED[1] = for comparing among legume[1] means. SED for varieties x AEZ interaction means = 0.31**
SED[2] = for comparing legume[1] means with legume[2] means. SED for legume[1] x AEZ interaction means = 0.16**
SED[3] = for comparing legume[1] means with legume[3] means. SED for legume[2] x AEZ interaction means = 0.22**
SED for legume[3] x AEZ interaction means = 0.31**
SED = Standard error of differences between means, ** = significant at $P<0.01$

Soyabean and Lima had improved performance in AEZ 2, with varieties SB17 (4.3) and SB20 (4.4) showing the best disease tolerance. However, groundnut performed worse than soyabean in AEZ 1. Varieties ICGV-12911 and ICGV-12988 had the best disease tolerance. Bean showed the least tolerance to diseases in AEZ 2, with a mean score of 1.6. O*kwuodo* (farmer variety) and KK20 showed the best disease tolerance. The performance of green manure and forage legume species in AEZ 2 was generally similar to AEZ 1. However, desmodium and stylo showed slightly better disease tolerance. The species were generally less infested by diseases in AEZ 3 compared with AEZs 1 and 2. As a result, Lima (4.3) and groundnut (3.7) showed great improvements in disease scores. Among the groundnut varieties, CG7 showed the greatest improvement in disease score (4.2) in AEZ 3, compared with AEZ 2 (2.8). Soyabean, green manure and forage legume performances were generally similar to AEZ 2.

Plant survival

Plant survival decreased significantly ($P<0.01$) with decreasing AEZ potential (Table 5). The percentage of plants which had survived at mid pod filling stage was highest in AEZ 1 (74%) and lowest in AEZ 3 (69%). Among the grain legumes, soyabean and groundnut had the highest survival rates of 84% each in AEZ 1, which were significantly ($P<0.01$) better than the rest of the grain legumes.

Table 5. Survival of legume species and varieties, at mid pod filling stage, in three agro-ecological zones in western Kenya, long rains 2003 season

Legume/variety		% Plant survival		
	AEZ1	AEZ2	AEZ3	Mean
Soyabean[1] mean	**84**	**78**	**78**	**80**
Var. TXG1831-32E (SB 2)	83	77	76	78
Var. TXG1835-10E (SB 3)	86	79	*78*	81
Var. TXG1893-10F (SB 17)	83	79	*78*	80
Var. TXG1448-2E (SB 20)	90	78	79	82
Groundnut[1] mean	**84**	**66**	**65**	**72**
Var. *Nyahela*	81	65	59	68
Var. ICGV-12911	83	73	73	76
Var. ICGV-12988	89	64	69	74
Var. CG7	84	61	61	68
Bean[1] mean	**30**	**35**	**35**	**33**
Var. *Okwuodo*	25	30	30	28
Var. KK 8	26	33	35	31
Var. KK 15	33	38	36	35
Var. KK 20	36	38	40	38
Green gram[2] mean	**66**	**73**	**72**	**70**
Var. LG	66	73	73	70
Var. RG	66	73	73	70
Lima[3]	64	60	60	61
Lablab[3]	74	67	67	69
Sunnhemp[3]	89	87	87	88
Crotalaria[3]	90	89	90	90
Velvet bean[3]	73	57	65	65
Jackbean[3]	76	73	57	69
Siratro[3]	80	84	84	82
Mean (varieties)	67	62	61	-
SED for varieties/legume[3] means	2.9**	2.9**	2.9**	1.7**
Mean (legumes)	74	70	69	-
SED[1]	1.7**	1.7**	1.7**	1.0**
SED[2]	2.6**	2.6**	2.6**	1.2**
SED3	2.9**	2.9**	2.9**	1.5**

SED[1] = for comparing among legume[1] means.
SED[2] = for comparing legume[1] means with legume[2] means
SED[3] = for comparing legume[1] means with legume[3] means

SED for varieties x AEZ interaction means = 2.9*
SED for legume[1] x AEZ interaction means = 1.7
SED for legume[2] x AEZ interaction means = 2.3
SED for legume[3] x AEZ interaction means = 3.3

SED = Standard error of differences between means, ** = significant at $P<0.01$.

Similarly, soyabean and groundnut varieties had over 80% survival, while the survival of the other grain legume varieties ranged from 66%, in green gram, to 25% in *Okwuodo*. Crotalaria (90%) and sunnhemp (89%) had significantly (P<0.01) better survival than the rest of the green manure and forage species. In AEZ 2, soyabean had the best survival (78%) among the grain legume species, while bean had the lowest (35%). However, the survival of groundnut decreased by about 21% in AEZ 2. Similar to AEZ 1, soyabean and green gram varieties survived best and bean worst. The survival of the green manure and forage legume species was consistent with that in AEZ 1. Crotalaria (89%) and sunnhemp (87%) had the best survival rates, which were significantly (P<0.01) better than jackbean (73%) and velvet bean (57%). Differences in the survival of legumes between AEZ 2 and AEZ 3 were negligible, except in groundnut variety *Nyahela,* which had 9% lower survival in AEZ 3, and velvet bean, whose survival was 14% higher in AEZ 3 compared with AEZ 2.

Species nodulation and N_2-fixation potential

Due to the inherent differences in nodulation characteristics between legumes, comparisons of the nodulation performance of the species studied are restricted to varieties within legume. P had significant (P<0.01) effects on the nodulation of the legumes (Table 6). In contrast to disease tolerance, which was best in AEZ 3, nodulation performance was significantly (P<0.01) better in AEZs 1 and 2, compared with AEZ 3. Mean nodulation score was 3.9 for both AEZs 1 and 2, and 3.5 for AEZ 3. Significant (P<0.01) differences were detected in nodulation performance of varieties (within legume species) in AEZ 1. In soyabean, variety SB17 had the best mean nodulation score of 4.4, which was significantly (P<0.01) better than the rest. However, only variety SB2 responded significantly to P. Among the groundnut varieties, ICGV-12911 and ICGV-12888 had the best nodulation scores of 4.6 and 4.7, respectively, and significant nodulation responses to P. In contrast, *Nyahela* (3.9) and CG7 (4.4) had the worst nodulation and non-significant responses to P. Nodulation was poor among the bean varieties. Varieties KK8 and KK20 had the best scores of 2.9 each, while *Okwuodo* had the worst score of 2.5. Only varieties O*kwuodo* and KK15 responded significantly to P. Green gram variety LG hadsignificantly better nodulation than variety RG. No clear nodulation response patterns were observed for the rest of the legume species in AEZ 1.

Nodulation performance of the legumes in AEZ 2 was generally consistent with that in AEZ 1. Among the soyabean varieties, SB17 had the best nodulation score (4.7) and SB20 the worst (3.7). However, varieties SB17 and SB20 responded significantly to P. Similar to AEZ 1, varieties ICGV-12911 and ICGV-12988 had the

Table 6. Nodulation of legume species and varieties in three agro-ecological zones in western Kenya, long rains 2003 season.

Legume species/variety	Nodule score AEZ1			AEZ2			AEZ3		
	0 kg P ha^{-1}	**30 kg P ha^{-1}**	**Mean**	**0 kg P ha^{-1}**	**30 kg P ha^{-1}**	**Mean**	**0 kg P ha^{-1}**	**30 kg P ha^{-1}**	**Mean**
Soyabean[1]	**3.9**	**4.1**	**4.0**	**4.2**	**4.3**	**4.2**	**4.0**	**3.8**	**4.1**
Var. TXG1831-32E (SB2)	4.0	4.3	4.2	4.3	4.3	4.3	4.0	4.0	4.0
Var. TXG1835-10E (SB3)	4.0	4.0	4.0	4.3	4.3	4.3	4.0	3.5	3.7
Var. TXG1893-10F (SB17)	4.3	4.5	4.4	4.8	4.5	4.7	4.0	4.5	4.3
Var. TXG1448-2E (SB20)	3.3	3.5	3.4	3.3	4.0	3.7	4.0	3.0	3.5
Groundnut[1]	**4.3**	**4.5**	**4.4**	**4.0**	**4.3**	**4.1**	**3.6**	**3.0**	**3.2**
Var. *Nyahela*	3.8	4.0	3.9	3.5	4.3	3.9	2.8	3.5	3.3
Var. ICGV-12911	4.3	4.8	4.6	4.8	4.0	4.4	4.0	2.8	3.4
Var. ICGV-12988	4.5	4.8	4.7	4.3	4.5	4.4	2.5	3.0	2.8
Var. CG7	4.3	4.5	4.4	3.3	4.3	3.8	4.2	4.5	4.3
Bean[1]	**2.5**	**3.0**	**2.8**	**2.9**	**2.9**	**2.9**	**2.5**	**2.6**	**2.6**
Var. Okwuodo	2.0	3.0	2.5	2.8	2.8	2.8	2.5	2.5	2.5
Var. KK 8	2.8	3.0	2.9	3.0	2.5	2.8	2.0	3.0	2.5
Var. KK 15	2.5	3.0	2.8	2.8	2.8	2.8	2.5	2.5	2.5
Var. KK 20	2.8	3.0	2.9	2.8	3.3	3.1	2.8	2.3	2.6
Green gram[2]	**4.3**	**4.2**	**4.2**	**3.4**	**3.4**	**3.4**	**3.0**	**3.5**	**3.3**
Var. LG	4.3	4.3	4.3	3.8	3.8	3.8	3.5	3.0	3.3
Var. RG	4.3	4.0	4.2	3.0	3.0	3.0	2.5	4.0	3.3
Lima[3]	4.8	4.3	4.6	4.0	5.0	4.5	3.5	3.5	3.5
Lablab[3]	4.3	4.8	4.6	4.0	5.0	4.5	4.0	3.0	3.5
Cowpea[3]	4.3	3.8	4.1	3.8	4.3	4.1	3.5	3.5	3.5
Sunnhemp[3]	4.3	4.3	4.3	4.3	4.5	4.4	4.3	4.3	4.3
Crotalaria[3]	4.3	4.3	4.3	4.3	4.8	4.6	4.3	4.3	4.3
Velvet bean[3]	4.3	3.8	4.1	3.8	4.3	4.1	4.0	4.0	4.0
Jackbean[3]	3.8	3.3	3.6	3.8	3.8	3.8	3.3	3.8	3.6
Desmodium[3]	4.0	3.6	3.8	4.3	4.3	4.3	3.8	4.3	4.1
Siratro[3]	4.5	4.0	4.3	4.3	4.8	4.6	4.3	4.3	4.3
Stylo[3]	4.3	4.3	4.3	4.3	4.3	4.5	4.3	4.3	4.3
Mean	3.9	4.0	3.9	3.8	4.0	3.9	3.4	3.5	3.5

SED for varieties within legume means = 0.10**
SED for varieties x P means= 0.23**
SED for varieties x AEZ means= 0.23**
SED for P means = 0.05**
SED for AEZ means = 0.06**
SED = standard error of differences between means, ** = significant at $p<0.01$.

best nodulation performance in AEZ 2, with *Nyahela* and CG7 showing response to P. For lima and lablab, nodulation was significantly (P<0.01) reduced in AEZ 2 compared with AEZ 1. However, for both the species nodulation was significantly improved with P. For the green manure species, nodulation was slightly improved compared with AEZ 1. While significant nodulation response to P was observed in crotalaria, there were no significant effects of P on the nodulation by desmodium, siratro and stylo.

Mean nodulation was about 11% lower in AEZ 3 compared with AEZ 2. Soyabean varieties SB2 (4.0) and SB17 (4.5) had the best nodulation performance. Although variety SB2 did not respond to P, the other varieties did. Among the groundnut, CG7 had the best mean nodulation, with a score of 4.3, which was significantly better than the rest. All the groundnut varieties showed nodulation responses to P. The differences between the bean varieties were small and KK8 showed significant nodulation response to P. Other significant nodulation responses to P were observed, e.g. in jackbean and desmodium.

Grain production

There were significant (P<0.01) differences in grain yield between the agro-ecological zones (Table 7). In AEZ 1, averaged across P rates, groundnut had the best grain yield of 1.42 Mg ha^{-1} in the high fertility (HF), field which was significantly (P<0.01) greater than that of soyabean (1.21 Mg ha^{-1}). The grain yield of lablab (0.60 Mg ha^{-1}) was significantly greater than green gram, cowpea and lima bean, while the grain yield of bean (0.04 Mg ha^{-1}) was the poorest. Among the soyabean varieties, SB17 (1.10 Mg ha^{-1}) and SB20 (1.97 Mg ha^{-1}) had the best grain yield performance. In groundnut, varieties ICGV-12911 (1.48 Mg ha^{-1}) and CG7 (1.54 Mg ha^{-1}) had the best grain yield. All soyabean varieties, except SB3 had significant grain yield responses to P, while in groundnut, only variety ICGV-12988 showed significant responses. In the low soil fertility field (LF), however, groundnut grain yield (0.97 Mg ha^{-1}) did not differ significantly (P<0.01) from that of soyabean (0.86 Mg ha^{-1}). While soil fertility had little effect on the grain yield of soyabean, that of groundnut reduced by about 32% in the LF field. Soyabean variety SB20 had the best grain yield (0.94 Mg ha^{-1}), while for groundnut, varieties ICGV-12911 and CG7 had the best grain yield of 1.10 Mg ha^{-1} and 1.07 Mg ha^{-1}, respectively. Soyabean varieties SB17 and SB20, and all groundnut varieties showed significant grain yield responses to P.

In contrast to AEZ 1, soyabean had the best mean grain yield of 1.16 Mg ha^{-1} in the HF field in AEZ 2, which was comparable with lablab (1.05 Mg ha^{-1}), but significantly (P<0.01) greater than groundnut (0.86 Mg ha^{-1}). Similar to AEZ 1, however, bean had the poorest grain yield performance among the grain legumes, although there were improvements in grain yield compared with AEZ 1. Only soyabean, groundnut and lablab showed significant grain yield responses to P. However, there were no significant grain yield responses to P by varieties SB2, *Nyahela* and ICGV-12988. Similarly, lima and cowpea did show significant grain yield responses to P.

In the LF field, soyabean had the best grain yield of 1.25 Mg ha^{-1}, which was significantly (P<0.01) greater than the rest of the legumes. The grain yield of groundnut (0.67 Mg ha^{-1}) and lablab (0.66 Mg ha^{-1}) were significantly better than green gram (0.18 Mg ha^{-1}) and bean (0.15 Mg ha^{-1}). Among the soyabean varieties, SB20 (1.87 Mg ha^{-1}) and SB17 (1.29 Mg ha^{-1}) had the best grain yield, while CG7 (0.85 Mg ha^{-1}) and ICGV-12911 (0.72 Mg ha^{-1}) had the best grain yield among the groundnut varieties. While soyabean and groundnut had significant (P<0.01) grain yield responses to P, the other legumes did not. Among the varieties, soyabean SB2 and SB20, and groundnut ICGV-12988 and CG7 did not show significant grain yield responses to P. Similarly, the grain yield responses to P by lima, lablab and cowpea were not significant. Significant effects of soil fertility status of the field on yields were observed. Averaged across P rates, groundnut, green gram, and lablab had significantly (P<0.01) greater grain yield in HF than in LF field.

Mean grain yield was about 11% less in AEZ 3 than in AEZ 2 (Table 7). In the HF field, groundnut had the best mean grain yield of 1.09 Mg ha^{-1}, which was significantly greater than the rest of the legume species. Unlike in AEZs 1 and 2, the grain yield of lablab (0.20 Mg ha^{-1}) was poorer than lima (0.72 Mg ha^{-1}) and cowpea (0.30 Mg ha^{-1}). However, further improvements were observed in the performance of bean, whose grain yield rose to 0.31 Mg ha^{-1}, about double that in AEZ 2. In soyabean, variety SB20 had the best grain yield, ICGV-12988 in groundnut, KK15 and KK20 in bean, and RG in green gram. Significant (P<0.01) grain yield responses to P were observed in soyabean SB3, groundnut ICGV-12988, bean KK8, lima, lablab and cowpea. Grain yield reduced by between 21 and 66% in the LF field. Groundnut (0.86 Mg ha^{-1}) and soyabean (0.75 Mg ha^{-1}) had the best grain yield, which were significantly greater than the rest of the legume species. All legume species, except bean, and all groundnut varieties responded significantly to P. However, among the soyabean varieties, SB20 did not show significant grain yield response to P. Other significant grain yield responses to P were by lima and lablab. Groundnut, bean and lima showed significant yield differences between the fields of high and low soil fertility.

Table 7. Grain production by legume species and varieties in three agro-ecological zones in western Kenya, long rains 2003 season.

	Grain production (Mg ha^{-1})																								
	AEZ1						AEZ2						AEZ3						Mean
	HF field			LF field			HF field			LF field			HF field			LF field			
Legume/variety	P0	P30	Mean	P0	P30	Mean	P0	P30	Mean	P0	P30	Mean	P0	P30	Mean	P0	P30	Mean	
Soyabean[1] mean	**0.87**	**1.51**	**1.21**	**0.76**	**0.96**	**0.86**	**1.03**	**1.29**	**1.16**	**1.16**	**1.34**	**1.25**	**0.48**	**0.56**	**0.52**	**0.55**	**0.94**	**0.75**	**0.87**
Var. SB2	0.63	0.88	0.76	0.72	0.78	0.75	0.81	1.00	0.91	0.98	0.87	0.93	0.41	0.44	0.43	0.50	0.81	0.66	0.74
Var. SB3	0.94	0.96	0.95	0.86	0.89	0.88	1.06	1.28	1.17	0.86	0.99	0.93	0.28	0.63	0.46	0.31	0.63	0.47	0.81
Var. SB17	0.79	1.41	1.10	0.70	1.05	0.88	1.13	1.38	1.26	0.93	1.64	1.29	0.63	0.50	0.57	0.49	1.31	0.90	1.00
Var. SB20	1.12	2.81	1.97	0.76	1.11	0.94	1.13	1.50	1.32	1.88	1.85	1.87	0.59	0.69	0.64	0.88	1.00	0.94	1.28
Groundnut[1] mean	**1.39**	**1.44**	**1.42**	**0.75**	**1.19**	**0.97**	**0.67**	**1.04**	**0.86**	**0.59**	**0.75**	**0.67**	**1.06**	**1.11**	**1.09**	**0.63**	**1.08**	**0.86**	**0.98**
Var. *Nyahela*	1.19	1.35	1.27	0.41	0.87	0.64	0.89	0.88	0.89	0.38	0.69	0.54	1.06	1.06	1.06	0.50	1.06	0.78	0.88
Var. ICGV-12911	1.40	1.55	1.48	0.97	1.23	1.10	0.56	1.19	0.88	0.56	0.88	0.72	1.19	1.13	1.16	0.50	1.06	0.78	1.02
Var. ICGV-12988	1.33	1.54	1.44	0.79	1.33	1.06	0.59	0.59	0.59	0.63	0.56	0.60	1.13	1.38	1.26	0.69	1.13	0.91	0.97
Var. CG7	1.61	1.46	1.54	0.81	1.33	1.07	0.63	1.50	1.07	0.81	0.88	0.85	0.88	0.88	0.88	0.81	1.06	0.94	1.06
Bean[1] mean	**0.01**	**0.06**	**0.04**	**0.04**	**0.11**	**0.08**	**0.07**	**0.12**	**0.10**	**0.12**	**0.18**	**0.15**	**0.27**	**0.34**	**0.31**	**0.13**	**0.20**	**0.17**	**0.14**
Var. *Okwuodo*	0.08	0.01	0.05	0.02	0.13	0.08	0.05	0.04	0.05	0.01	0.13	0.07	0.19	0.31	0.25	0.16	0.25	0.21	0.12
Var. KK 8	0.03	0.15	0.09	0.03	0.03	0.03	0.07	0.09	0.08	0.16	0.22	0.19	0.06	0.34	0.20	0.16	0.09	0.13	0.12
Var. KK 15	0.01	0.02	0.02	0.04	0.16	0.10	0.13	0.10	0.12	0.22	0.08	0.15	0.35	0.19	0.27	0.09	0.16	0.13	0.13
Var. KK 20	0.04	0.06	0.05	0.06	0.13	0.10	0.13	0.25	0.19	0.10	0.28	0.19	0.47	0.50	0.49	1.20	0.31	0.76	0.29
Green gram[2] mean	**0.26**	**0.14**	**0.20**	**0.03**	**0.07**	**0.05**	**0.28**	**0.28**	**0.28**	**0.16**	**0.19**	**0.18**	**0.34**	**0.28**	**0.31**	**0.20**	**0.25**	**0.23**	**0.21**
Var. LG	0.37	0.19	0.28	0.02	0.04	0.03	0.31	0.28	0.30	0.25	0.25	0.25	0.25	0.19	0.22	0.16	0.13	0.15	0.20
Var. RG	0.16	0.09	0.13	0.05	0.10	0.08	0.25	0.28	0.27	0.06	0.13	0.10	0.44	0.38	0.41	0.25	0.38	0.32	0.21
Lima[3]	0.19	0.25	0.22	0.31	0.34	0.33	0.31	0.44	0.38	0.25	0.38	0.32	0.25	1.19	0.72	0.38	0.75	0.57	0.42
Lablab[3]	0.50	0.69	0.60	0.63	0.88	0.76	0.84	1.25	1.05	0.63	0.69	0.66	0.09	0.31	0.20	0.31	0.63	0.47	0.62
Cowpea[3]	0.25	0.16	0.21	0.08	0.04	0.06	0.16	0.16	0.16	0.16	0.16	0.16	0.19	0.41	0.30	0.06	0.13	0.10	0.16
Mean (Varieties)	0.63	0.80	0.72	0.43	0.61	0.52	0.53	0.72	0.63	0.52	0.63	0.58	0.50	0.62	0.56	0.44	0.64	0.52	0.49
Mean (legumes)	0.50	0.61	0.51	0.37	0.51	0.44	0.48	0.65	0.57	0.44	0.39	0.58	0.38	0.60	0.49	0.32	0.57	0.45	0.49
SED[1] (**)	0.20	0.20	0.14	0.20	0.20	0.14	0.20	0.20	0.14	0.20	0.20	0.14	0.20	0.20	0.14	0.20	0.20	0.14	0.06
SED[2] (**)	0.12	0.12	0.09	0.12	0.12	0.09	0.12	0.12	0.09	0.12	0.12	0.09	0.12	0.12	0.09	0.12	0.12	0.09	0.04
SED[3] (**)	0.15	0.15	0.11	0.15	0.15	0.11	0.15	0.15	0.11	0.15	0.15	0.11	0.15	0.15	0.11	0.15	0.15	0.11	0.04
SED[4] (**)	0.20	0.20	0.14	0.20	0.20	0.14	0.20	0.20	0.14	0.20	0.20	0.14	0.20	0.20	0.14	0.20	0.20	0.14	0.06

SED[1] = for comparing variety and legume[3] means
SED[2] = for comparing among legume[1] means.
SED[3] = for comparing legume[1] means with legume[2] mean.
SED[4] = for comparing legume[1] means with legume[3] means.
SED = Standard error of differences between means, (**) = significant $P<0.01$.

SED for varieties x P interaction means= 0.20**
SED for legume[1] x P interaction means = 0.12**
SED for legume[2] x P interaction means = 0.15**
SED for legume[3] x P interaction means = 0.20**

SED for varieties x fertility interaction means = 0.18**
SED for legume[1] x fertility interaction means = 0.09**
SED for legume[2] x fertility interaction means = 0.12**
SED for legume[3] x fertility interaction means = 0.18**

Total dry matter production

Similar to grain production, mean total dry matter (TDM) increased significantly with increasing AEZ potential (Table 8). Averaged across legumes and treatments, mean TDM rose from 1.60 Mg ha^{-1} in AEZ 3 to 3.30 Mg ha^{-1} in AEZ 1. Significant ($P<0.01$) differences were observed in TDM accumulation by legume species and varieties. Among the grain legumes in AEZ 1, soyabean accumulated the highest TDM of 4.66 Mg ha^{-1} in the HF field. TDM accumulation of groundnut (4.20 Mg ha^{-1}), green gram (1.54 Mg ha^{-1}) and bean (0.51 Mg ha^{-1}) were significantly lower. However, lablab (dual purpose species) accumulated over 10 Mg ha^{-1}. Generally, the green manure and forage legume species accumulated greater TDM than the grain legume species, with velvet bean (10.54 Mg ha^{-1}) and siratro (7.87 Mg ha^{-1}) showing the best performance. Within the grain legume species, soyabean variety SB20 (5.94 Mg ha^{-1}), groundnut ICGV-12988 (4.81 Mg ha^{-1}), bean KK8 (0.82 Mg ha^{-1}) and green gram RG (2.05 Mg ha^{-1}) performed best. The TDM accumulation of soyabean SB20, groundnut ICGV-12988, lablab, sunnhemp, crotalaria and desmodium responded significantly ($P<0.01$) to P. TDM accumulation by soyabean, groundnut, green gram and lablab significantly ($P<0.01$) decreased in the LF field, with green gram and groundnut recording the largest decreases of 59 and 39%, respectively. Among the grain legumes, soyabean had the best TDM accumulation of 3.52 Mg ha^{-1}, while bean (0.37 Mg ha^{-1}) had the worst. Among the soyabean varieties, SB20 had the best TDM accumulation of 4.12 Mg ha^{-1}, while CG7 (2.88 Mg ha^{-1}) was best among groundnut varieties. Similar to HF field, green manure and forage legumes TDM accumulation was generally greater than that of grain legumes, with velvet bean (6.20 mg ha^{-1}) and desmodium (6.44 Mg ha^{-1}) showing the best TDM accumulation. Bean, green gram, lima and cowpea did not show significant ($P<0.01$) TDM responses to P while the rest of the legumes did.

There was up to 31% decrease in TDM production by legume species in AEZ 2 compared with AEZ 1, although the relative performance of the species was generally consistent. Green manure and forage legume species accumulated greater TDM than grain legume species. Lablab, velvet bean and siratro had the best performance, ranging from 6.4 to 11.3 Mg ha^{-1}. Similarly, soyabean and groundnut had the best TDM accumulation among the grain legume species. Best TDM accumulation by grain legume varieties were by soyabean SB17 and SB20 and groundnut ICGV-12911 and CG7. Similar to AEZ 1, significant ($P<0.01$) increases in TDM accumulation in response to P were observed in soyabean, groundnut, lablab, velvet bean and sunnhemp. Significant ($P<0.01$) effects of soil fertility status of the fields on TDM

Table 8. Total dry matter (TDM) production in three agro-ecological zones in western Kenya, long rains 2003 season.

	Total dry matter production (Mg ha^{-1})																		
	AEZ1						AEZ2						AEZ3						Mean
	HF field			LF field			HF field			LF field			HF field			LF field			
Legume species/varieties	P0	P30	Mean	P0	P30	Mean	P0	P30	Mean	P0	P30	Mean	P0	P30	Mean	P0	P30	Mean	
Soyabean[1] mean	**4.26**	**5.06**	**4.66**	**3.03**	**4.00**	**3.52**	**2.70**	**3.29**	**3.00**	**2.54**	**3.04**	**2.79**	**0.64**	**0.74**	**0.69**	**0.69**	**1.14**	**0.92**	**2.60**
Var. (SB 2)	3.56	3.81	3.69	3.47	3.96	3.75	2.19	2.69	2.44	1.98	2.24	2.11	0.54	0.60	0.57	0.66	0.76	0.71	2.21
Var. Var. (SB 3)	4.25	4.46	4.36	3.73	4.08	3.91	2.22	2.84	2.53	1.79	2.12	1..96	0.37	0.73	0.55	0.34	1.04	0.69	2.35
Var. (SB 17)	4.48	4.85	4.67	2.45	3.55	3.00	3.00	3.13	3.07	2.06	4.01	3.04	0.89	0.69	0.79	0.57	1.58	1.08	2.61
Var. (SB 20)	4.75	7.13	5.94	3.82	4.42	4.12	3.38	4.50	3.94	4.35	3.78	4.07	0.77	0.93	0.85	1.18	1.20	1.19	3.35
Groundnut[1] mean	**4.04**	**4.35**	**4.20**	**2.12**	**3.05**	**2.59**	**2.27**	**2.85**	**2.56**	**1.70**	**2.52**	**2.11**	**1.21**	**1.30**	**1.26**	**0.79**	**1.30**	**1.05**	**2.29**
Var. *Nyahela*	3.65	3.60	3.63	1.59	2.68	2.14	2.69	2.34	2.52	1.19	1.63	1.41	1.19	1.22	1.21	0.66	1.29	0.98	1.98
Var. ICGV-12911	3.86	4.10	3.98	2.41	3.11	2.76	1.44	2.38	1.91	1.88	2.75	2.32	1.31	1.26	1.29	0.61	1.22	0.92	2.20
Var. ICGV-12988	3.83	5.79	4.81	2.17	2.95	2.56	1.34	2.09	1.72	1.44	1.69	1.57	1.27	1.56	1.42	0.81	1.28	1.05	2.19
Var. CG7	4.83	3.89	4.36	2.31	3.45	2.88	3.63	4.59	4.11	2.28	4.00	3.14	1.05	1.15	1.10	1.11	1.43	1.27	2.81
Bean[1] mean	**0.25**	**0.76**	**0.51**	**0.28**	**0.46**	**0.37**	**0.48**	**0.43**	**0.46**	**0.39**	**0.38**	**0.39**	**0.32**	**0.39**	**0.36**	**0.16**	**0.25**	**0.21**	**0.38**
Var. *Okwuodo*	0.14	0.76	0.45	0.23	0.44	0.34	0.18	0.19	0.19	0.17	0.25	0.21	0.23	0.36	0.30	0.20	0.29	0.25	0.29
Var. KK 8	0.44	1.20	0.82	0.30	0.43	0.37	0.50	0.37	0.44	0.38	0.53	0.46	0.09	0.41	0.25	0.18	0.15	0.17	0.42
Var. KK 15	0.27	0.74	0.51	0.29	0.59	0.44	0.47	0.47	0.47	0.59	0.23	0.41	0.42	0.22	0.32	0.13	0.21	0.17	0.38
Var. KK 20	0.19	0.47	0.33	0.28	0.36	0.32	0.78	0.66	0.72	0.41	0.53	0.47	0.56	0.56	0.56	0.13	0.36	0.25	0.45
Green gram[2] mean	**1.57**	**1.50**	**1.54**	**0.71**	**0.55**	**0.63**	**0.96**	**0.97**	**0.97**	**0.69**	**0.80**	**0.75**	**0.44**	**0.41**	**0.43**	**0.29**	**0.38**	**0.34**	**0.77**
Var. LG	0.95	1.09	1.02	0.43	0.66	0.55	1.16	0.93	1.05	0.91	0.88	0.90	0.29	0.31	0.30	0.23	0.26	0.25	0.68
Var. RG	2.19	1.91	2.05	0.97	0.44	0.71	0.78	1.00	0.89	0.47	0.72	0.60	0.58	0.51	0.55	0.36	0.50	0.43	0.87
Lima[3]	1.31	2.19	1.75	1.99	2.21	2.10	3.22	3.19	3.21	2.56	3.00	2.78	0.46	0.41	0.44	0.48	0.93	0.71	1.83
Lablab[3]	8.25	12.25	10.25	6.63	11.00	8.82	8.78	13.88	11.33	4.94	7.78	6.36	0.46	0.78	0.62	0.93	1.87	1.40	6.46
Cowpea[3]	0.88	0.94	0.91	0.87	0.87	0.87	1.25	1.50	1.38	0.91	1.44	1.18	0.36	0.61	0.49	0.09	0.26	0.18	0.83
Sunnhemp[3]	3.90	5.12	4.51	4.15	5.84	5.00	4.27	5.27	4.77	2.21	2.01	2.11	6.76	8.49	7.62	5.85	6.93	6.39	5.38
Crotalaria[3]	4.57	6.52	5.55	4.51	5.33	4.92	7.88	6.41	7.15	3.64	3.50	3.57	4.13	5.10	4.62	4.05	5.02	4.54	4.64
Velvet bean[3]	10.62	10.45	10.54	5.68	6.71	6.20	8.34	9.86	9.10	6.16	4.13	5.15	4.04	4.82	4.43	4.64	5.16	4.90	6.72
Jackbean[3]	4.98	4.38	4.68	4.42	3.10	3.76	4.32	5.53	4.93	3.88	2.67	3.28	5.24	6.05	5.65	5.68	5.94	5.81	4.68
Desmodium[3]	5.33	6.95	6.14	6.98	5.89	6.44	4.31	3.80	7.25	5.21	5.26	5.24	3.34	2.17	2.76	1.01	1.08	1.05	4.46
Siratro[3]	9.26	6.48	7.87	5.33	4.82	5.08	8.27	6.22	8.28	8.49	7.60	8.05	3.66	4.37	4.02	2.78	2.74	2.76	5.89
Stylo	5.50	6.32	5.91	7.14	7.89	7.51	4.92	5.35	5.12	4.10	4.55	4.32	3.75	3.95	4.85	2.25	2.93	2.59	4.94
Mean (varieties)	2.67	3.13	1.54	1.75	2.22	1.99	1.70	2.01	1.86	1.42	1.81	1.55	0.68	0.75	0.72	0.51	0.83	0.67	1.55
SED[1] (**)	1.10	1.10	0.81	1.10	1.10	0.81	1.10	1.10	0.81	1.10	1.10	0.81	1.10	1.10	0.81	1.10	1.10	0.81	0.33
Mean (legumes)	4.55	5.15	4.85	3.59	4.14	3.87	4.39	4.86	4.95	3.33	3.39	3.37	2.46	2.59	2.53	2.47	2.75	2.61	3.66
SED[2] (**)							0.54	0.54	0.38	0.54	0.54	0.38							0.16
SED[3] (**)							0.77	0.77	0.47	0.77	0.77	0.47							0.19
SED[4] (**)							0.86	0.86	0.61	0.86	0.86	0.61							0.25

SED[1] = for comparing variety and legume[3] means.
SED[2] = for comparing among legume[1] means.
SED[3] = for comparing legume[1] means with legume[2] mean.
SED[4] = for comparing legume[1] means with legume[3] means.

SED for varieties x P interaction means= 1.10**
SED for legume[1] x P interaction means = 0.54**
SED for legume[2] x P interaction means = 0.77**
SED for legume[3] x P interaction means = 1.09**

SED for varieties x fertility interaction means = 0.81**
SED for legume[1] x fertility interaction means = 0.38**
SED for legume[2] x fertility interaction means = 0.54**
SED for legume[3] x fertility interaction means = 0.77**

SED = Standard error of differences between means, (**)= significant p<0.01.

accumulation were observed with all legumes species, except soyabean, bean, green gram and siratro.

Averaged across legume species and treatments, TDM accumulation in AEZ 3 was 47% less compared with AEZ 2 (Table 8). Among the grain legumes, groundnut and soyabean had the best TDM accumulation in both the HF and LF fields. Surprisingly, maximum TDM accumulation by lablab was only 1.87 Mg ha^{-1}, extremely poor compared with its performance in AEZ 1 and AEZ 2, where it accumulated over 10 Mg ha^{-1} TDM. Green manure and forage legume species had relatively good performance, with TDM accumulation ranging from about 1.01 Mg ha^{-1} in desmodium to 8.49 Mg ha^{-1} in sunnhemp. In contrast to AEZ 1 and AEZ 2, the grain legumes did not show significant TDM responses to P in AEZ 3, although the green manures did. Desmodium, siratro and stylo grew significantly (P<0.01) better in the HF field than in the LF field.

Farmer evaluation

Farmers' legume evaluation criteria were generally similar across the locations (AEZs). Surprisingly, legume scores were also generally similar across the locations and were therefore averaged. Most legume species were scored 8.0 and above for emergence by farmers (Table 9). However, green manure legume species were evaluated to be slightly better than the grain legume species. Among the grain legumes, lima was scored best (9.0) for emergence, followed by soyabean (8.4), while soyabean varieties SB20 and SB2 were scored best (8.7). Groundnut had the lowest emergence rating, with a mean score of 6.9, which was influenced by poor performance in AEZ 3 (see Table 3). There were little differences in emergence scores between varieties. The emergence scores closely reflected agronomic evaluation results, with respect to the performance of soyabean and green manure species. However, the poor emergence rating of groundnut by farmers differed sharply with agronomic results which had put groundnut among the best species overall.

While most legume species scored higher than 8.0 for early maturity, green gram (6.5), cowpea (6.3), lima (4.3), and lablab (2.0) were scored relatively poorly. However, farmers rated soyabean, groundnut and lablab higher than 8.0 for leafiness and good flowering, whereas green manure and forage legume species ranged from 8.0 to 9.7 in leafiness and good flowering scores. Lima and cowpea were scored 7.7 and 7.3, respectively, while bean, with a mean of 5.5 and green gram (6.5) had the poorest scores. Similarly, most legume species scored high for tolerance disease and pest attacks, while cowpea (5.3), green gram (3.5) and bean (2.7) had poor scores. The

Table 9. Participatory evaluation of grain, green manure and forage legume species, and the major evaluation criteria used by smallholders in western Kenya. Data are means across the AEZs.

Evaluation criteria	Good emergence	Early maturity	Leafiness & good flowering	Pest & disease tolerance	Good growth in poor soil	Drought tolerance	Productivity (Grain and biomass)	Mean rank
Grain legumes:				Scores				
Soyabean mean	**8.4**	**8.9**	**9.1**	**8.9**	**9.2**	**9.5**	**9.2**	**9.0**
TXG1831-32E (SB2)	8.7	9.3	8.7	8.7	8.7	9.3	8.7	8.9
TXG1835-10E (SB3)	8.3	9.0	8.7	9.0	9.2	9.7	8.7	8.9
TXG1893-10F (SB17)	8.0	9.0	9.3	8.7	8.8	9.7	9.3	9.0
TXG1448-2E (SB20)	8.7	8.3	9.7	9.3	10	9.3	10	9.3
Groundnut mean	**6.9**	**8.9**	**8.6**	**8.9**	**7.1**	**9.1**	**7.1**	**8.1**
Nyahela	6.7	9.0	7.0	8.3	7.0	9.0	4.7	7.4
ICGV-12911	7.0	9.0	8.7	9.0	7.3	9.3	7.7	8.3
ICGV-12988	7.0	8.7	9.0	9.0	7.3	9.0	7.7	8.2
CG7	7.0	9.0	9.7	9.3	6.7	9.0	8.3	8.4
Bean mean	**8.2**	**9.3**	**5.5**	**2.7**	**7.3**	**6.0**	**2.8**	**6.0**
Okwuodo	8.0	8.3	4.3	2.0	6.0	5.7	2.3	5.2
KK 8	8.0	9.3	5.3	2.3	7.0	5.3	2.3	5.6
KK 15	8.0	9.7	6.0	2.3	6.7	5.7	2.7	5.9
KK 20	8.7	10	6.3	4.3	9.3	7.3	3.7	7.1
Green gram mean	**8.2**	**6.5**	**6.5**	**3.5**	**7.2**	**8.5**	**3.5**	**6.3**
LG	8.3	6.3	6.7	3.3	6.7	8.3	3.7	6.2
RG	8.0	6.7	6.3	3.7	7.7	8.7	3.3	6.3
Other grain legumes:								
Lima	9.0	4.3	7.7	7.0	7.3	9.3	8.3	7.6
Cowpea	7.7	6.3	7.3	5.3	8.3	8.7	3.3	6.7
Lablab	7.3	2.0	9.0	9.7	7.7	9.7	1.7	6.7
Green manure legumes:								
Sunnhemp	10	9.2	8.3	9.0	9.0	9.7	9.3	9.2
Crotalaria	10	9.3	9.7	9.0	9.7	9.0	9.7	9.5
Velvet bean	9.3	8.9	9.7	10	9.0	9.7	10	9.5
Jackbean	8.3	8.5	8.0	8.7	7.7	9.3	8.0	8.4
Forage legumes:								
Desmodium*	7.6	8.5	9.2	9.0	7.7	7.9	8.3	8.3
Siratro*	10	9.2	8.0	8.7	7.7	9.0	7.9	8.7
Stylo*	8.2	8.3	8.2	9.0	9.2	8.0	9.2	8.6

farmer evaluation results for leafiness and good flowering, and pest and disease tolerance were consistent with those of agronomic evaluation.

Green manure legume species were generally scored high for ability to grow well in low fertility status soils, while grain legume species were generally perceived to have poorer ability to grow well in low soil fertility status soils, with the exception of soybean, with a mean score of 9.2. Variety SB20 was rated excellent, with a score of 10. Groundnut, bean, and green gram, were rated intermediate, with mean scores slightly above 7. Most of the legume species, except bean, were perceived to be drought tolerant by farmers, even in the drier AEZ 3. Among the grain legumes, lablab received the highest score of 9.7, followed by soyabean with a score of 9.5. Bean had the lowest mean score of 6.2, while the rest of the grain legume species scored above 8.0. There were only minor differences between the scores of grain legume varieties.

Soyabean (9.2) had the highest score for productivity among the grain legumes, and velvet bean (10) the highest among green manure species. Soyabean varieties SB20 and SB17, with scores of 10 and 9.3, respectively, had the highest scores for productivity. Surprisingly, farmers were still impressed by the productivity of lima, giving it a score of 8.3, after scoring it poorly under other criteria, e.g. leafiness and good flowering, pest and disease tolerance, etc. Groundnut had a productivity score of 7.1, with variety CG7 being the best. The scores of the other species and varieties were poor, ranging from 2.3 to 3.7. The productivity scores farmers gave to lima and groundnut were not consistent with the results of agronomic evaluation.

Based on all the seven evaluation criteria combined, soyabean was the best legume species, with an overall mean score of 9.1, followed by groundnut (8.1), lima (7.6), cowpea (6.7) and green gram (6.3). Bean, with a mean score of 6.1, was the most poorly performing legume species although it is the most established grain legume in the system. Soyabean SB20 (9.3) and SB17 (9.0) were scored the best varieties, followed by groundnut varieties CG7 (8.4) and ICGV-12911 (8.3). Bean variety KK20 scored 7.1, which was better than the two green gram varieties (LG and RG). All the green manure species screened received high overall scores of between 8.4 and 9.5.

Discussion

Legume productivity

The present study was conducted to evaluate whether the concept of the socio-ecological niche (Chapter 2) was useful for tailoring legumes to the heterogeneous conditions encountered in African smallholder farming systems. Factors considered were broad agro-ecological conditions, within farmer variability in soil fertility and response to P fertilizer, and farmers' evaluation. Each of these is considered in turn.

Agro-ecological zones

The TDM production of the legume species and varieties varied between the AEZs, ranging from 0.1 Mg ha^{-1} to 13.9 Mg ha^{-1} (Table 8). Legume species performed differently between AEZs due to their differential adaptation to agro-ecological conditions. Soyabean and groundnut were the best and most consistently performing grain legumes, in terms of both grain yield (Table 7) and TDM (Table 8). Groundnut produced about 0.2 Mg ha^{-1} more grain than soyabean in AEZ 1. However, TDM production of soyabean was greater than groundnut by 0.7 Mg ha^{-1}. In AEZ 2, soyabean excelled groundnut in both grain yield and TDM accumulation. Interestingly, in AEZ 3, groundnut outperformed soyabean in both grain yield and TDM accumulation. This suggests that although the two legume species show relatively better adaptation and productivity across the EAZs, groundnut would be a better choice for the lower rainfall environment of AEZ 3 than soyabean. While the TDM production of lablab consistently reduced with rainfall, its mean TDM accumulation in the low rainfall AEZ 3 was only about 15% of that in AEZ 2 (Table 8), and equal to that of groundnut. Thus groundnut, due to its superior grain yield (Table 7), is more suitable in AEZ 3 than lablab. However, lablab could be a useful alternative legume to soyabean, whose performance (0.80 Mg ha^{-1}) in AEZ 3 was also relatively poor. While lima had better grain production than lablab in AEZ 3, the TDM accumulation was poorer than lablab. The superior grain yield performance by soyabean and groundnut in all AEZ, and lima, in AEZ 3, indicates that these legume species are better alternatives to bean, which had consistently poor grain yield and TDM accumulation across the AEZs, but is an important legume in western Kenya because of farmers' food preferences.

The TDM accumulation of soyabean varieties consistently decreased with rainfall (Table 8). Similar to grain production (Table 7), variety SB20 had the best TDM production in all the EAZs. However, there were significant variations in the

TDM performance of groundnut, bean and green gram varieties. Groundnut variety ICGV-12988 had the best TDM production in AEZs 1 and 3, while variety CG 7 was best in AEZ 2. Although TDM production by bean varieties was relatively poor in all AEZs, variety KK8 was the most productive in AEZ 1, while in AEZ 2 and AEZ 3, variety KK20 produced the most dry matter. However, the grain production of variety KK20 was consistently greater than the rest of the bean varieties across AEZs. Green gram variety RG was the best in both AEZ 1 and AEZ 3, while in AEZ 2, variety LG had the best productivity. With the exception of lablab, which was best in AEZs 1 and 2, TDM accumulation by green manure and fodder legume species was consistently better than grain legume species in all AEZs (Table 8). However, there were large variations in TDM production trends among these legume species. While velvet bean, crotalaria and stylo showed consistently good TDM production across the AEZs, the TDM production of sunnhemp, desmodium, jackbean, and siratro varied with AEZ. TDM production of sunnhemp was best in AEZ 3 and worst in AEZ 2, where it was 49% lower. Desmodium was worst in AEZ 3, where there was about 70% reduction in its TDM production compared with AEZs 1 and 2. Similar to sunnhemp, TDM production of jackbean was best in AEZ 3 and worst in AEZ 2. While the TDM production of siratro was best in AEZ 2 and worst in AEZ 3, it was a better alternative forage legume to desmodium, whose TDM production in the same zone was less by 44%.

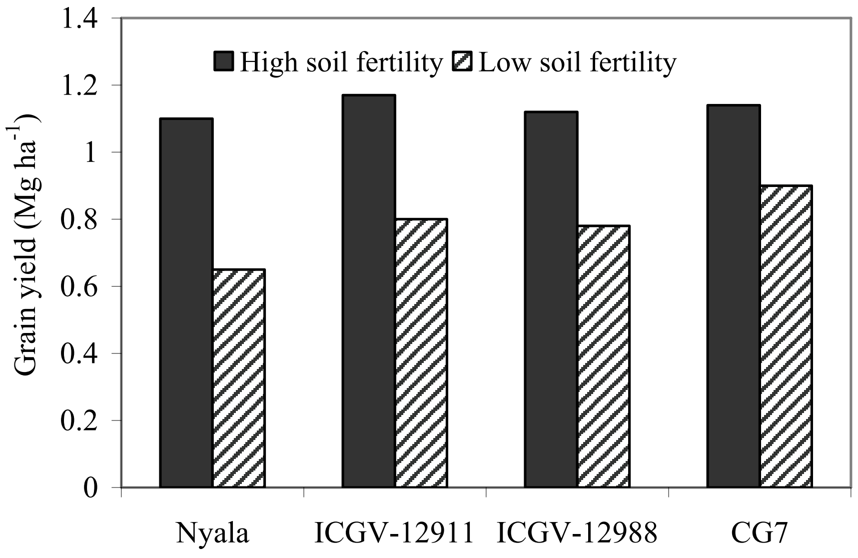


Figure 2a. Effect of soil fertility on the grain yield of groundnut varieties in western Kenya, long rains 2003 season. SED $_{(fertility)}$ = 0.14.

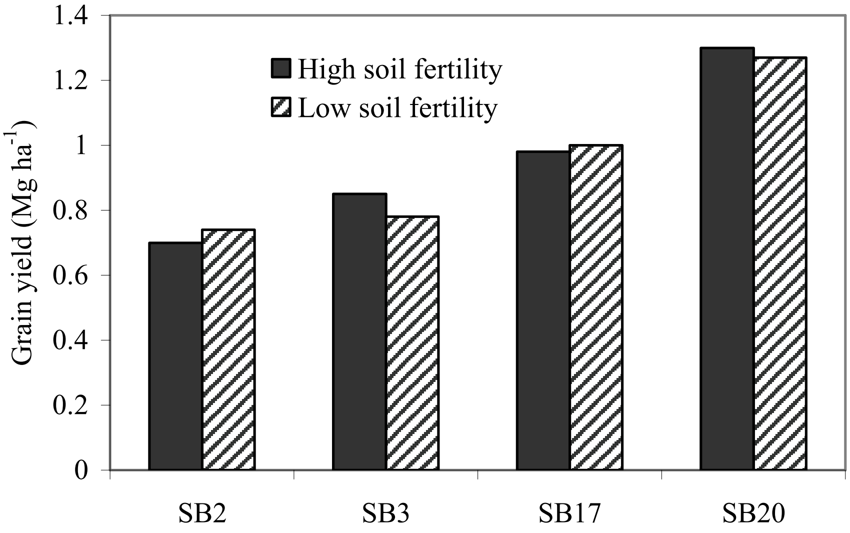


Figure 2b. Effect of soil fertility on the grain yield of soyabean varieties in western Kenya, long rains 2003 season. SED $_{(fertility)}$ = 0.14.

Soil fertility status of the fields

Generally, the legumes accumulated less TDM in the low fertility soil compared with the high soil fertility field (Table 8). However, the differences in TDM accumulation between high fertility and low fertility fields were relatively small in AEZ 3 (12%) compared with AEZ 1 (26%) and AEZ 2 (22%). This was probably due to poorer legume growth in AEZ 3 as a result of the poorer rainfall (Figure 1) and the resulting soil moisture deficit. Among the grain legumes, groundnut showed greater sensitivity to soil fertility than soyabean (Table 8). All the groundnut varieties showed consistently greater response to soil fertility (Figure 2a) than soyabean varieties (Figure 2b). This indicates that although groundnut has relatively more consistent production across the AEZ, it should be grown on fields of higher fertility status. Varieties *Nyahela*, ICGV-12988 and CG7 were particularly sensitive to poor soil fertility. Among the bean varieties, *Okwuodo*, KK8 and KK20 were relatively more sensitive to poor soil fertility than the rest. Based on these results, we recommend that *Nyahela* and *Okwuodo*, which are local farmer varieties, should be replaced by improved varieties of groundnut and bean with better performance in low fertility status soils. Among the green manure and forage legumes, siratro and velvet bean showed more sensitivity to soil fertility, while sunnhemp and desmodium were relatively insensitive to soil fertility and would be best choices for low fertility fields.

Phosphorus fertilization

Grain legume productivity showed differential response to P in the AEZs. The TDM production of soyabean varieties SB2 and SB20 was relatively good without P in all AEZs (Table 8). However, groundnut varieties ICGV-12911 and CG7 were good without P in AEZ 1, *Nyahela* and ICGV-12988 in AEZ 2 and CG7 and 12911in AEZ 3. Bean varieties KK15 and KK20 and lima had good productivity without P in both AEZ 2 and AEZ3. The productivity of the rest of the grain legumes and varieties showed greater sensitivity to P limitation. Green manure and forage legume species were relatively less responsive to P compared with grain legume species. However, TDM production of sunnhemp and crotalaria responded relatively more strongly to P, while that of siratro and jackbean were insensitive to P. While P is necessary for high legume production, these results demonstrate that some of the legume species and varieties tested are capable of relatively good production in soils with little available

Factors influencing legume productivity

Several factors were responsible for the variations observed in the productivity of the legume species and varieties. Plant emergence and survival affected the productivity of the legumes through their influence on final plant population. The decline in emergence from 83% in AEZ 1 to 64% in AEZ 3 (Table 3) was partly responsible for the lower productivity observed, reflecting the poorer production potential of AEZ 3. The variations in emergence were attributed to differences in precipitation between the AEZs (Figure 1), rotting of the seeds and pre-emergence attack by soil-borne pathogens. In addition, seeds were eaten by rodents and by wild and domestic birds. Although the emergence of jackbean and velvet bean was relatively poor compared with the other green manure legume species, this had little effect on their dry matter production.

The relatively high incidence of diseases in grain legumes, especially in AEZs 1 and 2 (Table 4), affected their productivity in these zones. Bean was the species most affected by diseases in AEZs 1 and 2 and as a result, its grain production (Table 7) was highly correlated with disease scores. Interestingly, bean is the most common legume species in the smallholder farming systems in western Kenya and many other parts of the east African highlands, and was the most susceptible species to diseases among the legumes studied, resulting in dramatic reductions in productivity. This is perhaps due to the fact that bean improvement has given much focus to tolerance to bean root rots, yet other diseases, e.g. angular leaf spot, anthracnose, rust, common blight and halo blight, appear to be equally important. Nevertheless, other grain legume species, such as soyabean, groundnut and lablab are suitable alternatives to beans, due to their high degree of disease tolerance. Disease incidence generally peaked before flowering and final dry matter production was therefore highly correlated with plant survival. In general, the legumes had less disease infestation in the drier AEZ 3 compared with the relatively wetter AEZ 1 and AEZ 2 (Table 4). This indicates that even though the productivity potential is greater in high rainfall agro-ecosystems, incidence of diseases threaten the realization of this potential. However, the observed variations in disease tolerance among the species and varieties offer opportunities for selecting more disease tolerant legumes for high disease incidence zones. Lablab appears to have high potential in AEZ 1 and AEZ 2 due to its multi-purpose nature, high biomass and seed production, in addition to disease tolerance.

Most of the species studied were capable of producing viable nodules with naturally occurring rhizobia in all AEZs, indicating that inoculants may not be necessary. Previous trials in a number of sites in Kenya (Mureithi et al., 2003) reported lack of response to inoculation in the majority of legumes studied. This is encouraging since the need for inoculation with commercial inoculants is generally a complicating factor limiting the adoption of legume technology by smallholder farmers. Mean nodulation performance was about 11% lower in AEZ 3 compared with AEZs 1 and 2. However, some legumes, e.g. soyabean SB2, groundnut CG7 and green gram RG had better nodulation in AEZ 3, suggesting that besides precipitation, there were other important factors influencing nodulation. The relatively more consistent nodulation performance by the green manure and forage legumes suggests their higher N_2-fixation potential in all the AEZs studied. Also, the good nodulation performance among the soyabean and groundnut varieties suggests that these varieties have higher N_2-fixation potential than bean, the traditional grain legume in western Kenya smallholder farming systems. Averaged across varieties, nodulation of the legumes was better with P than without P in all AEZs, indicating that P is essential for optimal N_2-fixation of the legumes.

Farmer assessment in relation to agronomic performance

Some of the criteria used by farmers to evaluate legumes were similar to those used in agronomic evaluation, e.g. emergence, leafiness, disease tolerance, etc. However, the results of farmer evaluation did not agree with those of agronomic evaluation in all cases. For example, groundnut and desmodium received relatively low emergence ratings, which were inconsistent with agronomic evaluation results, indicating that agronomic performance results alone are insufficient in identifying preferences of smallholder farmers for legumes.

Early maturity is an important criterion for smallholders due to high pressure on land. However, most of the legume species scored high for early maturity, indicating that they fitted well in the production systems studied. However, indeterminate species, e.g. green gram, cowpea, lima, and lablab received poor scores because farmers were concerned about the prolonged period of harvesting (pods matured at different stages), which would interfere with the following seasons' activities.

Leafiness and good flowering are early indicators of good biomass and seed production, while pests and diseases are major constraints to legume production in smallholder systems. The farmer evaluation results for leafiness and good flowering and pest and disease tolerance were consistent with those of agronomic evaluation, except for desmodium and siratro, which received relatively low scores for leafiness and good flowering, although they were among the best in terms of agronomic evaluation. Green manure legume species were generally scored high for ability to grow well in low fertility status soils, while grain legume species were generally perceived to have poorer ability to grow well in low soil fertility status soils, with the exception of soybean. Among the forage legumes, stylo was scored best for ability to grow well in poor soil status soils. This implies that green manure species are likely to be preferred in low soil fertility status fields, leaving the high soil fertility status soils for grain production.

Although bean, cowpea and green gram are relatively more established grain legumes in western Kenya smallholder systems, they received relatively poor evaluation scores on most criteria. This is an indication that soyabean and groundnut, which received high scores, may be suitable alternatives to bean. However, other factors, such as food preference, are likely to influence farmers' choices. The results of farmer evaluation suggest that participatory farmer assessment of legume species, based on locally formulated criteria, is an important tool that should be used, together with agronomic evaluation to identify suitable legumes that fit farmers' needs.

Conclusions

Our study confirms the utility of the socio-ecological niche concept. The results indicate that a number of the legume species studied have the potential for improving the productivity of the western Kenya smallholder farming systems. However, the legume species have differential performance due to variations in agro-ecological conditions, meaning that different species of grain, green manure and forage legumes and different varieties of those species need to be selected for different environments. Variations exist in emergence and survival, disease tolerance and nodulation of the legume species, offering opportunities for selection of species and varieties with greater potential for improving the productivity of the smallholder farming systems.

The study indicates that use of P is essential for enhancing the productivity of the legume species in western Kenya smallholder farming systems. However, the observed species and varieties x P interactions indicate that opportunities exist for selection and promotion of legume species and varieties adapted to low P status soils. Within-farm soil fertility variability has significant effects on legume productivity. Most of the grain legumes had better productivity in the high fertility fields than in the low fertility fields. Since food security is a primary household objective, farmers are likely to reserve the higher fertility status fields for the production of grain legumes, leaving the less fertile fields for production of the other legumes. This implies that the identification and promotion of non-food legume species with relatively good performance in less fertile soils is critical for improved smallholder productivity.

Farmer and agronomic evaluations were not always in agreement. For example, farmers scored variety SB20 best in emergence among soyabean, while the variety had the poorest emergence according to agronomic evaluation. Similarly, SB17 and SB20 were the best disease tolerant soyabean varieties, according to agronomic evaluation. However, farmers scored SB17 worst for disease tolerance. These results emphasize the need for integrating agronomic and farmer assessments in selecting legumes that match agro-ecological conditions and farmer needs, and confirm the utility of the socio-ecological niche concept. The capacity of the legumes to improve the productivity of the smallholder farming systems through fixation of atmospheric nitrogen is currently being investigated further as part of a broader study testing the utility of the socio-ecological niche concept.

Chapter 4

Niche-based assessment of contributions of legumes to the nitrogen economy of western Kenya smallholder farms

This Chapter is under review for publication as:

Ojiem, J.O., Vanlauwe, B., Ridder, N. de and Giller, K.E. Niche-based assessment of contributions of legumes to the nitrogen economy of western Kenya smallholder farms. *Plant and Soil.*

Chapter 4

Niche-based assessment of contributions of legumes to the nitrogen economy of western Kenya smallholder farms

Abstract

Nitrogen (N) deficiency is a major constraint to the productivity of the African smallholder farming systems. Grain, green manure and forage legumes have the potential to improve the soil N fertility of smallholder farming systems through biological N_2-fixation. The N_2-fixation of bean (*Phaseolus vulgaris*), soyabean *(Glycine max*), groundnut (*Arachis hypogaea*), Lima bean *(Phaseolus lunatus*), lablab (*Lablab purpureus*), velvet bean (*Mucuna pruriens*), crotalaria *(Crotalaria ochroleuca*), jackbean (*Canavalia ensiformis*), desmodium (*Desmodium uncinatum*), stylo *(Stylosanthes guianensis*) and siratro (*Macroptilium atropurpureum*) was assessed using the ^{15}N natural abundance method. The experiments were conducted in three agro-ecological zones (AEZ) in western Kenya, representing high rainfall (AEZ 1), medium rainfall (AEZ 2) and low rainfall (AEZ 3). Experimental fields were classified into high, medium and low fertility classes, to assess the influence of soil fertility on N_2-fixation performance. The legumes were planted with triple super phosphate (TSP) at 30 kg P ha^{-1}, with an extra soyabean plot planted without TSP, to assess response to P, and no artificial inoculation was done. Legume grain yield, shoot N accumulation, %N derived from N_2-fixation, N_2-fixation and net N inputs significantly ($P<0.01$) decreased with rainfall and soil fertility. Mean grain yield ranged from 0.86 Mg ha^{-1}, in AEZ 2, to 0.30 Mg ha^{-1}, in AEZ 3, and from 0.78 Mg ha^{-1}, in the high fertility field, to 0.48 Mg ha^{-1}, in the low fertility field. Shoot N accumulation ranged from a maximum of 486 kg N ha^{-1} in AEZ 2, to a minimum of 10 kg N ha^{-1} in AEZ 3. The species fixed 23-90% of their N requirements in AEZ 1, 25-90% in AEZ 2 and 7-77% in AEZ 3. Mean N_2-fixation by green manure legumes ranged from 232 kg ha^{-1} (crotalaria) in AEZ 1 to 29 kg ha^{-1} (jackbean) in AEZ 3. For the forage legumes, mean N_2-fixation ranged from 97 kg N ha^{-1} for desmodium in AEZ 2 to 39 kg N ha^{-1} for siratro in AEZ 3, while for the grain legumes, the range was from 172 kg N ha^{-1} for lablab in AEZ 1 to 3 kg N ha^{-1} for soyabean without P (soyabean-P) in AEZ 3. Lablab and groundnut showed consistently greater N_2-fixation and net N inputs across agro-ecological and soil fertility gradients. The use of maize as reference crop resulted in lower N_2-fixation values than when broad-leaved weed plants were used. The results demonstrate differential contributions of the green manure, forage and grain legume species to soil fertility improvement in different

biophysical niches in smallholder farming systems and suggest that appropriate selection is needed to match species with the niches and farmers' needs.

Key words: *agro-ecological zones, N_2-fixation, ^{15}N natural abundance, on-farm, trade-offs.*

Introduction

Soil fertility degradation is widely acknowledged as a major factor limiting productivity of the sub-Saharan Africa smallholder farming systems (Franzel, 1999; Sanchez et al., 1997; Tarawali et al., 1999). This degradation is particularly significant in the east African highlands, where rapid population growth, continuous cropping, and restricted use of organic inputs and fertilizers have led to low productivity of the systems. According to Smaling and Braun (1996), the average annual mining of nitrogen (N) in parts of western Kenya is up to 112 kg N ha^{-1} yr^{-1}. Nitrogen deficiency is therefore a major factor responsible for the low productivity of western Kenya smallholder systems.

Manure and mineral fertilizers are options for soil fertility restoration. However, as in many parts of sub-Saharan Africa, the use of animal manure in western Kenya is limited because the quantities available on-farm are often insufficient to maintain soil fertility (Jama et al., 1997), while the use of mineral fertilizers is constrained by unreliable returns (Ruthenberg, 1980; Anderson, 1992), limited access to capital by smallholders (Hoekstra and Corbett, 1995), and unreliable markets for agricultural produce (Hassan et al., 1998). Therefore, N input via biological N_2-fixation, using appropriate legume species, is a feasible alternative to N from mineral fertilizers. However, in restoring the productivity of the systems, legumes are important as a component of an integrated soil fertility management (ISFM) strategy, since phosphorus (P) has to be acquired from elsewhere. Legumes also require P for effective N_2-fixation, since P deficiency can prevent nodulation (Giller, 2001). According to Hudgens (2000), legumes can play a major role in improving farm productivity in smallholder agriculture as short duration fallow species. However, current knowledge on N_2-fixation performance under the non-ideal conditions encountered in African smallholder farming systems is limited, although some estimates have recently been made in northern Tanzania (Baijukya, 2004), and Zimbabwe (Chikowo et al., 2004).

western Kenya is typical of the agricultural conditions found in the densely populated highlands of east and central Africa. Due to this, it is one of the benchmark sites for the African Highlands Initiative (AHI), a collaborative research initiative working on key issues of natural resource management and agricultural productivity. Smallholder farms in western Kenya are characterized by a high degree of biophysical and socio-economic heterogeneity. Not only do farmers operate under diverse agro-ecological conditions, but there is wide diversity in within-farm soil fertility and farmers have varying resource endowments. Tittonell et al. (2005a,b) observed differences in the fertility status of fields in three sites in western Kenya, which were generally correlated with the resource endowment status of the farmers. For example, soil-extractable P was higher in the fields of high resource endowed farmers than in the fields of those with low resource endowment. These differences may affect legume N_2-fixation and production.

Soil fertility variability and differential resource endowments give rise to niches with biophysical and socio-economic dimensions, or socio-ecological niches (Chapter 2), into which legumes must fit in order to be widely accepted by farmers. N_2-fixation and the provision of certain goods (grains, fodder, etc.) are among the major criteria legumes must meet in order to fit into the socio-ecological niches.

A number of different methodologies are available for assessment of N_2-fixation. However, under field conditions, the ^{15}N natural abundance method (Peoples et al., 1989) has advantage over, for example, ^{15}N enrichment method because no addition of ^{15}N fertilizer is required, and can therefore be used on-farm, provided appropriate non-N_2-fixing reference plants are present. The choice of reference plants is a major factor that can influence the reliability of the methodology (Peoples et al., 2002). Maize is among the commonly used non-N_2-fixing plants in on-farm measurements of N_2-fixation because it is often readily available. The objectives of this study were: (i) to assess the capacities of a range of grain, green manure, and forage legumes to fix atmospheric N_2 under on-farm conditions across agro-ecological and soil fertility gradients in western Kenya; (ii) to compare the net N contributions (N balance) of the grain, green manure and forage legume species through N_2-fixation to the smallholder farming systems in western Kenya; and (iii) to evaluate the suitability of maize as a reference crop in on-farm N_2-fixation assessment using the ^{15}N natural abundance method.

Materials and Methods

Sites description

The experiments were conducted on-farm in Museno, Majengo and Ndori in western Kenya. The three sites were selected along an agro-ecological zone (AEZ) gradient: Museno (high rainfall, AEZ 1), located in Kakamega district at 00^{o} 14' N and 34^{o} 44' E at an altitude of 1570 m above sea level (masl), with a mean annual rainfall of 2000 mm; Majengo (medium rainfall, AEZ 2), located in Vihiga district at 00^{o} 00' N and 34^{o} 41' E at an altitude of 1385 masl, with a mean annual rainfall of 1600 mm; Ndori (low rainfall, AEZ 3) is located in Bondo district at 00^{o} 02' and 34^{o} 20' E at an altitude of 1170 masl, with a mean annual rainfall of 1200 mm. All the sites have bimodal rainfall pattern, with the first season (the long rains) extending from March to August, and the second (the short rains), from September to December.

In each site, experimental fields were selected to capture the within-farm soil fertility variability, which is a common feature within smallholder systems (Tittonell et al., 2005a). Three fields each were chosen to represent high, medium and low soil fertility conditions. The selections were based on farmer knowledge of within-farm soil fertility variability and the history of crop performance. However, further soil fertility characterization was done by sampling the soil in all fields in each site, prior to sowing the legumes, for laboratory analysis. Composite soil samples (0-20 cm depth) were taken from nine spots and bulked. A sub-sample of about 1 kg for each field was then taken for chemical and physical analysis. The soil samples were air dried, crushed and ground to pass through a 2 mm sieve and analysed for pH (1:2.5 soil/water suspension), texture (hydrometer method), extractable P (bicarbonate-EDTA), total N (macro-Kjeldahl), total soil organic carbon (Walkley-Black) and calcium, magnesium and potassium extracted in ammonium acetate (Anderson and Ingram, 1993). Although some soil fertility parameters did not show much variation, relatively large differences were observed in phosphorus (P), organic carbon (OC) and total N contents, especially between the high and the low fertility fields (Table 1). The farmer soil fertility classification took into consideration factors such as drainage properties of the field, soil depth, stoniness, presence of noxious weeds, etc, which are not captured in laboratory analysis but can affect crop performance.

Experimental design and plots establishment

The experiments were laid out in each field in randomized complete block design (RCBD) replicated in two blocks. Grain legume species: bean (*Phaseolus vulgaris* L.) variety KK20; soyabean (*Glycine max* (L.) Merr.) variety SB20; groundnut (*Arachis hypogaea* L.) variety CG 7*;* Lima bean (*Phaseolus lunatus* L.)*;* and lablab (*Lablab purpureus* (L.) Sweet) variety cv *Rongai*; green manure legumes: velvet bean (*Mucuna pruriens* (L.) Walp); crotalaria (*Crotalaria ochroleuca* (G.) Don); and jackbean (*Canavalia ensiformis* (L.) DC.); and forage legumes: desmodium (*Desmodium uncinatum* (Jacq.) DC.); stylo (*Stylosanthes guianensis* (Aublet) Sw)*;* and siratro (*Macroptilium atropurpureum* (DC.) Urban) were planted in mid September 2003 in plots measuring 4.5 m wide by 5.0 m long. The species and varieties were selected from a legume screening trial the season before (Chapter 3). All the legumes were planted at recommended spacing. Soyabean was planted in rows spaced 0.50 m at 0.05 m intra-row spacing, while groundnut and bean were spaced 0.50 m inter-row and 0.10 m intra-row. Lima bean was spaced 0.25 m inter-row, with

Table 1. Soil fertility parameters of the three categories of fields identified by farmers for experimentation in three agro-ecological zones in western Kenya (n=3).

	Soil fertility category	pH (H_2O)	% Total OC	% Total N	C:N ratio	P mg kg^{-1} soil	Ca $cmol_{(c)}$ kg^{-1}	Mg $cmol_{(c)}$ kg^{-1}	K $cmol_{(c)}$ kg^{-1}	% Clay	% Sand	% Silt
AEZ 1												
	High	5.95	1.64	0.17	10:1	8.78	6.30	1.48	0.40	24	35	45
	Medium	5.86	1.63	0.16	10:1	4.27	6.35	1.73	0.35	22	43	38
	Low	6.20	1.48	0.13	11:1	3.37	5.43	1.93	0.23	21	38	41
AEZ 2												
	High	5.86	1.50	0.19	8:1	15.42	6.96	2.10	0.36	22	33	48
	Medium	5.43	1.46	0.17	9:1	8.00	5.82	1.65	0.43	16	36	46
	Low	5.63	1.28	0.14	9:1	3.50	5.90	1.75	0.17	29	36	35
AEZ 3												
	High	5.84	1.52	0.17	9:1	2.48	6.40	2.30	0.39	37	28	30
	Medium	6.24	1.23	0.16	8:1	1.20	6.45	3.28	0.36	35	28	40
	Low	5.70	1.32	0.16	9:1	1.15	6.40	2.55	0.30	25	45	30

0.10 m intra-row spacing, while velvet bean, jackbean and lablab were planted in rows spaced at 0.60 m inter-row and 0.30 m intra-row. Crotalaria was drilled in rows spaced 0.30 m wide at a seed rate of 4 kg ha^{-1}. The legume seeds were not inoculated at planting because there is no existing infrastructure for supply of inoculants to smallholder farmers in the target area. In addition, previous research (Mureithi et al., 2003) did not demonstrate the need for artificial inoculation of similar legume species in several sites in western Kenya. In all legume plots, except crotalaria, two seeds were placed in each planting hole, later thinned to one seed per plant at first weeding. Maize was planted as a control, spaced 0.75 m inter-row and 0.30 m intra-row. Phosphorus (P) was applied at the rate of 30 kg P ha^{-1} to all legume plots and the maize plots. An extra soyabean plot with no P fertilization was included in the trial to check response to P.

Biomass production assessment

All the plots were sampled to determine legume biomass production. The above ground biomass was determined at near maximum dry matter accumulation, at mid pod filling stage. Biomass was determined by destructive sampling of plants in a 0.5 m by 0.5 m quadrat in 3 randomly selected positions within each plot, excluding the border rows. Biomass was immediately weighed in the field to determine fresh weight and then divided into two. One sub-sample was weighed with an electronic balance and then oven-dried at 65^{o}C for 4 days to determine dry weight and moisture content, which were used to calculate dry matter production. The other sub-sample was processed and used for quantification of N_2-fixation.

N_2-fixation methodology and calculations

The proportion of legume N derived from N_2-fixation was determined using the ^{15}N natural abundance method (Peoples et al., 1989). This method is based on the principle that provided the ^{15}N enrichment (δ^{15}N) of the plant-available soil N differs from atmospheric N_2, the %N from N_2-fixation can be determined. The %N from N_2-fixation calculated using the equation of Shearer and Kohl (1986) and Peoples et al. (1997) as follows:

$$\%\text{N from N}_2\text{-fixation} = 100\left(\frac{\delta^{15}\text{N}_{ref} - \delta^{15}\text{N}_{legume}}{\delta^{15}\text{N}_{ref} - B}\right) \qquad (1)$$

Where $\delta^{15}N_{ref}$ is the ^{15}N natural abundance of the shoots of a non-N_2-fixing reference plant deriving its entire N from the soil N; $\delta^{15}N_{legume}$ is the ^{15}N natural abundance of the shoots of the N_2-fixing legume plant growing in the same soil; and *B* is the $\delta^{15}N$ of the test legume fully dependent on N_2-fixation for growth, and a correction for isotopic fractionation during N_2-fixation.

The legume shoot samples were air-dried to constant weight, ground to < 1 mm in an electric mill in preparation for ^{15}N analysis. The ^{15}N analysis was done at the UC Davis Stable Isotope Facility, CA, USA, using a PDZ Europa 20-20 mass spectrometer. The ^{15}N natural abundance of the samples was computed using the equation of Shearer and Kohl (1986) as follows:

$$\delta^{15}N(‰) = 1000 \times \left[(R_{sample} / R_{standard}) - 1\right] \qquad (2)$$

Where $\delta^{15}N$ is the ^{15}N natural abundance of the samples expressed as parts per thousand (‰); and *R* is the ration of $^{15}N/^{14}N$ in the sample; and the atmospheric N_2 was used as the standard ($R_{standard}$). By definition, the $\delta^{15}N$ of the atmosphere is zero. A range of broad-leaved weed plants and maize, growing in the same fields as the legumes, were used as reference plants, while *B* values were obtained from the literature (see Table 4).

Grain production assessment

Grain production was assessed in all the fields at each site. The species matured at different times and were harvested between November and December, 2003. The pods were sun-dried for several days and then threshed. Grain was then weighed and grain moisture content determined using an electronic moisture meter. Grain yield was calculated at 12% moisture content.

Statistical analysis

Data was subjected to analysis of variance (ANOVA) procedure using SAS statistical software (SAS Institute Inc, Cary, NC, U.S.A.). A cross-site analysis was performed using agro-ecological zones, soil fertility and legumes as factors. Legume shoot ^{15}N natural abundance, %N derived from N_2-fixation, legume biomass, shoot N content and grain yield were analysed. Where significant differences were detected between means, standard error of difference (SED) values were calculated and used to compare means.

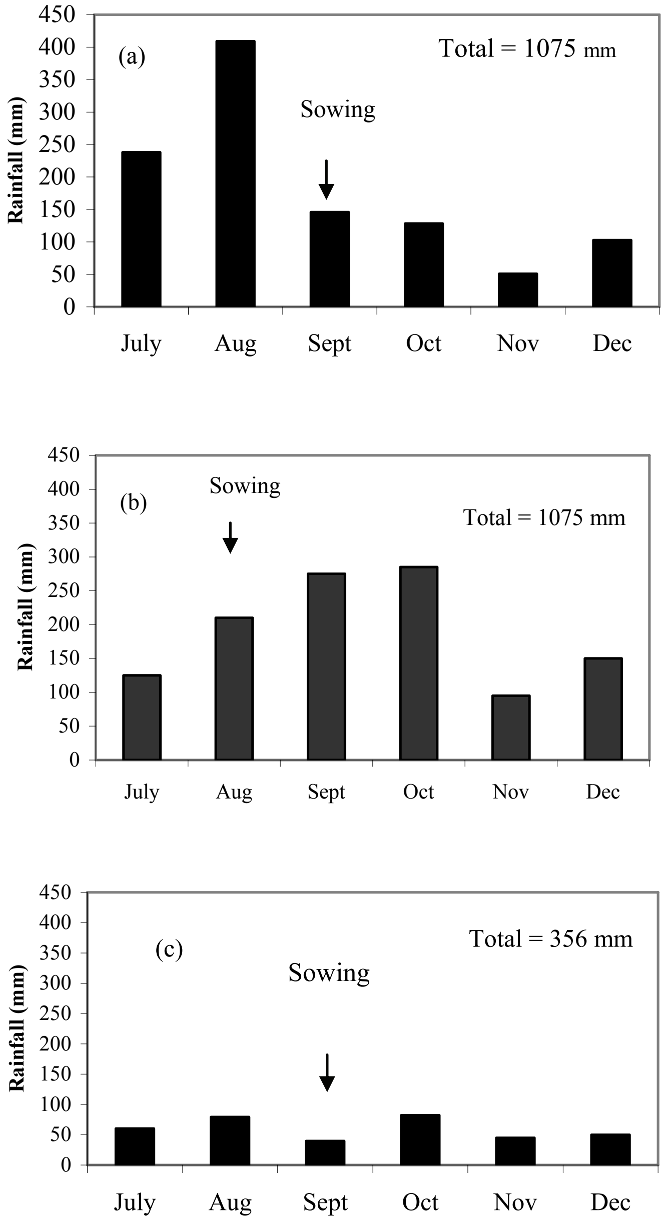


Figure 1. Rainfall recorded during the experimentation period in: (a) Museno (AEZ 1); (b) Majengo (AEZ 2); and (c) Ndori (AEZ 3) study sites in western Kenya.

Results

Legume establishment and performance

There was good legume emergence and growth at all sites. The legumes were well adapted to the agro-environmental conditions in the three agro-ecological zones and as a result, only minor incidence of pest and diseases were observed. The total amounts of rainfall received in AEZs 1 and 2 during the short rains 2003 season were nearly the same (Figures 1a and 1b). However, in AEZ 2, a total of 788 mm of rainfall was received in the period between sowing (September) and harvesting (December), while in AEZ 1 only 428 mm was received over the same period. However, relatively higher rainfall was recorded in AEZ 1 in August, before legume sowing, which should have recharged the soil with moisture. Nevertheless, the legume performance was relatively better in AEZ 2 than in AEZ 1. Rainfall was low in AEZ 3 (Figure 1c). A total of 356 mm of rainfall was recorded during the season, about 50% of the normal rainfall for the zone. The rainfall gradient in 2003 was therefore considered to be in the sequence AEZ 2-AEZ 1-AEZ 3.

Legume grain yield performance

Grain yield significantly (P<0.001) differed with species, AEZ and soil fertility (Table 2). Mean grain yield generally decreased with decreasing rainfall, ranging from 0.86 Mg ha^{-1} in AEZ 2, to 0.30 Mg ha^{-1} in AEZ 3. Similarly, grain yield consistently decreased with soil fertility. For example, in AEZ 1, grain yield of bean ranged from 1.25 Mg ha^{-1} in the high fertility field to 0.37 Mg ha^{-1} in the low fertility field. Similarly, the grain yield of soyabean fertilized with P (soyabean+P) ranged from 1.13 Mg ha^{-1} in the high fertility field to 0.68 Mg ha^{-1} in the low fertility field. Similar reductions in grain yield performance were observed in AEZs 2 and 3. In AEZ 1, bean (0.82 Mg ha^{-1}), lablab (0.77 Mg ha^{-1}) and soyabean+P (0.85 Mg ha^{-1}) had the best grain yield performance, while in AEZ 2, soyabean+P (1.04 Mg ha^{-1}), lablab (1.05 Mg ha^{-1}) and groundnut (1.06 Mg ha^{-1}) performed best. In AEZ 3, the best grain yield was with groundnut (0.32 Mg ha^{-1}), bean (0.33 Mg ha^{-1}) Lima (0.43 Mg ha^{-1}) and soyabean+P (0.43 Mg ha^{-1}).

^{15}N natural abundance of the soil and reference plants

The detected ^{15}N natural abundance signatures (δ^{15}N) for soil and non-N_2-fixing reference plants varied between species in all AEZs (Table 3). Generally, δ^{15}N signatures of maize plants of the same age as legumes, and growing in the same field, were lower than those of similar aged broad-leaved weeds growing in the same field. In AEZ 1, the δ^{15}N values for all reference plants ranged from +2.78 to +6.85 ‰. The mean for maize samples was +3.20‰, while the broad-leaved reference samples had a mean of + 5.89‰. The δ^{15}N signatures for all reference plants were slightly higher in AEZ 2 compared with AEZ 1. The maize reference plants had a mean value of +3.61‰, while the mean for broad-leaved weeds was +6.29‰. Maize had relatively higher δ^{15}N signatures in AEZ 3, with a mean of +4.14‰. The mean for broad-leaved

Table 2. Effect of agro-ecological zone and soil fertility on legume species grain yield (at 12% moisture content) in western Kenya, short rains 2003 season.

Species	Grain yield (Mg ha^{-1})											
	AEZ 1				AEZ 2				AEZ 3			
	High fertility field	Medium fertility field	Low fertility field	Mean	High fertility field	Medium fertility field	Low fertility field	Mean	High fertility field	Medium fertility field	Low fertility field	Mean
Bean	1.25	0.83	0.37	0.82	0.94	0.69	0.49	0.71	0.38	0.33	0.29	0.33
Groundnut	0.71	0.56	0.53	0.60	1.25	1.12	0.80	1.06	0.34	0.30	0.31	0.32
Lablab	0.84	0.69	0.78	0.77	1.40	0.96	0.78	1.05	0.05	0.07	0.05	0.06
Lima	0.76	0.72	0.61	0.70	0.49	0.53	0.41	0.48	0.50	0.45	0.33	0.43
Soyabean (+P)	1.13	0.74	0.68	0.85	1.39	0.94	0.79	1.04	0.53	0.42	0.34	0.43
Soyabean (-P)	0.84	0.57	0.44	0.62	1.05	0.84	0.54	0.81	0.30	0.29	0.13	0.24
Mean	**0.92**	**0.69**	**0.57**	**0.73**	**1.09**	**0.85**	**0.64**	**0.86**	**0.35**	**0.31**	**0.24**	**0.30**
***$SED_{(Species)}$					0.08							
***$SED_{(Fertility)}$					0.06							
***$SED_{(AEZ)}$					0.04							

SED =standard error of the difference in means, *** P<0.001

weeds was +5.74‰. The $\delta^{15}N$ signatures in the soils showed little variation between sites, with mean values ranging from +7.96‰ in AEZ 1 to +6.54‰ in AEZ 3. However, no consistent trends were observed in the relationship between $\delta^{15}N$ and soil fertility status of the trial fields.

^{15}N natural abundance of legumes and estimates of N_2-fixation

The ^{15}N natural abundance of the legume shoots differed significantly (P<0.01) with species and AEZs (Table 4). Mean shoot ^{15}N natural abundance consistently increased with decreasing rainfall for grain and green manure legume. For the forage legumes, however, the trend was not consistent. The mean $\delta^{15}N$ of the green manure species (+0.48‰) showed less enrichment than that of the grain (+0.97‰) and forage legumes (+1.55‰) in AEZ 1. A similar trend was observed in AEZ 2. However, in AEZ 3, the forage legume shoots showed relatively lower enrichment (+1.40 ‰) than the grain legumes (+2.71‰) and green manure legumes (+1.93‰). Among the grain legumes, soyabean-P (+0.15‰), soyabean+P (+0.37‰) and lablab (+0.82‰) showed the least shoot enrichment in AEZ 1, while in AEZ 2, soyabean-P (+1.36‰), soyabean+P (+1.51‰) and groundnut (+1.68‰) were the least enriched. In AEZ 3, groundnut (+1.58‰), lablab (+1.83‰) and Lima (+2.47‰), showed the least shoot enrichment. Among the green manure legumes, velvet bean (-0.70‰) showed least shoot enrichment in AEZ 1, jackbean (-0.31‰) in AEZ 2, and crotalaria (+0.49‰) in AEZ 3, while for forage legumes, stylo was least enriched in AEZ 1 (+1.23‰) and AEZ 2 (+1.42‰), while siratro (+1.25‰) was least enriched in AEZ 3.

The % N derived from atmospheric N_2-fixation was significantly (P<0.01) influenced by AEZ and legume species (Table 4). The use of maize as reference plant consistently resulted in smaller values of %N derived from N_2-fixation than when broad-leaved weeds were used. The $\delta^{15}N$ signatures of the broad-leaved weed plants, which were relatively consistent around 6‰, were closer to the total soil $\delta^{15}N$ (about 8‰) than the $\delta^{15}N$ signatures of maize, which were around 3.5‰. Based on this, the weed reference plants were considered better indicators of the $\delta^{15}N$ signatures of the available soil N, hence providing more accurate estimates of N_2-fixation than maize. Therefore, based on broad-leaved weeds as reference plants, the legumes derived 35-90% of their N requirements from atmospheric N_2-fixation in AEZ 1, 48-90% in AEZ 2 and 1-77% in AEZ 3. Averaged over species, the %N from N_2-fixation was higher for green manure legumes than for grain and forage legumes in AEZs 1 and 2. In AEZ

Table 3. Estimates of the ^{15}N natural abundance signatures detected in soil, maize and broad-leaved non-N_2-fixing reference plants in different agro-ecological zones and soil fertility conditions in western Kenya.

Site	Farm No.	Soil fertility status	Soil $\delta^{15}N$ (‰)	Reference plant	$\delta^{15}N$ (‰)	
					Maize	Weeds
Museno:	1	Low	8.61	*Zea mays*	3.82	-
High rainfall zone				*Bidens pilosa*	-	6.20
(AEZ 1)	2	High	7.80	*Zea mays*	3.36	-
				Bidens pilosa	-	6.85
	3	High	7.55	*Zea mays*	2.78	-
				Bidens pilosa	-	3.98
	4	Low	7.72	*Zea mays*	2.79	-
				Bidens pilosa	-	6.00
				Galinsoga spp.	-	5.79
	5	High	8.05	*Zea mays*	3.17	-
				Bidens pilosa	-	5.63
	6	Medium	7.34	*Zea mays*	3.78	-
				Bidens pilosa	-	6.11
	7	Medium	9.19	*Zea mays*	2.97	-
				Bidens pilosa	-	6.16
	8	Low	7.71	*Zea mays*	2.99	-
				Lantana trifolia	-	5.83
				Bidens pilosa	-	6.11
	9	Medium	7.73	*Zea mays*	3.15	-
				Lantana trifolia	-	6.17
		Mean	**7.96**	-	**3.20**	**5.89**
Majengo	1	High	6.87	*Zea mays*	4.19	-
Medium rainfall zone				*Bidens pilosa*	-	5.88
(AEZ 2)	2	Low	7.56	*Zea mays*	3.58	-
				Lantana trifolia	-	5.14
	3	Medium	8.25	*Zea mays*	3.13	-
				Lantana trifolia	-	7.23
	4	High	7.72	*Zea mays*	3.24	-
				Bidens pilosa	-	6.15
	5	High	8.38	*Zea mays*	3.89	-
				Galinsoga spp.	-	6.81
	6	Low	7.93	*Zea mays*	2.21	-
				Bidens pilosa	-	6.39
	7	Medium	7.87	*Zea mays*	6.19	-
				Bidens pilosa	-	6.82
	8	Medium	7.54	*Zea mays*	3.05	-
				Conyza banariensis	-	6.42
	9	Low	7.15	*Zea mays*	3.05	-
				Conyza banariensis	-	5.80
		Mean	**7.69**	-	**3.61**	**6.29**
Ndori	1	Low	6.83	*Zea mays*	4.13	-
Low rainfall zone				*Bothriocline laxa*	-	5.76
(AEZ 3)	2	High	5.93	*Zea mays*	4.23	-
				Leonoptis nepetifolia	-	5.82
	3	Medium	5.45	*Zea mays*	4.40	-
				Bidens pilosa	-	5.59
	4	Low	8.07	*Zea mays*	4.40	-
				Bidens pilosa	-	5.82
	5	Low	6.30	*Zea mays*	3.89	-
				Leonoptis nepetifolia	-	3.82
	6	Medium	6.06	*Zea mays*	4.40	-
				Leonoptis nepetifolia	-	6.30
	7	High	6.60	*Zea mays*	3.92	-
				Bidens pilosa	-	6.30
	8	Medium	6.61	*Zea mays*	3.89	-
				Bidens pilosa	-	6.25
	9	High	7.05	*Zea mays*	4.03	-
				Leonoptis nepetifolia	-	6.44
				Bothriocline laxa	-	5.30
		Mean	**6.54**	-	**4.14**	**5.74**

3, however, the %N from N_2-fixation was higher for forage legumes than for green manure and grain legumes. Bean showed the least dependence on N_2-fixation for its N requirements in AEZs 1 and 2, while in AEZ 3, soyabean+P showed the least dependence on N_2-fixation for its N requirements.

Biomass production and N_2-fixation by the green manure and forage legumes

AEZ and soil fertility had significant (P<0.01) effects on biomass production, shoot N yield and biological N_2-fixation by the green manure and forage legume species (Table 5). Averaged across species, legume biomass production, shoot N accumulation and N_2-fixation increased with rainfall, performing better in AEZ 2 than in AEZ 1 due to differences in rainfall, as discussed earlier. Averaged over all species and soil fertility, mean biomass production ranged from 6.86 Mg ha^{-1} in AEZ 2 to 3.28 Mg ha^{-1} in AEZ 3, and shoot N accumulation from 177 kg N ha^{-1} in AEZ 2 to 85 kg N ha^{-1} in AEZ 3. Use of maize as a reference crop generally underestimated N_2-fixation compared with using the broad-leaved weeds in all AEZs. Mean N_2-fixation, estimated using broad leaved weeds as reference plants (N_2-fixed$_w$), ranged from 135 kg N ha^{-1} in AEZ 2 to 50 kg N ha^{-1} in AEZ 3, and that estimated using maize as reference crop (N_2-fixed$_m$), ranged from 94 kg N ha^{-1} in AEZ 2 to 40 kg N ha^{-1} in AEZ 3. Mean shoot biomass production, shoot N accumulation, and N_2-fixation decreased with soil fertility, although the trend was more consistent in AEZ 2, compared with AEZs 1 and 3. Also, the differences in mean shoot biomass production, shoot N accumulation, and N_2-fixation between the high and the medium fertility fields were more consistent across the AEZs than those between the medium and the low fertility fields.

Shoot biomass production showed an interaction between AEZ and soil fertility (Table 5). Among the green manure legumes in AEZ 1, shoot biomass production was best with crotalaria (8.01 Mg ha^{-1}) in the high fertility field, and best with velvet bean in the medium fertility field (7.23 Mg ha^{-1}) and low fertility field (8.42 Mg ha^{-1}). For the forage legumes, shoot biomass production was best with desmodium (5.76 Mg ha^{-1}) in the high fertility field, stylo (4.66 Mg ha^{-1}) in the medium fertility field, and desmodium (5.00 Mg ha^{-1}) in the low fertility field. However, in AEZ 2, where legume performance was best, shoot biomass production was best with velvet bean in all fields, and ranged from 14.46 Mg ha^{-1} in the high fertility field, to 8.37 Mg ha^{-1} in the low fertility field, while forage legume biomass production was best with desmodium in the high fertility field (5.92 Mg ha^{-1}), stylo in the medium fertility field (4.65 Mg ha^{-1}), and desmodium in the low fertility field (4.07 Mg ha^{-1}). In AEZ 3, among the green manure legumes, jackbean had the best shoot biomass production in

Table 4. *B* values, shoot ^{15}N natural abundance and estimates of N derived from atmospheric N_2-fixation for grain, green manure and forage legumes in three agro-ecological zones in western Kenya, short rains 2003 season.

Species	*B*-value	AEZ 1				AEZ 2				AEZ 3			
		Shoot $\delta^{15}N$ (‰)	%N from N_2-fixation			Shoot $\delta^{15}N$ (‰)	%N from N_2-fixation			Shoot $\delta^{15}N$ (‰)	%N from N_2-fixation		
			[f]Maize	[g]Weeds	[h]Mean		[f]Maize	[g]Weeds	[h]Mean		[f]Maize	[g]Weeds	[h]Mean
Grain legumes:													
Bean	-1.00[a]	2.22	23	35-59	53	2.44	25	48-61	56	3.24	18	12-43	37
Groundnut	-1.40[b]	0.89	50	57-72	69	1.68	39	65-73	70	1.58	46	43-62	58
Soyabean (-P)	-2.00[ac]	0.15	59	64-76	73	1.36	40	70-77	74	3.41	12	7-36	30
Soyabean (+P)	-2.00[ac]	0.37	54	60-73	70	1.51	37	67-74	71	3.74	7	1-32	26
Lima	-1.00[d]	1.35	44	53-70	66	2.46	25	62-71	68	2.47	32	28-53	49
Lablab	-1.36[c]	0.82	52	59-73	70	1.75	37	66-75	72	1.83	42	38-59	55
Mean	**-**	**0.97**	**47**	**55-71**	**67**	**1.87**	**34**	**63-72**	**69**	**2.71**	**26**	**22-48**	**43**
Green manure legumes:													
Velvet bean	-2.09[b]	-0.70	74	77-84	83	0.12	61	81-85	83	0.55	58	55-69	66
Jackbean	-1.00[d]	1.41	43	52-69	65	-0.31	85	61-71	67	3.37	15	9-41	35
Crotalaria	-1.31[b]	-0.46	81	84-90	88	1.41	45	87-90	89	0.49	67	65-77	74
Mean		**0.48**	**66**	**71-81**	**77**	**0.55**	**64**	**76-82**	**78**	**1.93**	**47**	**43-62**	**55**
Forage legumes:													
Desmodium	-1.55[c]	1.46	37	46-64	60	1.84	34	55-66	62	1.54	46	42-61	58
Siratro	-1.99[c]	1.63	30	39-59	54	1.53	37	49-61	56	1.25	47	44-62	58
Stylo	-0.74[c]	1.23	50	58-74	70	1.42	50	66-75	72	1.45	55	52-69	66
Mean		**1.55**	**39**	**48-66**	**61**	**1.69**	**41**	**57-67**	**63**	**1.40**	**49**	**46-64**	**61**
Mean	**-**	**1.01**	**48**	**57-72**	**67**	**1.51**	**42**	**65-73**	**69**	**2.17**	**36**	**34-56**	**50**
$SED_{(species)}$						0.43	9	-	9				
$SED_{(AEZ)}$						0.15	3	-	3				
$SED_{(AEZ\ x\ species)}$						0.19	4	-	4				

[a] Value from Peoples, 2005 (personal communication).
[b] Okito et al., 2004
[c] Boddey et al., 2000
[d] Assumed.
[e] Gathumbi et al., 2002
[f] Percent N derived from atmospheric fixation estimated using maize as reference plant.
[g] Percent N derived from atmospheric fixation estimated using several broad-leaved weed plants presented in Table 3 as reference plants.
[h] Mean percent N derived from atmospheric fixation calculated using the mean Shoot $\delta^{15}N$ values of the broad-leaved weed reference plants.

the high fertility field (4.93 Mg ha^{-1}) and the low fertility field (4.10 Mg ha^{-1}), while crotalaria (3.59 Mg ha^{-1}) was best in the medium fertility field. Forage legume biomass production was best with stylo (3.17 Mg ha^{-1}) in the high fertility field, desmodium (3.10 Mg ha^{-1}) in the medium fertility field, and siratro (3.14 Mg ha^{-1}) in the low fertility field.

The trends in shoot N accumulation closely followed those of shoot biomass accumulation (Table 5). Averaged over all species and soil fertility, N_2-fixed$_m$ and N_2-fixed$_w$ differed by 20-30%. In AEZ 1, mean N_2-fixed$_m$ was 78% of N_2-fixed$_w$, while in AEZs 2 and 3, N_2-fixed$_m$ was 70% and 80% of N_2-fixed$_w$, respectively. The green manure legumes fixed greater quantities of N_2 than the forage legumes. However, the differences were greater in AEZ 2, where mean N_2-fixation by the forage legumes was only 35-38% of that of green manure legumes, compared with 57-64% for AEZ 1, and 79-94% for AEZ 3. Among the green manure legumes in AEZ 1, crotalaria and jackbean had the best and the worst N_2-fixation, respectively, in the high, medium and low fertility fields, based on N_2-fixed$_w$. In the high fertility field, crotalaria fixed 232 kg N ha^{-1}, compared with 66 kg N ha^{-1} for jackbean, while in the low fertility field, crotalaria fixed 154 kg N ha^{-1}, compared with 78 kg N ha^{-1} for jackbean. Among the forage legumes, the differences in N_2-fixation between species were relatively small compared with the green legume species. In AEZ 1, desmodium had the best N_2-fixation in the high fertility field (92 kg N ha^{-1}) and in the low fertility field (80 kg N ha^{-1}, while stylo (83 kg N ha^{-1}) had the best N_2-fixation in the medium fertility field. In AEZ 2, stylo had the best N_2-fixation of 96 kg N ha^{-1} in the high fertility field, and 86 kg N ha^{-1} in the medium fertility field. However, in the low fertility field, desmodium had the best N_2-fixation of 64 kg N ha^{-1}. Averaged over all species and soil fertility, mean N_2-fixed$_w$ in AEZ 3 was only 37% of that of AEZ 2. Among the green manure legumes, N_2-fixation was consistently best with crotalaria across the soil fertility gradient, with a range from 56 kg N ha^{-1} in the high fertility field, to 95 kg N ha^{-1} in the medium fertility field. Among the forage legumes, stylo had the best N_2-fixation in the high fertility field (53 kg N ha^{-1}) and the medium fertility field (52 kg N ha^{-1}), while in the low fertility field, siratro (45 kg N ha^{-1}) had the best N_2-fixation.

N_2-fixation, N export and net N contributions of the grain legumes

AEZ and soil fertility had significant (P<0.01) effects on the species shoot N accumulation, N_2-fixation, grain N accumulation and net N inputs from N_2-fixation (Table 6). Averaged across species and soil fertility, shoot N accumulation by the legumes decreased with rainfall. Mean shoot N accumulation was greatest (135 kg N ha^{-1}) in AEZ 2, 111 kg N ha^{-1} in AEZ 1, and least (40 kg N ha^{-1}) in AEZ 3. In contrast,

Table 5. Shoot biomass, N yield, and N_2-fixation by green manure and forage legume species grown under three soil fertility conditions three agro-ecological zones in western Kenya, short rains 2003 season.

Species	AEZ 1					AEZ 2					AEZ 3				
	[a]Shoot biomass (Mg ha^{-1})	Shoot N yield (kg ha^{-1})	N_2-fixed (kg N ha^{-1})			[a]Shoot biomass (Mg ha^{-1})	Shoot N yield (kg ha^{-1})	N_2-fixed (kg N ha^{-1})			[a]Shoot biomass (Mg ha^{-1})	Shoot N yield (kg ha^{-1})	N_2-fixed (kg N ha^{-1})		
			Maize	weeds	[b]Mean			Maize	Weeds	[b]Mean			Maize	Weeds	[b]Mean
						High fertility field									
Velvet bean	6.68	141	104	109-118	117	14.86	384	234	311-326	319	2.87	74	43	41-51	49
Jackbean	4.46	102	44	53-70	66	7.03	153	130	93-109	103	4.93	128	19	12-52	45
Crotalaria	8.01	264	214	222-238	232	9.48	311	140	140-271	277	3.64	76	51	49-59	56
Mean: GM legumes	*6.38*	*169*	*121*	*128-142*	*138*	*10.46*	*283*	*168*	*181-235*	*233*	*3.81*	*93*	*38*	*34-54*	*50*
Desmodium	5.76	153	57	70-98	92	5.92	157	53	86-104	97	3.07	81	37	34-49	47
Siratro	4.74	118	35	46-70	64	5.05	125	46	61-76	70	2.79	69	32	30-43	40
Stylo	4.94	126	63	73-93	88	5.18	133	67	88-100	96	3.17	81	45	42-56	53
Mean: forage legumes	*5.15*	*132*	*52*	*63-87*	*81*	*5.38*	*138*	*55*	*78-93*	*88*	*3.01*	*77*	*38*	*35-49*	*47*
						Medium fertility field									
Velvet bean	7.23	146	108	112-123	121	13.96	334	204	271-284	277	3.18	67	39	37-46	44
Jackbean	2.57	70	30	36-48	46	4.18	100	85	61-71	67	3.24	82	12	7-34	29
Crotalaria	5.55	187	151	157-168	165	10.42	302	136	263-272	269	3.59	128	86	83-99	95
Mean: GM legumes	*5.12*	*134*	*96*	*102-113*	*111*	*9.52*	*245*	*142*	*198-209*	*204*	*3.34*	*92*	*46*	*44-60*	*56*
Desmodium	4.54	120	44	55-77	72	4.10	105	36	58-69	65	3.10	82	38	34-50	48
Siratro	4.34	108	32	42-64	58	4.49	112	41	55-68	63	2.72	67	31	29-42	39
Stylo	4.66	119	60	69-88	83	4.65	119	60	79-89	86	3.07	79	43	41-55	52
Mean: forage legumes	*4.51*	*116*	*45*	*55-76*	*71*	*4.41*	*112*	*46*	*64-75*	*71*	*2.96*	*76*	*37*	*35-49*	*46*
						Low fertility field									
Velvet bean	8.42	178	132	137-150	148	8.37	196	120	159-167	163	3.85	73	42	40-50	48
Jackbean	5.82	120	52	62-83	78	7.39	155	132	95-110	104	4.10	113	17	10-46	40
Crotalaria	6.05	175	142	147-158	154	7.84	238	107	207-214	212	3.20	109	73	71-84	81
Mean: GM legumes	*6.76*	*158*	*109*	*115-130*	*127*	*7.87*	*196*	*120*	*154-164*	*160*	*3.72*	*98*	*44*	*40-60*	*56*
Desmodium	5.00	133	49	61-85	80	4.07	104	35	57-69	64	2.86	76	35	32-46	44
Siratro	4.35	108	32	42-64	58	3.03	75	28	37-46	42	3.14	78	37	34-48	45
Stylo	4.32	112	56	65-83	78	3.37	86	43	57-65	62	2.57	66	36	34-46	44
Mean forage legumes	*4.56*	*118*	*46*	*56-77*	*72*	*3.49*	*88*	*35*	*50-60*	*56*	*2.86*	*73*	*36*	*33-47*	*44*
Mean	**5.41**	**138**	**78**	**87-104**	**100**	**6.86**	**177**	**94**	**121-139**	**135**	**3.28**	**85**	**40**	**37-51**	**50**
$^{**}SED_{(Legumes)}$						0.67	20	-	-	21					
$^{**}SED_{(Fields)}$						0.28	9	-	-	9					
$^{**}SED_{(AEZ)}$						0.15	5	-	-	5					

SED = Standard error of difference between means, ** = P<0.01, GM = green manure, [a]= above ground biomass, [b]= Mean N2-fixation computed using broad-leaved weeds as reference plants.

mean N_2-fixation (N_2-fixed$_w$) was greatest in AEZ 1 (76 kg N ha^{-1}), 53 kg N ha^{-1} in AEZ 2, and least (20 kg N ha^{-1}) in AEZ 3, while mean grain N accumulation was 40 kg N ha^{-1} in AEZ 2, 32 kg N ha^{-1} in AEZ 1, and 13 kg N ha^{-1} in AEZ 3. Net N input followed a similar trend to N_2-fixation. The species had greater net N input (44 kg N ha^{-1}) in AEZ 1, compared with AEZ 2 (13 kg N ha^{-1}) and AEZ 3 (8 kg N ha^{-1}).

Similarly, shoot N accumulation, N_2-fixation and grain N decreased with soil fertility. Averaged across species, in AEZ 1, shoot N accumulation ranged from 142 kg N ha^{-1}, in the high fertility field, to 89 kg N ha^{-1}, in the low fertility field, while in AEZ 2, the range was from 172 kg N ha^{-1}, in the high fertility field, to 105 kg N ha^{-1}, in the low fertility field. In AEZ 3, the range was relatively narrow, from 42 kg N ha^{-1} in the high fertility field, to 39 kg N ha^{-1}, in the low fertility field. Mean N_2-fixation decreased with soil fertility in AEZs 1 and 3, but showed no consistent pattern in AEZ 2. In AEZ 1, mean N_2-fixation ranged from 97 kg N ha^{-1}, in the high fertility field, to 61 kg N ha^{-1} in the low fertility field, while in AEZ 2, a mean of 40 kg N ha^{-1} was fixed in the high fertility field, 69 kg N ha^{-1} in the medium, and 50 kg N ha^{-1}, in the low fertility field. In AEZ 3, where N_2-fixation performance was poorest, mean N_2-fixation ranged from 42 kg N ha^{-1}, in the high fertility field, to 20 kg N ha^{-1}, in the low fertility field.

Significant ($P<0.01$) differences were observed between the grain legumes in shoot N accumulation, N_2-fixation and net N contributions to soil N fertility. In the high fertility field in AEZ 1, legume shoot N accumulation was best with lablab (246 kg N ha^{-1}) and groundnut (179 kg N ha^{-1}) and worst with bean (58 kg N ha^{-1}). N_2-fixation and net N input followed trends similar to shoot N accumulation. Lablab (172 kg N ha^{-1}) and groundnut (124 kg N ha^{-1}) had the best N_2-fixation, while bean (31 kg N ha^{-1}) had the worst. Similarly, lablab (+131 kg N ha^{-1}) and groundnut (+89 kg N ha^{-1}) had the best net contributions to soil N fertility, while bean (-8 kg N ha^{-1}) had the worst. The relative performance of the species was consistent in the medium and low fertility fields. In the high fertility field in AEZ 2, lablab (486 kg N ha^{-1}) and soyabean+P (158 kg N ha^{-1}) had the best shoot N accumulation. However, net N contribution to soil N fertility was negative for all the legumes, except lablab (+42 kg N ha^{-1}). Soil N mining was relatively greater with soyabean+P (-27 kg N ha^{-1}) and bean (-25 kg N ha^{-1}). Similar to the high fertility field, lablab (165 kg N ha^{-1}) and soyabean+P (79 kg N ha^{-1}) had the best N_2-fixation in the medium fertility field. However, net N contributions to soil N fertility were best with lablab (+106 kg N ha^{-1}) and Lima (+27 kg N ha^{-1}). In the low soil fertility, N_2-fixation was best with lablab (94 kg N ha^{-1}) and soyabean-P (58 kg N ha^{-1}), as well as net N inputs, which were +68 kg N ha^{-1} and +28 kg N ha^{-1} for lablab and soyabean-P, respectively. In AEZ 3, lablab and groundnut were consistently the best in shoot N accumulation, N_2-fixation and net

Table 6. Legume shoot N yield, N_2-fixation, N harvest index , N export, and net N contribution to the N fertility of soils under variable soil fertility and agro-ecological conditions in western Kenya, short rains, 2003 season

Species	AEZ 1					AEZ 2					AEZ 3				
	[a]Shoot N yield (kg ha^{-1})	[b]Fixed N (kg ha^{-1})	Grain N (kg ha^{-1})	N harvest index (%)	Net N input (kg ha^{-1})	[a]Shoot N yield (kg ha^{-1})	[b]N fixed (kg ha^{-1})	Grain N (kg ha^{-1})	N harvest index (%)	Net N input (kg ha^{-1})	[a]Shoot N yield (kg ha^{-1})	[b]N fixed (kg ha^{-1})	Grain N (kg ha^{-1})	N harvest index (%)	Net N input (kg ha^{-1})
High fertility field															
Bean	58	31	39	67	-8	45	14	39	87	-25	21	8	13	62	-5
Groundnut	179	124	35	20	+89	140	43	50	36	-7	70	41	12	17	+29
Soyabean (-P)	102	74	53	52	+21	120	43	64	53	-21	21	6	14	67	-8
Soyabean (+P)	160	112	73	46	+39	158	46	73	46	-27	39	10	28	72	-18
Lima	107	71	29	27	+42	82	10	23	28	-13	26	12	11	42	+1
Lablab	246	172	41	17	+131	486	86	44	9	+42	76	42	-	-	+42
Mean	*142*	*97*	*45*	*38*	*+52*	*172*	*40*	*49*	*43*	*-9*	*42*	*20*	*16*	*52*	*+7*
Medium fertility field															
Bean	34	18	19	56	-1	46	18	19	41	-1	14	5	10	71	-5
Groundnut	149	103	21	14	+82	113	50	58	51	-8	69	40	12	17	+28
Soyabean (-P)	62	45	26	42	+19	112	59	61	54	-2	24	7	15	63	-8
Soyabean (+P)	82	57	40	49	+17	145	79	64	44	+15	25	7	17	68	-10
Lima	79	52	17	22	+35	89	43	16	18	+27	28	13	15	54	-2
Lablab	201	141	32	16	+109	267	165	59	22	+106	81	45	-	-	+45
Mean	*101*	*69*	*26*	*33*	*+44*	*129*	*69*	*46*	*38*	*+23*	*40*	*20*	*12*	*55*	*+8*
Low fertility field															
Bean	23	12	10	43	+2	29	9	10	34	-1	18	7	9	50	-2
Groundnut	115	79	20	17	+59	123	50	33	27	+17	63	37	13	21	+24
Soyabean (-P)	63	46	29	46	+17	106	58	30	28	+28	10	3	5	50	-2
Soyabean (+P)	99	69	41	41	+28	125	55	41	33	+14	17	4	13	76	-9
Lima	70	46	18	26	+28	38	32	10	26	+22	27	12	14	52	-2
Lablab	163	114	28	17	+86	210	94	26	12	+68	98	54	-	-	+54
Mean	*89*	*61*	*24*	*32*	*+37*	*105*	*50*	*25*	*27*	*+25*	*39*	*20*	*9*	*50*	*+11*
Mean	**111**	**76**	**32**	**34**	**+44**	**135**	**53**	**40**	**36**	**+13**	**40**	**20**	**13**	**52**	+8
**$SED_{(legumes)}$						20	18	5							
**$SED_{(fields)}$						9	9	2							
$SED_{(AEZ)}$						5	5	1							

[a]= The above ground biomass, [b]= Mean N_2-fixation computed using broad-leaved weeds as reference plants, **= P<0.01

N inputs, across the soil fertility gradient. Net N input by groundnut ranged from +24 kg N ha^{-1} to +29 kg N ha^{-1}, while for lablab net N input ranged from +42 kg N ha^{-1} to +54 kg N ha^{-1}. The rest of the grain legumes resulted in net N removal (negative net N inputs).

Discussion

N_2-fixation by the legumes in response to AEZ and soil fertility

The ^{15}N natural abundance signatures detected in the legume shoots varied with AEZ (Table 4). The enrichment of the legume grain, green manure and forage legume shoots decreased with rainfall, demonstrating greater N_2-fixation potential by the legumes in AEZ 2 than in AEZs 1 and 3. Legume biomass production also varied with rainfall (Table 5). In AEZ 1, biomass production was between 2.5 Mg ha^{-1} and 8.0 Mg ha^{-1}, while in AEZ 2 production was between 3.0 Mg ha^{-1} and 14.8 Mg ha^{-1}. In the lower rainfall environment of AEZ 3, however, the species showed a considerable reduction in biomass production capacity, with production of between 2.5 Mg ha^{-1} and 4.9 Mg ha^{-1}. Consequently, N_2-fixation in AEZ 2 was generally greater than that for AEZs 1 and 3, with green manure legumes showing a more consistent trend than the forage and grain legumes (Tables 5 and 6). These trends confirm the importance of rainfall in legume productivity and suggest that the impact of the legumes on smallholder productivity, especially of the soil improving green manure species, is likely to be small in low rainfall agro-ecological zones.

The species N_2-fixation also varied with soil fertility. N_2-fixation generally decreased with soil fertility, for green manure and forage legumes (Table 5) and grain legumes (Table 6). For the green manure and forage legume species, N_2-fixation decreased by up to 36% from the high to low fertility field (Table 5), while for the grain legumes, the decrease was by up to 44% (Table 6), suggesting that the benefits of including legumes, especially grain legumes, in the smallholder farming systems is likely to be small when soil fertility is poor.

N_2-fixation performance of the species showed interaction with AEZ and soil fertility. For the green manure legumes, crotalaria was the best species in N_2-fixation across the soil fertility gradient in AEZ 1 (Table 5). In AEZ 2, however, velvet bean was the best in the high and medium fertility fields, while crotalaria was the best in the low fertility field. In AEZ 3, similar to AEZ 1, crotalaria had the best N_2-fixation across the fertility gradient. For forage legumes (Table 5), desmodium was best in the high and low fertility fields in AEZs 1 and 2, while stylo was best in the medium

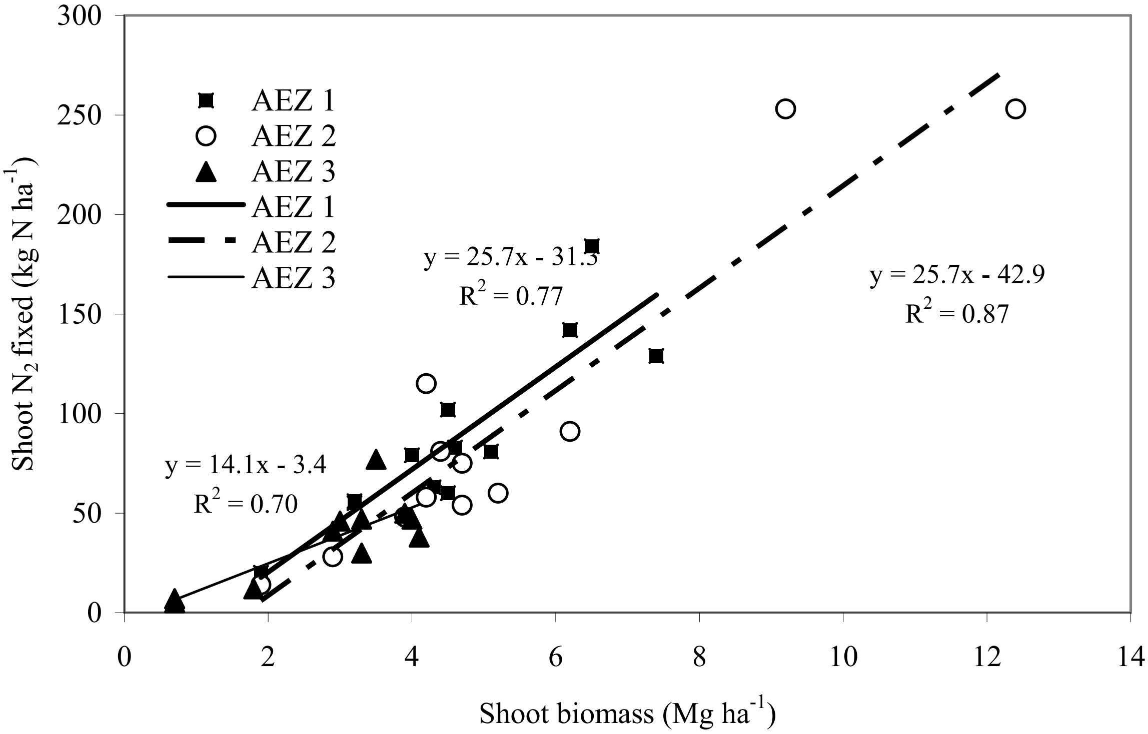


Figure 2. Relationship between shoot biomass production and shoot N fixed by the legume species in the three agro-ecological zones of western kenya, short rains 2003

fertility fields in the same zones. In AEZ 3, however, stylo was the best species in the high and the medium fertility fields, while siratro was the best in the low fertility field. For the grain legumes (Table 6), N_2-fixation was best with lablab and groundnut across the fertility gradient in AEZs 1 and 3, while in AEZ 2, lablab and soyabean were the best species in N_2-fixation across the fertility gradient.

There were strong linear relationships between legume shoot biomass and the computed N_2-fixation in all the AEZs (Figure 2), suggesting that N_2-fixation was highly dependent on the capacities of the legumes for growth and biomass accumulation in the different AEZs. There were differences in the N_2-fixation efficiencies in the three AEZs. The species fixed about 26 kg N per Mg of legume biomass in AEZs 1 and 2, and 14 kg per Mg of biomass in AEZ 3. These figures are in reasonable agreement with those obtained in the high and low rainfall zones in Bukoba in northern Tanzania (Baijukya, 2004), and those obtained in different farming systems in eastern Australia (Peoples et al., 2001). In AEZs 1 and 2, biomass production below about 1.50 Mg ha^{-1} resulted in no N_2-fixation, while in AEZ 3, there was still some N_2-fixation at biomass production levels below 1 Mg ha^{-1}.

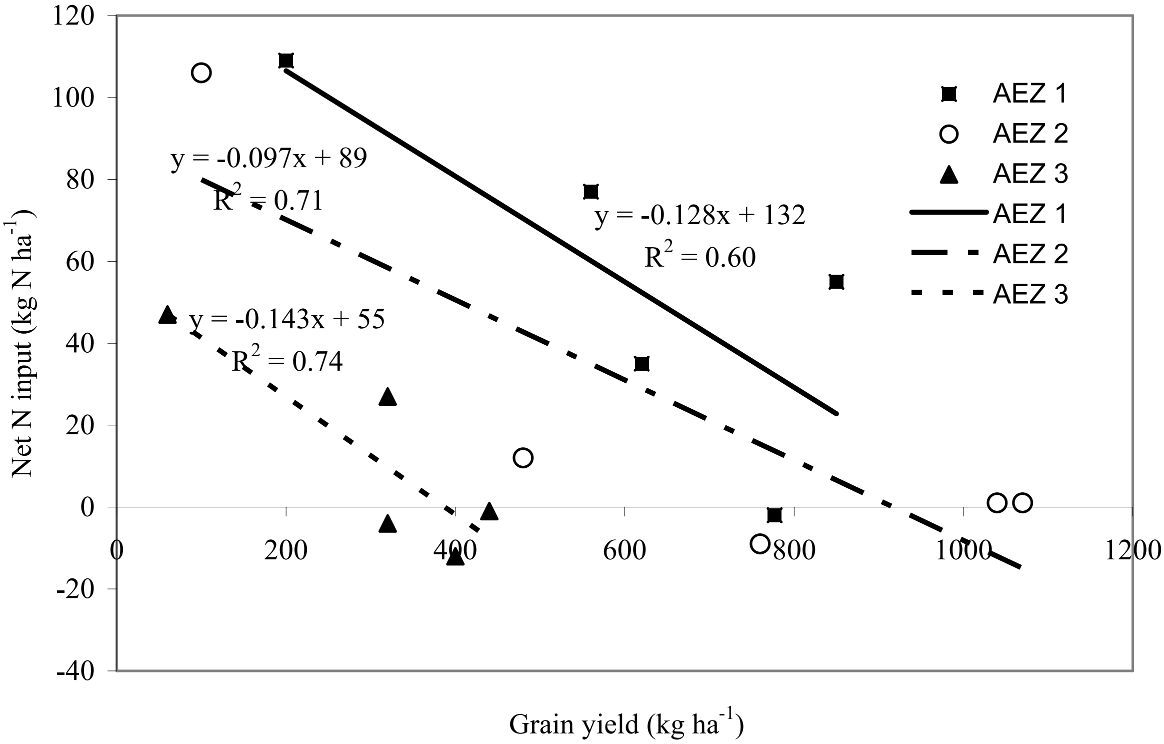


Figure 3. Relationship showing the trade-offs between legume grain yield and net N contributions to soil N fertility in the three agro-ecological zones in western Kenya, short rains 2003 season.

Net N contributions to soil N fertility through N_2-fixation

Net N inputs by the grain legume species varied with AEZ and soil fertility (Table 6), indicating differential contributions by the legumes to soil N fertility maintenance in the AEZs. Mean net N input generally decreased with rainfall, ranging from 44 kg N ha^{-1} in AEZ1, to 8 kg N ha^{-1} in AEZ 3, suggesting fairly limited capacity of the grain legumes to substantially improve productivity in the low rainfall agro-ecological zones, through N_2-fixation. The performance of the individual species varied with AEZ. In AEZs 1 and 3, lablab and groundnut had consistently the greatest net N inputs across the soil fertility gradient, while in AEZ 2, lablab and groundnut had the greatest inputs in the high fertility field, lablab and Lima in the medium fertility field, and lablab and soyabean+P the greatest inputs in the low fertility field. In AEZ 3, only lablab and groundnut had positive net N inputs (Table 6). The net N inputs of the rest of the grain legumes were negative, with soyabean+P showing relatively greater soil N mining potential than the rest of the grain legumes. These results suggest that lablab and groundnut have the potential to make substantial contributions to the improvement of soil N fertility, besides contributing to the household food needs.

The relatively large net N contribution by lablab resulted from its high N_2-fixation capacity but relatively low N export (Table 6). However, lablab is a poor grain producer in certain environments, e.g. AEZ 3 (Table 2), hence farmers would be better off with groundnut, which had a lower net N input in AEZ 3 (24-29 kg N ha^{-1}) compared with lablab (42-54 kg N ha^{-1}) (Table 6) but a relatively much greater grain yield (Table 2). A general assessment of such trade-offs was done for the grain legumes (Figure 3). Legume grain yield and net N inputs to soil N fertility showed strong linear relationships in all AEZs. Grain yield was negatively correlated with net N input, indicating that the more grain a legume produces the less its contribution to soil N fertility. The relationships also indicated differences between the AEZs in the trade-offs between grain yield and N inputs for soil N fertility improvement. In AEZ 1, 128 kg N was traded-off for every 1 Mg of grain harvested, while in AEZ 2, 98 kg N was traded-off for every Mg of grain harvested. In AEZ 3, 143 kg N was traded-off for every Mg of grain harvested. In AEZ 1, net N input become negative at grain yield of 1.0 Mg ha^{-1}, while in AEZs 2 and 3, net N inputs were zero at grain yields of 0.90 Mg ha^{-1}, and 0.40 Mg ha^{-1}, respectively (Figure 3). This shows that in AEZs 1 and 2, grain yields of up to 1 Mg ha^{-1} can be produced without much concern about soil N mining, while in AEZ3, yields of 0.5 Mg ha^{-1} are likely to result in soil N mining of about 20 kg ha^{-1}. Since grain legumes showed grain yield potential of up to 1.40 Mg ha^{-1} in AEZs 1 and 2 (Table 3), potential for soil N mining is high and a critical consideration of these trade-offs is essential in deriving suitable legume options for smallholder systems with competing objectives of food production and soil fertility management.

Estimates of contributions from the below-ground biomass

The N_2-fixation and net N input values presented in this study do not include the contributions from the below-ground biomass, due to problems associated with the recovery of complete root systems. However, assuming that the amount of N contained in legume root biomass accounts for 30-35% of the total plant N (Khan et al., 2002; McNiel et al., 1997), the N input values in Table 6 become much greater, changing most of the indications of net N removal to positive inputs of N. For example, in the medium fertility field in AEZ 2 (Table 6), where most of the legumes had negative net N inputs, when below-ground N contributions of 30% is assumed, the net N input of bean changes from -25 kg N ha^{-1} to -8 kg N ha^{-1}, and that of soyabean-P from -21 kg N ha^{-1} to +50 kg N ha^{-1}, etc, suggesting a greater capacity of the grain legumes for the maintenance of soil N fertility in smallholder farming systems, in addition to providing food.

The ^{15}N natural abundance methodology and on-farm N_2-fixation assessment

The flexibility of the ^{15}N natural abundance method (since no addition of ^{15}N-enriched fertilizer is required) makes it ideal for N_2-fixation assessments on-farm. However, the reliability of the method depends on the choice of appropriate reference species (Peoples et al., 2002). The $\delta^{15}N$ signatures of maize and the broad-leaved weeds used as reference species differed considerably. Except for one or two cases, the $\delta^{15}N$ values for broad-leaved weeds plants were much greater than those for maize, and were closer to the $\delta^{15}N$ signatures of the total soil N (Table 3). Due to this, large variations were obtained in the estimates of %N derived from N_2-fixation. The %N derived from N_2-fixation values computed using maize as reference plant were consistently smaller than those computed using broad-leaved weeds (Table 4), indicating that the use of maize as a reference crop underestimated N_2-fixation by the legumes. The ^{15}N signatures detected in the soil varied slightly with field and AEZ. However, the values were between 5.93‰ and 9.19‰, which was within the range recommended for the use of the ^{15}N natural abundance method for N_2-fixation (Peoples et al., 1989).

Conclusions

The productivity of the legumes varied greatly with agro-ecological zones and soil fertility, suggesting that different legumes are needed for the improvement of productivity of smallholder farms in different agro-ecological zones and soil fertility conditions in western Kenya. All the legume species (green manure, forage and grain legumes) studied were capable of fixing atmospheric N_2 on-farm without artificial inoculation. Mean N_2-fixation by the legume species differed greatly in the three agro-ecological zones, and ranged from 14-253 kg ha^{-1} in AEZ 2, to 5-77 kg N ha^{-1} in AEZ 3. Lablab and groundnut showed the greatest resilience in N_2-fixation and net N input across the agro-ecological and soil fertility gradients. The results of the study indicates that maize is less appropriate as a non-N_2-fixing reference species than the tested broad-leaved weeds in N_2-fixation assessment using the ^{15}N natural abundance method. The study demonstrates that the green manure, forage and grain legumes studied have the potential for making significant contributions to the N economy and productivity of the smallholder farming systems through atmospheric N_2-fixation.

However, the potential of species vary in the different biophysical niches and careful selection is therefore needed to optimize productivity.

Chapter 5

Benefits of legume-maize rotations: Assessing the impact of heterogeneity on the productivity of smallholder farms in western Kenya

Chapter 5

Benefits of legume-maize rotations: Assessing the impact of heterogeneity on the productivity of smallholder farms in western Kenya

Abstract

Although legumes have the potential for improving the agricultural productivity of sub-Saharan Africa by providing food and fodder, and improving soil nitrogen (N) status through fixation of atmospheric N_2, there is little information available regarding their productivity, and economic benefits, especially under the biophysically and socio-economically heterogeneous smallholder farming systems. On-farm experiments were conducted in the high (AEZ 1), the medium (AEZ 2) and the low rainfall (AEZ 3) agro-ecological zones in western Kenya to assess the agronomic and economic benefits of promising grain and green manure legumes. In each zone, the experiments were planted in high, medium and low fertility fields, to assess the effect of within-farm soil fertility heterogeneity on the productivity and economic benefits of bean (*Phaseolus vulgaris*), soyabean (*Glycine max*), groundnut (*Arachis hypogaea*), Lima bean (*Phaseolus lunatus*), lablab (*Lablab purpureus*), velvet bean (*Mucuna pruriens*), crotalaria (*Crotalaria ochroleuca*) and jackbean (*Canavalia ensiformis*), grown in rotation with maize. Continuous maize fertilized with both N and P (Maize+NP), maize with P only (maize+P), and maize without N and P (maize-NP) were used as controls. The legumes were planted during the short rains season, followed by maize, during the long rains season, and fertilized with phosphorus at 30 kg P ha^{-1} and no nitrogen (N). The maize crop following the legumes received P at 50 kg ha^{-1}, and apart from the controls, which were fertilized with urea, relied on N inputs by legumes. Legume and maize grain yields were determined at harvest, and enterprise budgets constructed to evaluate the returns to land and labour for each of the options tested. The total productivity and economic benefits derived from incorporating the legumes into the cropping systems increased significantly ($P<0.01$) with rainfall and soil fertility. Averaged over all treatments, total productivity was 47% higher in AEZ 1, compared with AEZ 3, and 33% higher in the high fertility field, compared with the low fertility field. Although the grain yield of maize following the green manure legumes was 25-30% greater than that of maize following grain legumes, total maize production was greater with continuous maize+NP in AEZs 1 and 2, and with green manure-maize in AEZ 3. However, the grain legumes provided the greatest economic benefits. In AEZ 2, where soil moisture was not limiting, mean returns to land for the grain legume-maize options treatments were

US$ 879 ha^{-1}, compared with US$ 533 ha^{-1} for green manure-maize, and US$ 459 ha^{-1} for continuous maize+NP. In comparison, in AEZ 3, where moisture was limiting, mean returns to land for both grain legume-maize and green manure-maize treatments decreased to US$ 47 ha^{-1}, while continuous maize+NP had negative returns to land of US$ -107 ha^{-1}. Averaged over species and AEZs, the legumes had 35% higher returns to land in the high fertility field than in the low fertility field. Mean returns to labour for grain legume-maize treatments ranged from US$ 2.23 day^{-1} in AEZ 1 to US$ 0.99 day^{-1} in AEZ 3, while for the green manure-maize treatments, the range was from US$ 1.68 day^{-1} in AEZ 1 to US$ 0.91 day^{-1} in AEZ 3. Groundnut-maize, soyabean-maize and lablab-maize options generally gave the best economic returns. These results demonstrate the significant impact of the smallholder biophysical heterogeneity on the productivity of the legumes and suggest careful targeting of these niches, for optimum economic benefits.

Key words: Agro-ecological zones, costs and benefits, cropping systems, niches.

Introduction

Low Soil fertility is a major constraint to the productivity of smallholder farmers in sub-Saharan Africa (Oldeman et al., 1991). In the East African highlands, where high population growth has led to continuous cultivation with little use of mineral fertilizers, loss of nutrients has resulted in low labour and land productivity (Swinkles et al., 1997). western Kenya, with its high population pressure on land, and mixed farming subsistence agriculture, is typical of the East African highlands' smallholder sector. Nitrogen (N) and phosphorus (P) are the major nutrients limiting crop production (Shepherd et al., 1997). Provision of N is therefore necessary for improved productivity of the farms. However, use of mineral fertilizers to supply the much needed N is constrained by a number of factors, such as unreliable returns, inappropriate production packages, unreliable markets for produce (Anderson, 1992; Hassan et al., 1998), and lack of access to capital (Hoekstra and Corbett, 1995). Nevertheless, opportunities exist for part of the N requirement of crops to be met from biological N_2-fixation.

Sustainable incorporation of legumes into the smallholder farming systems is impeded by the high degree of biophysical and socio-economic heterogeneity inherent in the smallholder systems in the region. The smallholders in western Kenya operate under diverse agro-ecological conditions. In addition, studies in the region, for example, Tittonell et al. (2005b), have confirmed the existence of within-farm soil fertility variability and resource management strategies designed by farmers to exploit this variability. Socio-economic heterogeneity is an additional challenge to the sustainable incorporation of legumes into western Kenya smallholder systems. Tittonell et al. (2005a) identified five farm types in western Kenya based on different levels of land, labour and capital endowment, production objective (e.g. subsistence or market orientation) and access to off-farm income. The socio-economic and biophysical variability provide socio-economic and ecological opportunities (or socio-ecological niches) for legumes in the systems (Chapter 2). The choice of appropriate legumes that would result in sustainable improvements in productivity in such systems is complex since the species must fit into the available socio-ecological niches. In doing so, the species must not only match farmers' preferences and production objectives, but should also be well adapted to the prevailing biophysical constraints.

This paper is part of a series of studies in western Kenya testing the socio-ecological niche concept for integration of legumes in smallholder farming systems. It addresses both the biophysical and socio-economic dimensions of the socio-ecological niche by investigating the agronomic and economic benefits of various legume-maize rotation systems. The objectives were: (1) to evaluate the effect of grain and green manure legume species on the yield of the subsequent maize crop; (2) to assess the influence of agro-ecological zones and within-farm soil fertility variations on the productivity of the grain and green manure legume-maize rotations; and (3) to determine the economic benefits of the above systems.

Materials and Methods

Sites selection and characterization

The experiment was conducted at three agro-ecologically diverse sites in western Kenya. Museno (high rainfall agro-ecological zone) is situated at 00^o 14' N and 34^o 44' E and an altitude of 1570 m above seal level (masl). Mean annual rainfall is 2000 mm and mean annual temperature is 18^{o}C. Majengo (medium rainfall agro-ecological zone) is situated 00^o 00' N and 34^o 41' at an altitude of 1385 masl. Mean annual rainfall is 1600 mm and mean annual temperature is 19^{o}C. Ndori (low rainfall agro-ecological zone) is situated at 00^o 02' S and 34^o 20' E and an altitude of 1170 masl. Mean annual rainfall and temperature are 1200 mm and 22^{o}C, respectively. The three sites have bimodal rainfall patterns, with the first season extending from March to August, and the second one, from September to January. At the farm level, in each agro-ecological zone, experimental fields were selected to take into account the variability in soil fertility conditions, which is a common feature within western Kenya smallholder farming systems (Tittonell et al., 2005b). Fields were categorized into three farmer-designated fertility classes (high, medium and low). Three fields were identified for experimentation in each soil fertility class. Fertility categorization was based on knowledge of the local soil fertility gradients and history of crop responses and confirmed by soil fertility characterization. The latter was done by sampling the soil in all experimental fields in each site, prior to sowing the legumes. In each field (high, medium and low fertility), top-soil (0-0.2 m) samples were taken at nine points. The samples were mixed then a composite sample of approximately 0.5 kg taken for laboratory analysis. The samples were air dried, crushed and ground to pass through a 2 mm sieve and subsequently analysed for pH, texture, extractable P, total N, total soil organic carbon, and exchangeable calcium, magnesium and potassium, following standard procedures recommended for tropical soils (Anderson and Ingram, 1993). The results of physical and chemical analyses (Table 1) confirmed the farmer fertility classification. Although there were minimal differences in texture between the soils from the different fertility categories, relatively large differences were observed in phosphorus, organic carbon and total nitrogen contents, particularly in AEZ 2. The gradient in rainfall was not typical as AEZ 2 (Figure 1b) received about 30% more rainfall than AEZ 1 (Figure 1a).

Experimental design and treatments

The experiment was laid out in a randomized complete block design (RCBD) replicated twice in each field. Treatments consisted of grain and green manure legumes grown in rotation with maize. Continuous maize was used as control. The legume phase of the experiment was established at the beginning of the short rains season in early September 2003, and the maize phase at the beginning of the long rains season in March, 2004. Details of all treatments are presented in Table 2.

The legume crops

Grain legume species: bean (*Phaseolus vulgaris* L.); soyabean *(Glycine max* (L.) Merr.); groundnut (*Arachis hypogaea* L.)*;* Lima bean (*Phaseolus lunatus* L.)*;* and lablab (*Lablab purpureus* (L.) Sweet); green manure legumes: velvet bean (*Mucuna pruriens* (L.) Walp*);* crotalaria *(Crotalaria ochroleuca* (G.) Don); and jackbean (*Canavalia ensiformis* (L.) DC.) were planted in plots measuring 4.5 m wide by 5.0 m long, replicated twice. The legume seeds were not inoculated with rhizobium prior to planting. However, P was applied to all plots at 30 kg ha^{-1}. Three maize plots (continuous maize controls) were planted along with the legumes. The first control maize plot received no fertilizer N and P (maize-NP), the second received 50 kg P ha^{-1} but no N (maize+P), and the third received N at 50 kg ha^{-1} and P at 50 kg ha^{-1} (maize+NP). All the P was applied as triple super phosphate (TSP) at planting, while urea-N was top-dressed in two split applications, at 26 days after planting (DAP), after the first weeding, and at 56 DAP, after the second weeding.

The green manure plots were cut between flowering and early pod-filling stage in January 2004 and weighed to determine biomass accumulation, after which all the biomass was incorporated into the soil to a depth of about 15 cm. The maize and grain legume species matured at different times and were harvested between January and February 2004, threshed and grain and legume residue weighed. Maize and legume grain yields were calculated at 12% moisture content (MC). Legume residues were then returned to the respective plots and incorporated into the soil to a depth of about 15 cm using hand hoes. Maize and legume plots were sampled 45 days after residue incorporation. The samples were taken at 0-15 cm depth at three points in each plot and bulked. Sub-samples of about 0.75 kg were then taken and analysed for total mineral N.

Table 1. Soil fertility parameters of the three categories of fields identified by farmers in three agro-ecological zones in western Kenya, in which the experiments were conducted (n=3).

	Fertility category	pH (H_2O)	% Total OC	% Total N	C:N ratio	P mg P/kg soil	Ca cmol $_{(c)}$ kg^{-1}	Mg cmol $_{(c)}$ kg^{-1}	K cmol $_{(c)}$ kg^{-1}	% Clay	% Sand	% Silt
AEZ 1												
	High	5.95	1.64	0.17	10:1	8.78	6.30	1.48	0.40	24	35	45
	Medium	5.86	1.63	0.16	10:1	4.27	6.35	1.73	0.35	22	43	38
	Low	6.20	1.48	0.13	11:1	3.37	5.43	1.93	0.23	21	38	41
AEZ 2												
	High	5.86	1.50	0.19	8:1	15.42	6.96	2.10	0.36	22	33	48
	Medium	5.43	1.46	0.17	9:1	8.00	5.82	1.65	0.43	16	36	46
	Low	5.63	1.28	0.14	9:1	3.50	5.90	1.75	0.17	29	36	35
AEZ 3												
	High	5.84	1.52	0.17	9:1	2.48	6.40	2.30	0.39	37	28	30
	Medium	6.24	1.23	0.16	8:1	1.20	6.45	3.28	0.36	35	28	40
	Low	5.70	1.32	0.16	9:1	1.15	6.40	2.55	0.30	25	45	30

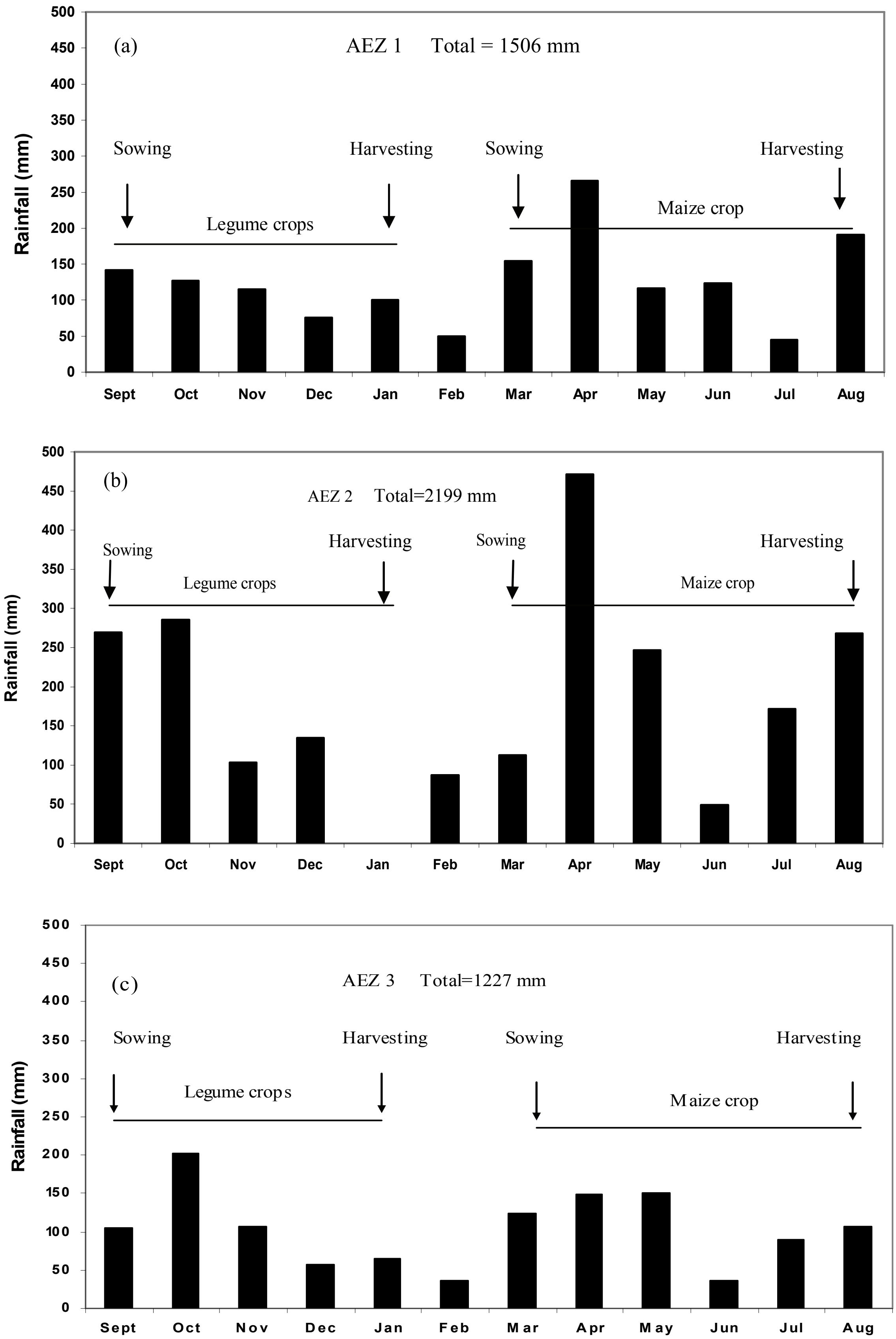


Figure 1. Monthly rainfall recorded at: (a) Museno; (b) Majengo; and, (c) Ndori study sites during the short rains 2003 and long rains 2004 growing seasons.

Maize crop

At the beginning of the long rains season in mid March 2004, the plots were manually tilled and planted with hybrid maize to succeed the legumes and continuous maize. The trial plots in the high rainfall agro-ecological zone (AEZ 1) and medium rainfall agro-ecological zone (AEZ 2) were planted with late maturing hybrid maize (H614 D), while the trial plots in the low rainfall agro-ecological zone (AEZ 3) were planted with an open-pollinated maize variety resistant to a systemic herbicide (Imazapyr). Multi-site field tests have demonstrated that seed-coating of herbicide-resistant maize with this systemic herbicide controls *Striga* spp. (Kanampiu et al., 2003). This new maize variety was planted in AEZ 3 because of high incidence of striga (*Striga hermonthica* (DEL.) Benth). Planting took place approximately 30-45 days after the incorporation of grain legume residue or green manure legume biomass. Maize was spaced at 0.75 m inter-row and 0.30 m intra-row with one plant per hill.

Except for the continuous maize without fertilizer, other maize plots were fertilized with P at 50 kg P ha^{-1}, applied in planting holes using TSP. However, the maize plots following legume treatments received no mineral N fertilizers and the N generated during the legume phase was relied on for maize growth. The plots were weeded twice at all sites and appropriate insecticides were applied to control stalk borers. Maize was harvested at the end of the long rains season in August 2004. Maize grain and stover samples were taken from all plots for the determination of N content. Grain was weighed and grain yield determined at 12% MC**.**

Economic evaluation

Data on labour and other management inputs associated with both legume and maize phases of the experiment was collected by monitoring work rates for planting, weeding, legume biomass cutting and incorporation into the soil, and grain harvesting and threshing on the trial fields and on neighbouring farms belonging to farmers, to derive estimates of labour requirements for production (Table 3). Seed (maize and legumes) and fertilizer (TSP) costs were determined by multiplying the rate (kg ha^{-1}) by the unit cost. Seed and fertilizer prices were obtained from the nearest local input dealers, while output prices (maize and legume grain) were obtained through price surveys at the local markets around each trial site. Due to common seasonal fluctuation in produce prices, maize and legume grain prices were monitored at monthly intervals for a period of one year. Costs of transporting the produce to the nearest local market were taken into account. All monetary values were converted to US$ at the prevailing exchange rate of US$ 1.0 = KSh 78.0.

Table 2. List of treatments applied during the short rains 2003 and the long rains 2004 growing seasons in all the trial fields. Treatments were similar in all the agro-ecological zones studied.

Treatment	Maize and legume crops (Short rain 2003 season)				Maize crop (Long rains 2004 season)			
	Species	Spacing	Fertilizer applied (kg ha^{-1})		Main crop	Intercrop	Fertilizer applied (kg ha^{-1})	
			N	P			N	P
	Grain legumes:							
1	Soybean	0.5 m x 0.05 m	-	30	Maize	-	-	50
2	Soybean	0.5 m x 0.05 m	-	30	Maize	Bean	-	50
3	Groundnut	0.5 m x 0.01 m	-	30	Maize	-	-	50
4	Bean	0.50m x 0.01 m	-	30	Maize	-	-	50
5	Lima bean	0.25 m x 0.15 m	-	30	Maize	-	-	50
6	Lablab	0.60 m x 0.30 m	-	30	Maize	-	-	50
	GM legumes:							
7	Crotalaria	0.3 m x drill	-	30	Maize	-	-	50
8	Velvet bean	0.3 m x drill	-	30	Maize	-	-	50
9	Jackbean	0.6 m x 0.3 m	-	30	Maize	-	-	50
	Control treatments:						-	
10	Maize	0.75 m x 0.30 m	-	-	Maize	-	-	-
11	Maize	0.75 m x 0.30 m	-	50	Maize	-	-	50
12	Maize	0.75 m x 0.30 m	50	50	Maize	-	50	50

Table 3. Estimates of labour requirements for a variety of operations involved in the production of maize and various legume species in western Kenya.

	Land cultivation (days ha^{-1})	Planting (days ha^{-1})	First weeding (days ha^{-1})	Second weeding (days ha^{-1})	Third weeding (days ha^{-1})	Biomass cutting (days Mg^{-1})	[a]Biomass incorporation (days Mg^{-1})	Harvesting (days Mg^{-1})	Threshing (days Mg^{-1})
Bean	50	30	42	36	16	-	-	14	17
Groundnut	50	30	42	36	16	-	-	26	46
Soyabean	54	43	43	37	16	-	-	22	25
Lima	50	40	43	37	16	-	-	14	25
Lablab	50	24	39	33	15	-	-	14	17
Velvet bean	50	24	39	33	-	14	34	-	-
Jackbean	50	24	39	40	-	11	32	-	-
Crotalaria	54	19	47	43	-	12	32	-	-
Maize+NP	50	22	37	31	14	-	-	9	18
Maize+P	50	22	37	31	14	-	-	9	18
Unfertilized maize	50	22	35	31	14	-	-	9	18

[a] For the grain legumes, biomass incorporation operation was combined with land cultivation.
Labour cost: US$ 1.30 day^{-1}
Exchange rate 1.0 US$ = KSh 78.0

Results

Effect of the legumes on maize grain yield

The studied cropping systems of grain and green manure legumes in rotation with maize, resulted in significant ($P<0.01$) increases in the grain yield of the maize crop following the legumes (Table 4). However, maize grain yield varied with rainfall and soil fertility status. The grain yield performances in the three AEZs are discussed in turn below.

The high rainfall agro-ecological zone (AEZ 1)

In AEZ 1 (Table 4a), averaged across species and soil fertility, the incorporation of green manure legumes into the cropping systems resulted in 26% greater yield of the following maize, compared with grain legumes. In the high fertility field of AEZ 1, mean grain yield of maize following green manure legumes was 4.65 Mg ha^{-1}, compared with 3.82 Mg ha^{-1} for maize following grain legumes. Incorporation of the green manure species into the cropping systems improved maize grain yield in the long rains season by 2.5 Mg ha^{-1} when compared with continuous maize-NP, by 1.9 Mg ha^{-1} when compared with continuous maize+P, and by 1.2 Mg ha^{-1} when compared with continuous maize+NP. In contrast, inclusion of grain legumes in the cropping systems improved the grain yield of the following maize by 1.7 Mg ha^{-1} compared with continuous maize-NP, and by 1.1 Mg ha^{-1} compared with continuous maize+P, while grain yield of continuous maize+NP was greater by 0.3 Mg ha^{-1} compared with that of maize following grain legumes. Only maize following lablab (4.75 Mg ha^{-1}) was significantly ($P<0.01$) better than continuous maize+NP (4.10 Mg ha^{-1}). However, maize grain yield benefits after groundnut, soyabean and Lima were significantly greater than maize-NP and maize+P. The incorporation of bean into the cropping systems resulted in the least grain yield benefits, although significantly greater than continuous maize-NP and continuous maize+P.

There was a 15% reduction in the grain yield of maize in the medium fertility field, compared with the high fertility field (Table 4a). The mean grain yield of maize following the grain legumes was 0.3 Mg ha^{-1} less than that of continuous maize+NP, while that of maize following green manure legumes was 0.9 Mg ha^{-1} greater than maize following continuous maize+NP. Among the grain legume-maize treatments, only the grain yield of maize following groundnut (3.85 Mg ha^{-1}) was significantly ($P<0.01$) greater than continuous maize+NP (3.43 Mg ha^{-1}).

Table 4a. Grain and green manure legume yields, effects of their rotation with maize, and within-farm soil fertility variability on the grain yield of maize in Museno (AEZ 1), western Kenya

Rotation	High fertility field				Medium fertility field				Low fertility field			
	Short rains 2003 season		Long rains 2004 season		Short rains 2003 season		Long rains 2004 season		Short rains 2003 season		Long rains 2004 season	
	Grain (Mg ha^{-1})		Grain (Mg ha^{-1})		Grain (Mg ha^{-1})		Grain (Mg ha^{-1})		Grain (Mg ha^{-1})		Grain (Mg ha^{-1})	
	Legume	Maize	Legume	Maize	Legume	Maize	Legume	Maize	Legume	Maize	Legume	Maize
Grain legumes:												
Bean/maize	1.25	-	-	3.00	0.83	-	-	2.02	0.37	-	-	1.49
Groundnut/maize	0.71	-	-	3.80	0.56	-	-	3.85	0.43	-	-	2.22
Soyabean/maize	1.20	-	-	3.65	0.74	-	-	3.25	0.68	-	-	2.27
Soyabean/maize+bean	1.13	-	0.63	3.90	0.72	-	0.60	3.40	0.61	-	0.35	2.32
Lima/maize	0.76	-	-	3.83	0.69	-	-	2.98	0.53	-	-	2.49
Lablab/maize	0.84	-	-	4.75	1.10	-	-	3.40	0.77	-	-	3.26
Mean	**0.98**	**-**		**3.82**	**0.77**	**-**		**3.15**	**0.57**	**-**	**-**	**2.34**
Green Manure legumes:												
Velvet bean/maize	-	-	-	4.94	-	-	-	4.53	-	-	-	3.76
Jackbean/maize	-	-	-	4.35	-	-	-	4.09	-	-	-	3.61
Crotalaria/maize	-	-	-	4.65	-	-	-	4.22	-	-	-	3.28
Mean				**4.65**	**-**	**-**	**-**	**4.28**	**-**	**-**	**-**	**3.55**
Continuous maize:												
Maize only	-	1.27	-	2.15	-	1.13	-	1.76	-	0.89	-	1.05
Maize + P	-	1.46	-	2.77	-	1.37	-	2.29	-	1.00	-	1.35
Maize + NP	-	1.96	-	4.10	-	1.72	-	3.43	-	1.36	-	2.25
Mean	**0.98**	**1.56**	**-**	**3.82**	**0.77**	**1.41**	**-**	**3.27**	**0.57**	**1.08**	**-**	**2.45**
$SED_{(Crop)}$					0.11	0.20	-	0.48				
$SED_{(Field)}$					0.05	0.11	-	0.14				
$SED_{(Field\ x\ crop)}$					0.11	0.20		0.48				

Maize grain yield reduced by 25% in the low fertility field compared with the medium fertility field (Table 4a). The mean grain yield of maize following the green manure legumes was 35% greater that of maize following grain legumes. The mean grain yield of maize following the grain legumes was 0.1 Mg ha^{-1} greater than that of continuous maize+NP. Maize after lablab (3.26 Mg ha^{-1}) and maize after Lima (2.49 Mg ha^{-1}) were significantly better than continuous maize+NP (2.25 Mg ha^{-1}), while the grain yield of maize following bean (1.49 Mg ha^{-1}) was significantly poorer. The maize grain benefits of incorporating the green manure legumes in the cropping system were nearly double those of grain legumes, and generally greater than continuous maize+NP.

Medium rainfall agro-ecological zone (AEZ 2)

Higher rainfall was recorded in AEZ 2 than AEZ 1 during both seasons of experimentation (Figures 1a and b). As a result, the grain yield performance of maize was better in AEZ 2 (Table 4b) than in AEZ 1 (Table 4a) and AEZ 3 (Table 4c). Similar to AEZ 1, the green manures had greater effect on the yield of the following maize crop than the grain legumes. In the high fertility field, the mean grain yield of maize following the green manure legumes was 24% greater than that following the grain legumes. In the medium and low fertility fields, the differences in mean maize grain yield between the green manure and grain legumes were 28% and 35%, respectively.

In the high fertility field, maize grain yield following grain legumes was greater than continuous maize+NP by 0.9 Mg ha^{-1}, while that following green manure legumes was greater by 2.5 Mg ha^{-1}. The trends in the relative performances of the legumes were similar in the medium and low fertility fields, although mean maize grain yield reduced by 10% in the medium fertility field, compared with the high fertility field, and by 25% in the low fertility field, compared with the high fertility field.

Low rainfall agro-ecological zone (AEZ 3)

Mean maize grain yield decreased by 49-62% in AEZ 3 (Table 4c), compared with AEZ 2 (Table 4b). However, the trends in the relative performance of the species were generally similar to those in AEZs 1 and 2. The grain yield of maize following green manure legumes performed better than that of maize following grain legumes. Averaged across species, in the high fertility field, maize grain yield following the green manure legumes was 35% greater than that following the grain legumes, while

Table 4b. Grain and green manure legume yields, effects of their rotation with maize, and within-farm soil fertility variability on the grain yield of maize in Majengo (AEZ 2), western Kenya.

Rotation	High fertility field				Medium fertility field				Low fertility field			
	Short rains 2003 season		Long rains 2004 season		Short rains 2003 season		Long rains 2004 season		Short rains 2003 season		Long rains 2004 season	
	Grain (Mg ha^{-1})		Grain (Mg ha^{-1})		Grain (Mg ha^{-1})		Grain (Mg ha^{-1})		Grain (Mg ha^{-1})		Grain (Mg ha^{-1})	
	Legume	Maize	Legume	Maize	Legume	Maize	Legume	Maize	Legume	Maize	Legume	Maize
Grain legumes:												
Bean/maize	0.94	-	-	3.20	0.69	-	-	2.59	0.49	-	-	2.00
Groundnut/maize	1.25	-	-	5.83	1.12	-	-	5.20	0.80	-	-	4.17
Soyabean/maize	1.39	-	-	4.50	0.94	-	-	4.10	0.79	-	-	3.53
Soyabean/maize+bean	1.22	-	0.63	4.90	0.86		0.37	4.58	0.70	-	0.35	3.54
Lima/maize	0.49	-	-	4.85	0.53	-	-	4.55	0.41	-	-	3.52
Lablab/maize	1.40	-	-	6.90	0.96	-	-	6.02	0.78	-	-	4.55
Mean	**1.12**			**5.03**	**0.85**			**4.51**	**0.66**			**3.55**
Green manure legumes:												
Velvet bean/maize	-	-	-	7.24	-	-	-	6.73		-	-	5.68
Jackbean/maize	-	-	-	6.10	-	-	-	5.79		-	-	5.35
Crotalaria/maize	-	-	-	6.32	-	-	-	6.15		-	-	5.29
Mean				**6.55**				**6.22**				**5.44**
Continuous maize:												
Maize only	-	1.90	-	2.10	-	1.45	-	1.90		1.33	-	1.22
Maize + P	-	2.04	-	3.42	-	1.52	-	2.81		1.42	-	2.30
Maize + NP	-	2.49	-	4.09	-	1.96	-	3.60		1.93	-	3.18
Mean	**1.12**	**2.14**	**-**	**4.95**	**0.85**	**1.64**	**-**	**4.50**	**0.66**	**1.56**	**-**	**3.69**
$SED_{(Crop)}$					0.11	0.20	-	0.48				
$SED_{(Field)}$					0.05	0.11	-	0.14				
$SED_{(Field\ x\ crop)}$	-	-	-	-	0.11	0.20		0.48		-	-	-

Table 4c. Grain and green manure legume yields, effects of their rotation with maize, and within-farm soil fertility variability on the grain yield of maize in Ndori (AEZ 3), western Kenya.

Rotation	High fertility field				Medium fertility field				Low fertility field			
	Short rains 2003 season		Long rains 2004 season		Short rains 2003 season		Long rains 2004 season		Short rains 2003 season		Long rains 2004 season	
	Grain (Mg ha^{-1})		Grain (Mg ha^{-1})		Grain (Mg ha^{-1})		Grain (Mg ha^{-1})		Grain (Mg ha^{-1})		Grain (Mg ha^{-1})	
	Legume	Maize	Legume	Maize	Legume	Maize	Legume	Maize	Legume	Maize	Legume	Maize
Bean/maize	0.38	-	-	1.99	0.33	-	-	1.19	0.29	-	-	0.85
Groundnut/maize	0.34	-	-	2.59	0.30	-	-	1.95	0.31	-	-	1.52
Soyabean/maize	0.53	-	-	2.48	0.42	-	-	2.26	0.34	-	-	1.25
Soyabean/maize+bean	0.59	-	0.32	2.40	0.40	-	0.33	2.24	0.30	-	0.32	1.20
Lima/maize	0.50	-	-	2.11	0.45	-	-	1.97	0.33	-	-	1.59
Lablab/maize	0.05	-	-	3.41	0.07	-	-	2.97	0.05	-	-	1.79
Mean	**0.40**	**-**	**-**	**2.50**	**0.33**	**-**	**-**	**2.10**	**0.27**	**-**	**-**	**1.37**
Velvet bean/maize				4.31				3.25				1.79
Jackbean/maize	-	-	-	3.75	-	-	-	2.23	-	-	-	2.05
Crotalaria/maize	-	-	-	3.56	-	-	-	2.49	-	-	-	1.94
Mean				**3.87**				**2.66**				**1.93**
Continuous maize	-	0.45	-	1.10	-	0.30	-	0.86	-	0.25	-	0.49
Continuous maize + P	-	0.52	-	1.35	-	0.49	-	1.23	-	0.46	-	0.78
Continuous maize + NP	-	0.82	-	1.65	-	0.78	-	1.56	-	0.67	-	1.45
Mean	**0.40**	**0.60**		**2.56**	**0.33**	**0.52**	**-**	**2.02**	**0.27**	**0.46**	**-**	**1.39**
$SED_{(Crop)}$					0.11	0.20	-	0.48				
$SED_{(Field)}$					0.05	0.11	-	0.14				
$SED_{(Field\ x\ crop)}$					0.11	0.20		0.48				

in the medium and low fertility fields, maize grain yield following green manures was greater than that following the grain legumes by 21% and 29%, respectively. Similar to AEZs 1 and 2, the maize grain yield benefits due to legumes decreased with soil fertility.

Among the individual species, in the high fertility field, except for bean-maize (1.99 Mg ha^{-1}) and Lima (2.11 Mg ha^{-1}), the grain yield of maize following the rest of the legume species were significantly greater than that of continuous maize+NP (1.65 Mg ha^{-1}). In the medium fertility field, however, maize grain yield following soyabean, lablab and all the green manure legumes were greater than continuous maize+NP, while in the low fertility field, only the grain yield following jackbean and crotalaria were greater than that of continuous maize+NP.

Total productivity of the cropping systems

The rotation of the green manure and grain legumes with maize resulted in substantial maize grain yield increases in the following long rains season in all the AEZs, as already discussed in the previous section. However, when the total maize productivity (seasons 1 and 2) of the rotations are taken into account, continuous maize+NP consistently gave the best total maize productivity in AEZ 1 (Figure 2a), while in AEZ 2 (Figure 2b), the best total maize productivity was by continuous maize+NP in the high fertility field, and green manure-maize in the medium and the low fertility fields. In contrast, in AEZ 3 (Figure 2c), the best total maize productivity was by green manure-maize in the high and the medium fertility fields, and by continuous maize+NP, in the low fertility field. Although total maize productivity was 29-34% greater with green manure legumes than with grain legumes (Figures 2a, b and c), legume grain, which has higher market value, was sacrificed to fit the green manure legumes into the rotation. When a second grain legume crop was introduced as an intercrop in the maize following grain legumes, grain legume production increased by 38-56% in AEZ 1 (Figure 2a), 30-36% in AEZ 2 (Figure 2b) and 45-54% in AEZ 3 (Figure 2c). These options were assessed to determine the economic benefits of legumes in the smallholder farming systems studied and how these benefits are influenced by agro-ecological conditions and soil fertility status.

Economic benefits of legumes

Incorporation of the grain and green manure legumes in the cropping systems studied resulted in significant economic benefits over continuous maize cropping systems. However, the benefits varied with legumes, rainfall and soil fertility. In

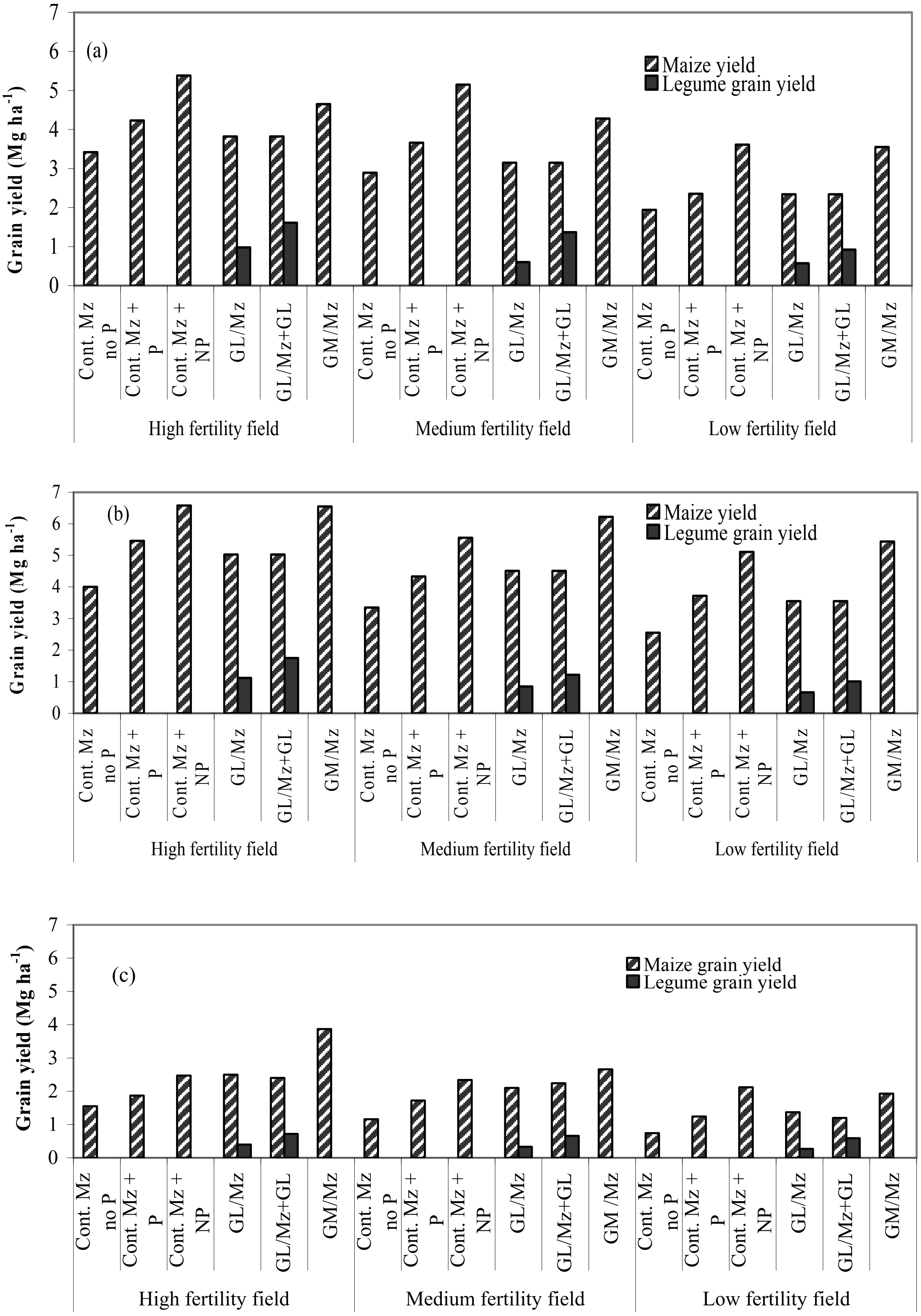


Figure 2. The total productivity of continuous maize without P (cont. Mz no P), with P (cont. Mz + P), with both N and P (cont. Mz + NP), grain legume followed by maize (GL /Mz), grain legume followed by maize and bean (GL/Mz +GL) and green manure followed by maize (GM/Mz) across soil fertility gradients in: (a) AEZ 1; (AEZ 2); and (c) AEZ 3 in Western Kenya.

AEZs 1 and 2 (Tables 5a and b), averaged across species, incorporation of the grain legumes resulted in significantly ($P<0.01$) greater net returns to land and labour, compared with green manure legumes, while in AEZ 3 (Table 5c), mean returns to land and labour, were slightly higher for the green manure-maize treatments in the high fertility field, although the differences were not significant ($P<0.01$). In AEZ 1 (Table 5a), mean returns to land for the grain legume-maize treatments ranged from US\$ 644 ha^{-1}, for the high fertility field, to US\$ 209 ha^{-1}, for the low fertility field, while the returns to land for the green manure-maize treatments ranged from US\$ 346 ha^{-1}, for the high fertility field, to US\$ 162 ha^{-1}, for the low fertility field. Similarly, mean returns to labour for the grain legume-maize treatments ranged from to US\$ 1.90 day^{-1}, for the high fertility field, to US\$ 1.24 day^{-1}, for the low fertility field, while for green manure-maize treatments, the range was from US\$ 1.41 day^{-1}, for the high fertility field, to US\$ 1.16 day^{-1}, for the low fertility field. Averaged over species, returns to land and labour, were consistently greater for grain legume-maize than for continuous maize-NP, continuous maize+P and continuous maize+NP, across the soil fertility gradient. The mean returns to land for grain legume-maize for the high fertility field were US\$ 644 ha^{-1}, compared with US\$ 206 ha^{-1} for continuous maize-NP, US\$ 333 ha^{-1} for continuous maize+P, and US\$ 539 ha^{-1} for continuous maize+NP. The returns to labour followed a similar trend. The inclusion of a second grain legume as an intercrop in maize during the long rains season resulted in further improvements in the net benefits of grain legume-maize over continuous maize treatments. Soyabean-maize+bean had the highest returns to land of US\$ 900 ha^{-1} in the high fertility field, which was US\$ 121 ha^{-1} greater than soyabean-maize, and US\$ 361 ha^{-1} greater than continuous maize+NP. Soyabean-maize+bean also gave the highest returns to labour of US\$ 2.20 day^{-1}, compared with US\$ 2.09 day^{-1} for soyabean-maize, and US\$ 1.70 day^{-1} for continuous maize+NP. These trends were consistent in the medium and low fertility fields. Apart from soyabean-maize+bean, lablab-maize and soyabean-maize performed well in the high fertility field, lablab-maize and groundnut-maize in the medium fertility field, and lablab-maize and soyabean-maize in the low fertility field. In contrast to grain legume-maize, the mean returns to land and labour for green manure-maize were less than those for the continuous maize treatments in the high fertility field. Mean returns to land for green manure-legume ranged from US\$ 346 ha^{-1}, for high fertility field, to US\$ 162 ha^{-1}, for the low fertility field, while for continuous maize+NP, the range was from US\$ 539 ha^{-1}, for the high fertility field, to US\$ 137 ha^{-1}, for the low fertility field. Among the individual green manure-maize treatments, velvet bean-maize had the best returns to land and labour, across the soil fertility gradient.

Table 5a. Net present value of returns to land and labour, for different legume-maize cropping systems and continuous maize, as influenced by soil fertility, in Museno (AEZ 1), western Kenya.

Rotation system	High fertility field		Medium fertility field		Low fertility field	
	Returns to land (US$ ha^{-1})	Returns to Labour (US$ day^{-1})	Returns to land (US$ ha^{-1})	Returns to Labour (US$ day^{-1})	Returns to land (US$ ha^{-1})	Returns to Labour (US$ day^{-1})
Grain legumes:						
Bean/maize	482	1.71	181	1.22	-49	0.74
Groundnut/maize	572	1.78	497	1.72	152	1.16
Soyabean/maize	779	2.09	475	1.68	280	1.38
Soyabean/maize+bean	900	2.20	659	2.04	313	1.41
Lima/maize	472	1.64	301	1.40	172	1.18
Lablab/maize	657	1.95	508	1.80	383	1.59
Mean	**644**	**1.90**	**437**	**1.64**	**209**	**1.24**
Green manure legumes:						
Velvet bean/maize	380	1.46	311	1.40	182	1.19
Jackbean/maize	286	1.32	242	1.29	161	1.16
Crotalaria/maize	371	1.46	300	1.38	142	1.12
Mean	**346**	**1.41**	**284**	**1.36**	**162**	**1.16**
Continuous maize:						
Maize-NP	206	1.26	106	1.08	-36	0.76
Maize+P	333	1.47	223	1.29	23	0.90
Maize+NP	539	1.70	369	1.49	137	1.13
Mean	**359**	**1.48**	**233**	**1.29**	**41**	**0.93**
SED $_{(Crops)}$			50	0.06		
SED $_{(Fields)}$			10	0.01		

Table 5b. Net present value of returns to land and labour, for different legume-maize cropping systems and continuous maize, as influenced by soil fertility, in Majengo (AEZ 2), western Kenya.

Rotation system	High fertility field		Medium fertility field		Low fertility field	
	Returns to land (US$ ha^{-1})	Returns to labour (US$ day^{-1})	Returns to land (US$ ha^{-1})	Returns to Labour (US$ day^{-1})	Returns to land (US$ ha^{-1})	Returns to labour (US$ day^{-1})
Grain legumes:						
Bean/maize	536	1.84	323	1.49	134	1.14
Groundnut/maize	1488	2.92	1281	2.73	875	2.35
Soyabean/maize	1399	2.95	970	2.41	758	2.14
Soyabean/maize+bean	1585	3.10	1109	2.51	804	2.16
Lima/maize	593	1.82	564	1.78	346	1.48
Lablab/maize	1355	2.78	1008	2.42	690	2.06
Mean	**1159**	**2.57**	**876**	**2.22**	**601**	**1.89**
Green manure legumes:						
Velvet bean/maize	703	1.87	622	1.79	455	1.58
Jackbean/maize	526	1.68	477	1.62	407	1.53
Crotalaria/maize	598	1.75	571	1.72	434	1.55
Mean	**609**	**1.77**	**557**	**1.71**	**432**	**1.55**
Continuous maize:						
Maize-NP	246	1.38	135	1.15	6	0.86
Maize+P	513	1.80	326	1.50	228	1.33
Maize+NP	597	1.87	426	1.62	353	1.51
Mean	**851**	**2.15**	**660**	**1.91**	**466**	**1.70**
SED $_{(Crops)}$			50	0.06		
SED $_{(Fields)}$			10	0.01		

Due to higher rainfall received in AEZ 2 (Figure 1b) than AEZ 1 (Figure 1a), the legumes had greater economic benefits in AEZ 2 (Table 5b), compared with AEZ 1 (Table 5a). For example, mean returns to land for grain legume-maize treatments in AEZ 2 was 45- 65% greater, compared with AEZ1. Similarly, mean returns to labour for grain legume-maize was 26-35% greater in AEZ 2, compared with AEZ 1. Similar to AEZ1, incorporation of the grain legumes into the cropping system resulted in greater net benefits than green manure legumes. In the high fertility field, mean returns to land for the grain legume-maize treatments were 48% greater than for green manure-maize treatments, while in the low fertility field, the returns for grain legume-maize treatments was 28% greater. The trends in returns to labour were similar. The mean returns to land for the grain legume-maize treatments were greater than for continuous maize+NP, and ranged from US$ 1,159 ha^{-1} in the high fertility field, to US$ 601 ha^{-1} in the low fertility field, compared with the range from US$ 597 ha^{-1} in the high fertility field to US$ 353 ha^{-1} in the low fertility field, for continuous maize+NP. Similar to AEZ 1, intercropping bean with maize improved the economic benefits. The net returns to land were 22% greater in soyabean-maize+bean compared with soyabean-maize, in the high fertility field, 15% greater in the medium fertility field, and 5% greater in the low fertility field. Among the grain legume-maize treatments, bean-maize had the poorest net benefits, which were lower than continuous maize+NP, across the soil fertility gradient. The other grain legume-maize treatments had generally greater net benefits than continuous maize+P. Apart from soyabean-maize+bean, groundnut-maize and soyabean-maize were best in the high fertility field, groundnut-maize and lablab-maize in the medium fertility field, and groundnut-maize and soyabean-maize in the low fertility field. Mean returns to land for the green manure-maize rotations in the high fertility field was US$ 609 ha^{-1}, which was slightly higher than US$ 597 ha^{-1} for continuous maize+NP. However, the mean returns to labour for green manure-maize were significantly (P<0.01) lower (US$ 1.77 day^{-1}) than for continuous maize+NP (US$ 1.87 day^{-1}). In contrast, mean returns to land and labour were greater for green manure-maize than continuous maize+NP, in the medium and low fertility fields. Velvet bean-maize had consistently greater returns to land and labour, than jackbean-maize and crotalaria-maize, across the soil fertility gradient.

Compared with AEZs 1 and 2, net benefits were least in AEZ 3 (Table 5c). Mean returns to land for grain legume-maize and green manure-legume treatments decreased by 65-83% in the high fertility field, compared with the corresponding field in AEZ 2, while in the medium fertility field, the decrease was by 78-90%. In contrast to AEZs 1 and 2, green manure-legume treatments had greater returns to land and labour, than grain legume-maize. In the high fertility field, mean returns to land for

Table 5c. Net present value of returns to land and labour, for different legume-maize cropping systems and continuous maize, as influenced by soil fertility, in Ndori (AEZ 3), western Kenya.

	High fertility field		Medium fertility field		Low fertility field	
Rotation system	Returns to land (US$ ha^{-1})	Returns to labour ($ day^{-1})	Returns to land (US$ ha^{-1})	Returns to labour (US$ day^{-1})	Returns to land (US$ ha^{-1})	Returns to labour (US$ day^{-1})
Grain legumes:						
Bean/maize	37	0.93	-110	0.58	-255	0.39
Groundnut/maize	291	1.44	95	1.06	-62	0.92
Soyabean/maize	253	1.35	161	1.18	-134	0.74
Soyabean/maize+bean	306	1.43	188	1.22	-135	0.77
Lima/maize	92	1.04	56	0.97	-117	0.77
Lablab/maize	199	1.27	130	1.14	-152	0.67
Mean	**196**	**1.24**	**87**	**1.03**	**-143**	**0.71**
Green manure legumes:						
Velvet bean/maize	274	1.34	97	1.04	-239	0.52
Jackbean/maize	185	1.20	-70	0.70	-192	0.63
Crotalaria/maize	189	1.20	10	0.87	-166	0.68
Mean	**216**	**1.25**	**123**	**0.87**	**-199**	**0.61**
Continuous maize:						
Maize-NP	-139	0.47	-207	0.27	-353	0.03
Maize+P	-49	0.72	-75	0.66	-228	0.43
Maize+NP	-48	0.74	-69	0.68	-204	0.59
Mean	**143**	**1.12**	**30**	**0.88**	**-184**	0.35
SED $_{(Crops)}$			50	0.06		
SED (Fields)			10	0.01		

grain legume-maize was US$ 196 ha^{-1}, compared with US$ 216 ha^{-1} for green manure-maize, while in the medium fertility field, grain legume-maize had a mean returns to land of US$ 87 ha^{-1}, compared with US$ 123 ha^{-1} for green manure-maize. However, both grain legume-maize and green manure-maize performed better than continuous maize+NP, which had a returns to land of US$ -48 ha^{-1}, in the high fertility field, and US$ -69 ha^{-1}, in the medium fertility field. Bean-maize gave the poorest returns to land of US$ 37 ha^{-1}, while soyabean-maize+bean (US$ 306 ha^{-1}), groundnut-maize (US$ 291 ha^{-1}) and soyabean-maize (US$ 253 ha^{-1}) were the best options in the high fertility field. In the medium fertility field, soyabean-maize+bean (US$ 188 ha^{-1}), soyabean-maize (US$ 161 ha^{-1}) and lablab-maize (US$ 130 ha^{-1}) performed best. For the green manure-maize options, velvet bean-maize had the best returns to land of US$ 274 ha^{-1} in the high fertility field, and US$ 97 ha^{-1}, in the medium fertility field. In the low fertility field, however, returns to land were negative for all treatments.

Discussion

Grain production performance

The incorporation of the grain and green manure legumes into the cropping systems studied resulted in substantial improvements in productivity in all the AEZs (Tables 4a, b and c). However, grain yields varied in response to rainfall and soil fertility status. Averaged over all treatments and soil fertility status, mean legume grain yield was 13% lower in AEZ 1 (Table 4a), compared with AEZ 2 (Table 4b), where higher rainfall was atypical during the experimentation period and was 32% higher than in AEZ 1 (see Figures 1a and b). Similarly, mean maize grain yield was 27% lower in AEZ 1, compared with AEZ 2. In AEZ 3, where rainfall was lowest (Figure 1c), the smallest legume and maize grain yields were obtained (Table 4c). Both, mean legume grain and maize yield were 65% less compared with AEZ 2. These results demonstrate the importance of moisture on the productivity of legumes and suggest that legumes are likely to have limited impact on productivity in low rainfall agro-ecological zones, such as AEZ 3.

Similar to rainfall, the productivity of the legumes and maize varied with soil fertility (Tables 4a, b and c). For example, in AEZ 1, legume grain yield decreased by 22% in the medium fertility field, compared with the high fertility field, and by 26% in the low fertility field, compared with the medium fertility field. Similarly, maize grain yield reduced by 15% in the medium fertility field, compared with the high fertility field, and by 25% in the low fertility field, compared with the medium fertility field. Similar reductions were observed in AEZs 2 and 3, indicating that the variations in within-farm soil fertility had significant impact on the productivity of legumes and maize. The total organic carbon content and the available P were generally greater in higher fertility fields than in the low fertility fields (Table 1). However, P deficiencies were corrected by uniform application of 30 kg P ha^{-1}. The differences in grain productivity between the fields might be due to deficiencies of other nutrients, possibly micronutrients, since manure, the main resource for soil fertility management in western Kenya smallholder systems, is applied preferentially to different categories of fields (Tittonell et al., 2005b). Fields close to the homestead (or high fertility fields) receive more manure than the middle distance (medium fertility) and remote (low fertility) fields, leading to relatively greater organic carbon content (Table 1) and possibly better replenishment of essential nutrients lost through continuous cropping. In addition, the low fertility fields are in many cases poor in land quality, e.g. shallow soils, poor drainage properties, or presence of noxious weeds, which are not captured in laboratory analysis but affect crop performance.

The incorporation of grain and green manure legumes into the cropping systems studied resulted in remarkable increases in the grain yield of the subsequent maize, compared with maize without N, in all AEZs (Tables 4a, b and c). For example, in AEZ 1 (Table 4a), the grain yield of maize following grain legumes increased by up to 1.4 Mg ha^{-1}, compared with maize without N after a maize crop, while the grain yield of maize following green manure legumes increased by up to 2.4 Mg ha^{-1}, demonstrating significant impact of N inputs through BNF. However, the impact of green manure legumes on maize grain yield was greater than that of grain legumes. For example, in AEZ 1, where moisture was not limiting, maize following green manure legumes produced 16% greater yield in the high fertility fields than maize following grain legumes, while in the medium and the low fertility fields, the differences in maize grain yield were 26% and 34%, respectively, indicating that the impact of the green manures was increasingly important with decreasing soil fertility.

However, the incorporation of the grain and green manure species in rotation with maize results in one maize crop being sacrificed to accommodate the legume. So when the total maize production (for both seasons) is considered, continuous maize+NP was best in AEZ 1 (Figure 2a). However, in AEZ 2, there was poor response to mineral N due to heavy rainfall, which coincided with the application of the first split of urea top-dress. This might partly explain the relatively better performance of green manure-maize rotations in the medium and low fertility fields (Figure 2b). The other possibility is that the green manures alleviated other nutrient deficiencies, besides N, as a result of nutrient recycling. In AEZ 3, where moisture was a major limitation to productivity (Figure 1c), green manure-maize performed better than continuous maize+NP in the high and medium fertility fields (Figure 2c), probably as a result of greater moisture capture and conservation. In the low fertility field, moisture deficiency led to poor legume growth, and as a result, minimal quantities of legume biomass were available for incorporation into the soil, which, coupled with poor rainfall in the long rains season, resulted in poor grain yield of the subsequent maize.

Although bean is an important food crop in the farming systems in western Kenya, the performance of bean-maize option was consistently poor across the AEZs and soil fertility conditions. This was related to the amount of N available for plant uptake, following the legumes. Mineral N available after velvet bean and selected grain legume residues incorporated at maize sowing was highest for velvet bean, intermediate for groundnut, soyabean and lablab, and least for bean (Figure 3). Consequently, the grain yield of maize following velvet bean was best in all AEZs, except in the low fertility field in AEZ 3, where the maize following crotalaria was better (Tables 4a, b and c). The relationships between legume-N applied and maize grain yield were best described by second order equations (Figure 4), although a poor fit was obtained for the AEZ 3 data, probably due to relatively poor responses to applied legume N as a result of moisture deficit in the zone during the growing season (Figure 1c). Incorporation of legume biomass resulted in large amounts of N (up to 450 kg N ha^{-1}) being available in the soil at sowing (Figure 3), and before the plant roots were well developed to fully utilize it. This resulted in poor N use efficiency, as can be deduced from Figure 4. This implies that part of the green manure biomass produced could have been reserved and applied elsewhere, or fed to livestock, without affecting maize yields.

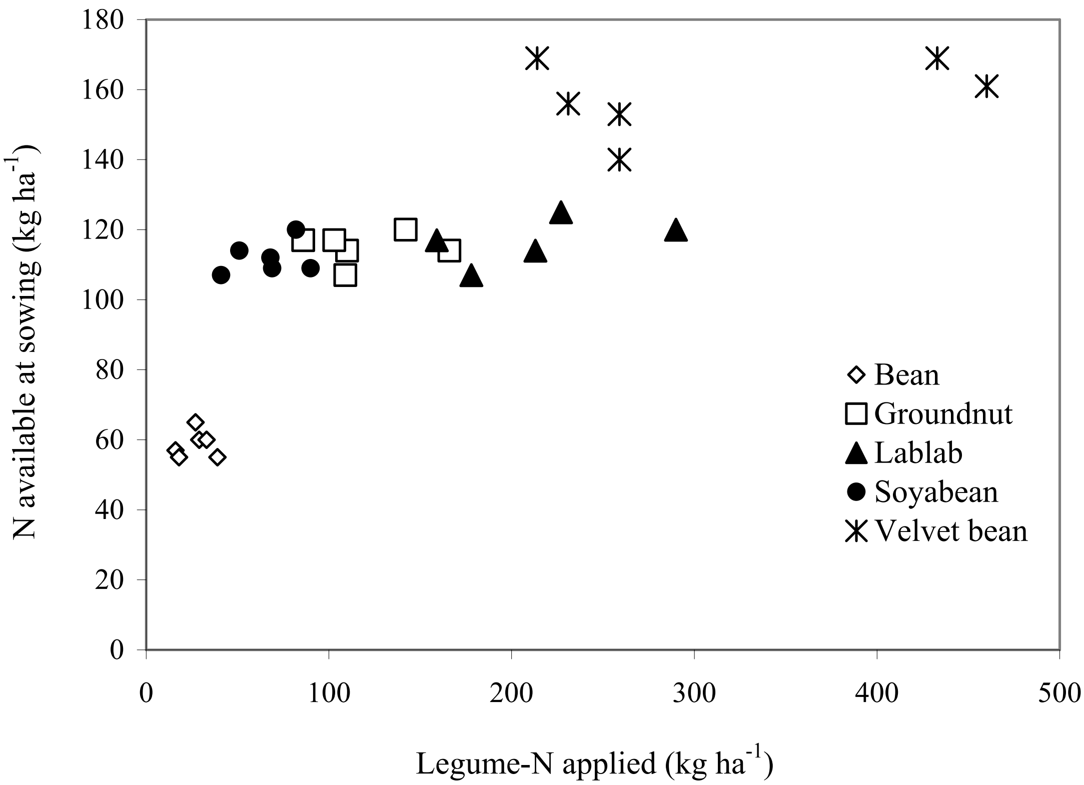


Figure 3. Relationship between legume-N applied through legume biomass incorporation and mineral N available in the soil at maize sowing, 5-6 weeks after biomass incorporation. Measurements were made for only five selected legume species and data are mean of AEZs 1 and 2.

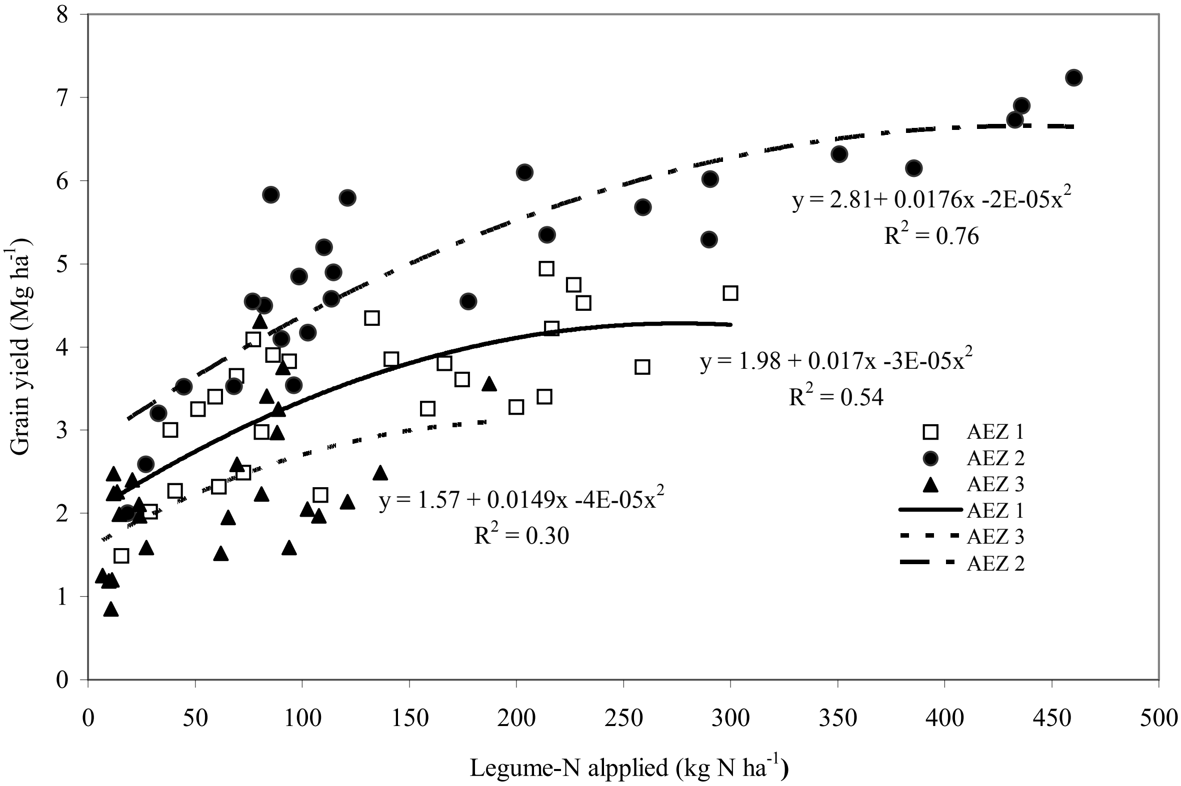


Figure 4. Relationship between legume-N applied and maize grain yield in the three agro-ecological zones in western Kenya, long rains 2003 season.

The relative economic benefits of the legume-maize cropping systems

Incorporation of the legumes into the cropping systems studied resulted in significant economic benefits (Tables 5a, b and c). The net present values of returns to land and labour decreased with rainfall and soil fertility status, but were generally greater with grain legume-maize and green manure-maize options than with continuous maize without N (continuous maize-NP and continuous maize+P). Although total maize production (seasons 1 and 2) was greater with continuous maize+NP and green manure-maize options (Figures 2a, b and c), when moisture was not limiting, the grain legume-maize options had greater economic benefits than continuous maize+NP and green manure-maize options. Mean net present values of returns to land and labour, were greater for grain legume-maize than for continuous maize+NP and green manure-maize options. For example, in AEZ 2 (Table 5b), the grain legume-maize options had 47% greater returns to land, compared with green manure-maize options, and 48% greater returns to land, compared with continuous maize+NP, in the high fertility field. Similarly, returns to labour improved by 32% compared with green manure-maize options, and by 27%, compared with continuous

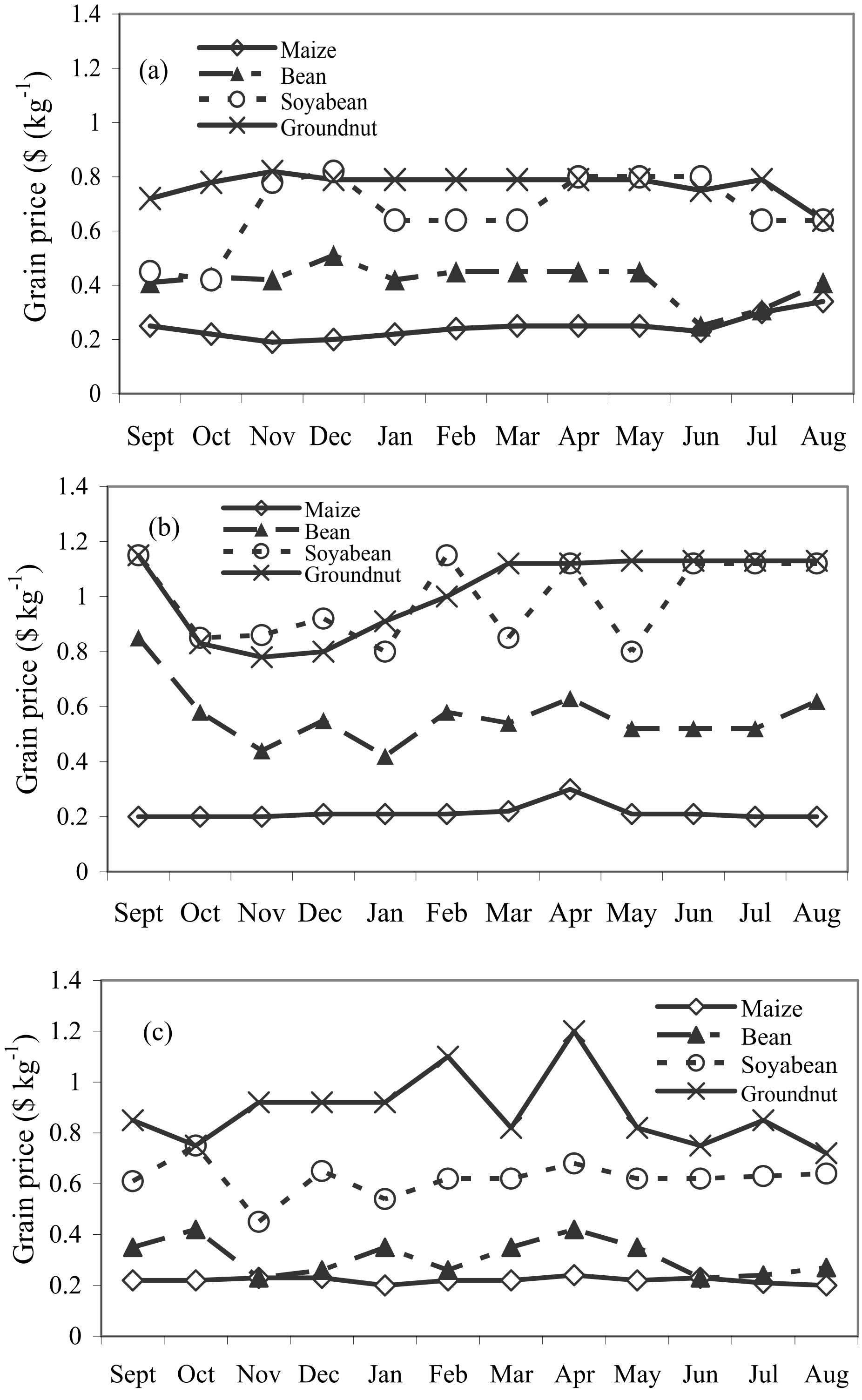


Figure 5. Mean maize and legume grain prices recorded at monthly intervals in selected local markets in: (a) Kakamega (AEZ 1); (b) Vihiga (AEZ 2); and (c) Bondo (AEZ 3) study sites in western Kenya.

maize+NP. The trends in the returns to land and labour for the medium and low fertility fields were generally similar to the high fertility field.

In contrast, in the low rainfall environment of AEZ 3 (Table 5c), green manure-maize options had greater mean net benefits than grain legume-maize options and continuous maize+NP. In the high and medium fertility fields, mean returns to land by green manure-maize option was higher than grain legume-maize option by 10% and 30%, respectively, while continuous maize+NP had negative returns to land. In the low fertility field, however, all the options had negative returns to land. These results indicate that in the high rainfall agro-ecological zones, where soil moisture is not limiting, productivity can be improved by close to 50% if grain legumes are incorporated into the cropping systems in rotation with maize, compared with continuous maize+NP. However, in the low rainfall environments, e.g. AEZ 3, green manure legumes have a slight advantage over grain legume-maize option, while continuous maize+NP is not a viable option.

Among the grain legume-maize options, except for one or two cases, soyabean-maize and groundnut-maize resulted in the best returns to land across the agro-ecological and soil fertility gradients, while bean-maize had the lowest returns to land. The superior returns to land for soyabean-maize and groundnut-maize options were due to the higher prices of soyabean and groundnut, relative to bean (see Figures 5a, b and c). Therefore, for land constrained farmers, soyabean-maize and groundnut-maize are better options than bean-maize, which had relatively low or negative returns to land. However, bean is an important crop in eastern Africa farming systems due to food preferences. Our results show that incorporating a second legume as an intercrop in maize during the long rains season substantially improves the returns to land (Tables 5a, b and c). For example, the returns to land for soyabean-maize+bean was 12-25% higher than soyabean-maize in AEZ 1 (Table 5a), indicating that soyabean-maize+bean better utilized land, which is a scarce resource in the farming systems studied.

Since labour is often a scarce resource in smallholder farming systems, technologies that improve labour productivity stand a better chance of acceptance by the farmers. The grain legume-maize options had greater labour productivity than continuous maize+NP and green manure-maize options (Figure 6). Mean returns to labour for grain legume-maize options was US\$ 1.60 day^{-1}, compared with US\$ 1.30 day^{-1} for green manure-maize, and US\$ 1.26 day^{-1} for continuous maize+NP, which were both below the daily local wage rate of US\$ 1.33 day^{-1}. However, labour productivity was strongly influenced by rainfall and soil fertility. In AEZ1 (Figure 6), the returns to labour in high fertility fields by grain legume-maize, green manure-maize and continuous maize+NP were above the local daily wage rate, while in the

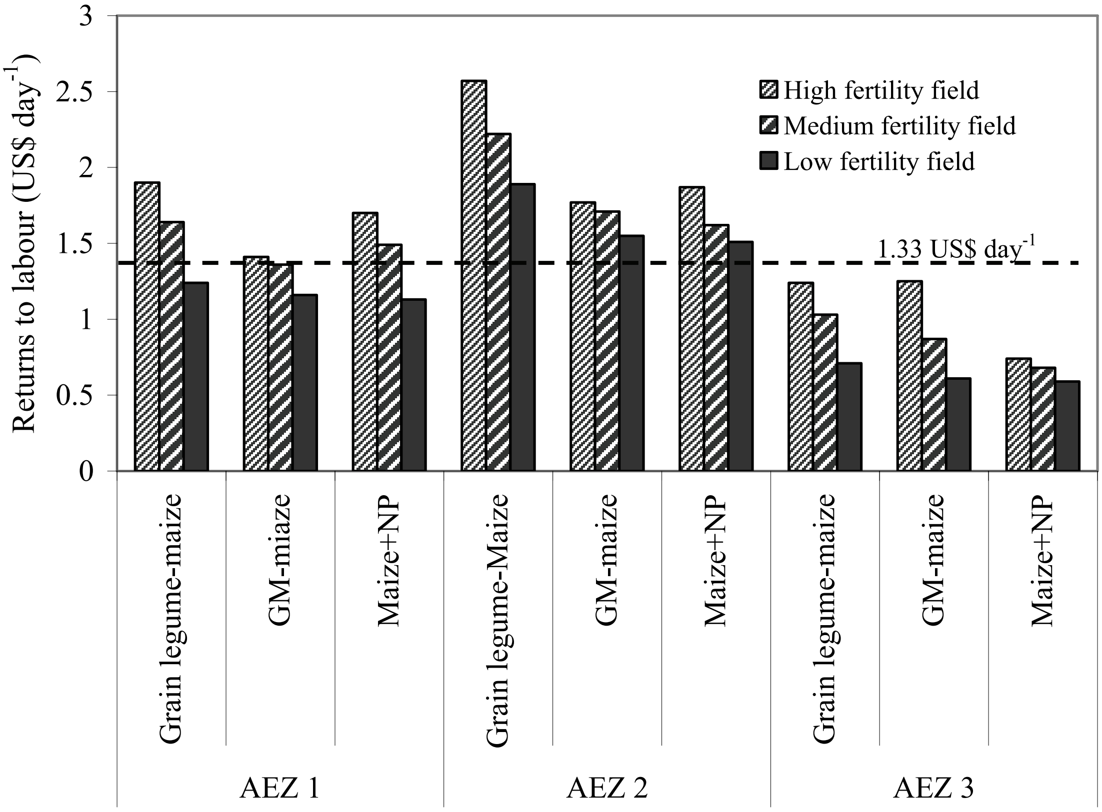
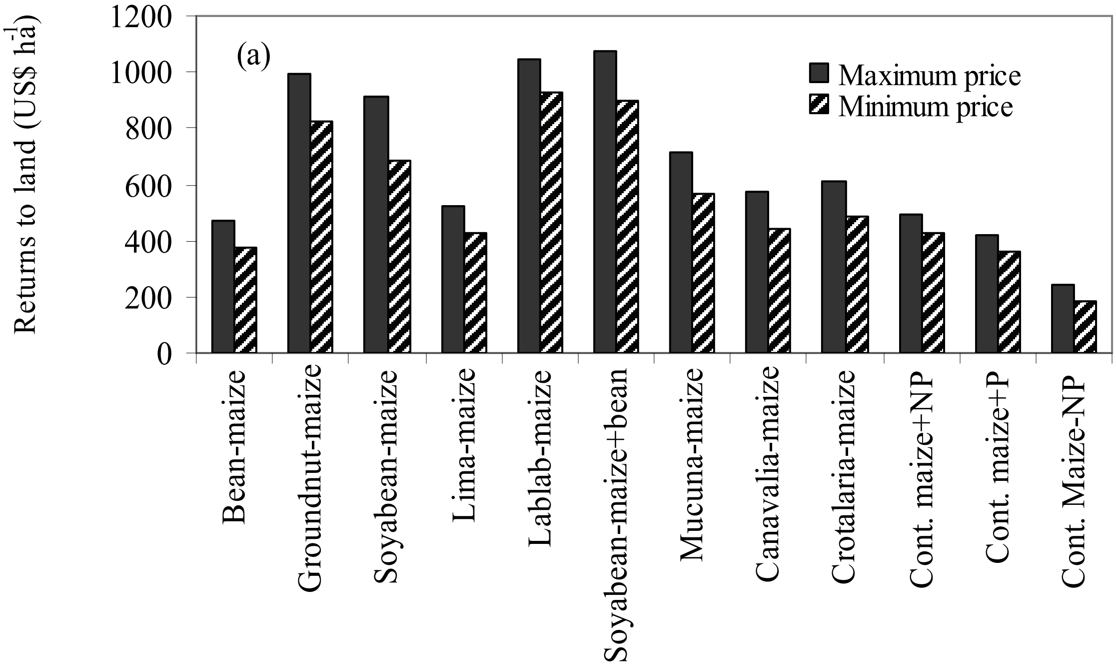


Figure 6. Net present value of returns to labour for grain legume-maize and green manure-maize rotations,and continuous maize fertilized with both N and P (maize+NP), as influenced by agro-ecological and soil fertility conditions in western Kenya

low fertility fields, returns were below the local daily wage rate. In AEZ 2, the returns were above the local daily wage rate across the fertility gradient, while in AEZ 3, all the returns to labour were below the local daily wage rate, indicating that none of the options was economic in AEZ 3.

Significant variations in the net benefits were observed (Figures 7a and b), depending on whether the returns to land were computed at minimum produce prices (normally at harvest) or at maximum produce prices (during food scarcity periods). On average, the returns to land for the high fertility field in AEZ 2 (Figure 7a) was 17% higher when computed at maximum produce prices than when computed at minimum produce prices, while for the low fertility field in the same zone (Figure 7b), the returns increased by 70%. In particular, the returns of options incorporating grain legumes were significantly increased. These results demonstrate that improved marketing can have significant impact on the productivity of the farming systems studied by improving the economic viability of the legume technologies.



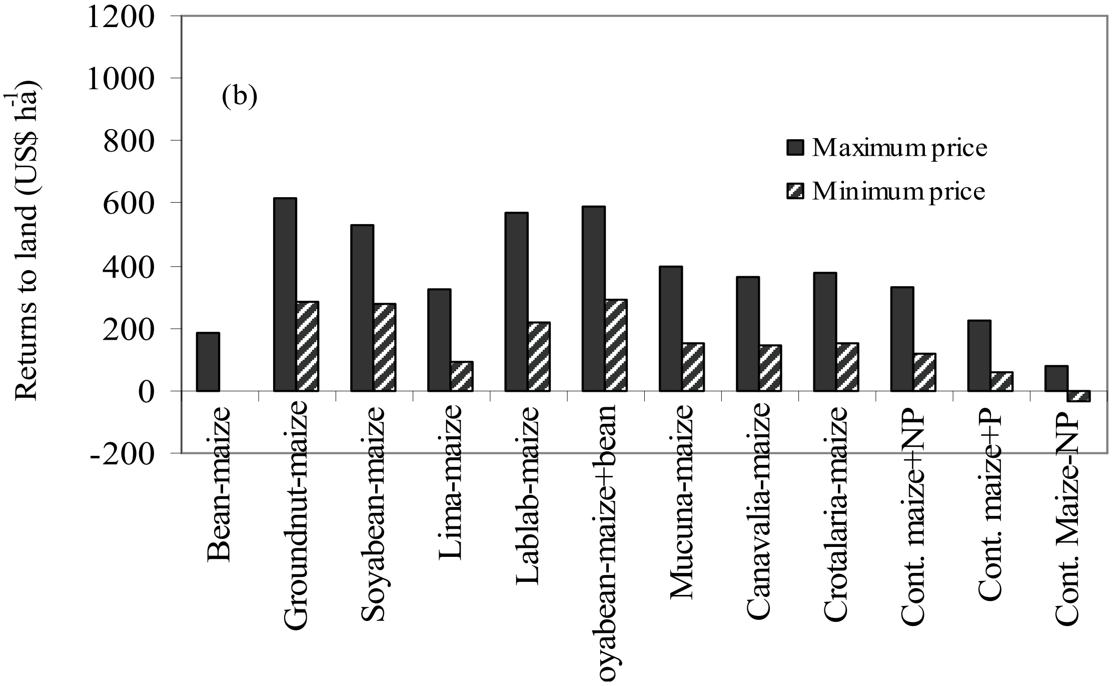


Figure 7. Net benefits of grain legume-maize, green manure-maize and continuous maize cropping for: (a) high soil fertility field; and (b) low soil fertility field, as influenced by fluctuations in produce prices in Majengo (AEZ 2) site.

Conclusions

Agro-ecological zones and soil fertility had significant influence on the productivity of the grain legumes and the maize following the legumes. Legume and maize grain yield increased with rainfall and soil fertility. Total maize productivity was generally greater with continuous maize+NP and green manure-maize treatments than with grain legume-maize treatments. However, when the grain contributed by the legumes was taken into account, the grain legume-maize cropping systems were superior. Net returns to land were greater for grain legume-maize than green manure-maize and continuous maize cropping systems. Labour productivity was also greater for grain legume-maize than for green manure-maize and continuous maize cropping systems. However, green manure-maize system had lower returns to labour than continuous maize+NP. Net benefits were greater with lablab-maize, soyabean-maize and groundnut-maize than with bean-maize and lima-maize but were relatively small or negative in AEZ 3. This study demonstrates that agro-ecological zones, within farm heterogenity in soil fertility, and markets, have significant potential influence on legume integration into smallholder farming systems, and suggests careful targeting of the technology to the biophysical and socio-economic niches, to optimize economic benefits.

Chapter 6

General discussion and conclusions: The socio-ecological niche as a tool for exploring the potential for legumes in smallholder farming systems in western Kenya

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Introduction

Sustainable use of legume technologies by smallholder farmers in sub-Saharan Africa is constrained by the high degree of biophysical and socio-economic heterogeneity (e.g. Tittonell et al., 2005a,b). The socio-ecological niche concept (Chapter 2) was proposed as an innovative framework for exploring niches for legumes to facilitate their sustainable integration into smallholder farming systems. The concept is an extension of that of the "ecological niche" of an organism in classical ecological theory (Hutchinson, 1957), to include, in addition to biophysical factors, a range of socio-economic (including cultural and institutional) factors that have significant influence on technology adoption. By making use of the socio-ecological niche concept, legume technologies that take into account the broader biophysical and socio-economic heterogeneity that characterize smallholder farming systems can be identified and promoted, to enhance the productivity of the smallholder farming systems of sub-Saharan Africa.

The western Kenya region is typical of many sub-Saharan Africa farming systems, especially the highlands of eastern and central Africa, where soil fertility depletion has been identified as a major cause of the chronic food insecurity (Sanchez et al., 1996). Although agricultural potential is high, productivity is severely constrained by nutrient depletion (Shepherd et al., 1996, 1997). High population density and food insecurity are major features of the farming systems of western Kenya (Table 1). The development of appropriate legume technologies is constrained by a variety of biophysical and socio-economic variables, which have significant influence on farmer acceptable and sustainable legume technologies, yet these are never factored in an integrated manner in the legume technology development process. The socio-ecological niche concept offers a framework for achieving this integration.

The broad objective of this thesis was to test the utility of the socio-ecological niche concept as a framework for matching legumes to appropriate biophysical and socio-economic circumstances of the farmers, and facilitating sustainable integration of legumes into smallholder farming systems. The specific objectives were: (i) to conduct socio-economic surveys to identify the major factors with potential influence on the sustainable use of legume technologies in smallholder farming systems in three contrasting agro-ecological zones in western Kenya; (ii) to integrate the information derived from socio-economic surveys with those of on-farm experimentation (Chapter 3,4,5) to identify legume species with potential for improving productivity under different farmer socio-economic conditions, agro-ecological zones and soil fertility status. In this final chapter, we test the utility of the agro-ecological niche concept by performing a production scenario analysis to determine the impact of the identified 'best bet' legume species on the productivity of farms under different resource endowment, agro-ecological and soil fertility conditions.

Table 1. General characteristics of the western Kenya smallholder farming systems

	Kakamega (AEZ 1)	Vihiga (AEZ 2)	Bondo (AEZ 3)
Agro-climatic:			
Agro-ecological classification	Upper midland zone 1 (UM1)	Upper midland zone 2 (UM2)	Lower midland zone 3 (LM3)
Mean altitude (masl)	1500	1385	1270
Mean annual rainfall (mm)	2000	1600	1200
Mean annual temperatures (^{o}C)	18	19	22
Major soil types	Acrisols, nitisols	Acrisols	Ferralsols
Demographic:			
Population density (persons km^2)	[a] 800	[b]1000-1200	[a]400
Male-headed households (%)	70	80	53
Female-headed households (%)	30	20	47
Household head > 50 yrs (%)	36	37	22
Household heads with primary education (%)	54	61	64
Household heads with > primary education (%)	30	34	22
Number of persons in household (median)	9	10	8
Food production and security:			
Households with farm size < 1 ha (%)	51	72	43
Dominant cropping system	Maize-bean	Maize-bean	Maize-bean
Cash crops	Tea	Tea-coffee	-
Food insecure (% of farmers)	95	96	93
Months of food insecurity	1-8	0-11	0-8
Livestock ownership:			
Own livestock (% of farmers)	77	85	74
Type of livestock (cattle)	Zebu, crosses and grade	Zebu, crosses and grade	Mainly zebu
Importance of dairy	High	High	Low

[a] Jaetzold and Schmidt, 1983
[b] Shepherd and Soule, 1998

Methodology

The utility of the socio-ecological niche concept in facilitating the identification and matching of appropriate legume technologies to the broad heterogeneity of smallholder farming systems was tested by analysing two legume production scenarios, using the framework presented in Figure 1. On-farm surveys were undertaken in the three agro-ecological zones to characterize the farmer socio-economic environment. The following were characterized in detailed on-farm surveys of farmers in AEZ 1 (n=41), and AEZs 2 and 3 (n=54 in both zones): (i) social-cultural factors (farmer production objectives and preference, norms and attitudes); (ii) economic factors (land, labour and cash availability, and input-output prices); and (iii) institutional factors (extension support, access to input dealers, input type and packaging, etc). The major farmer production constraints identified (Table 2) were organized according to the different dimensions of the socio-ecological niche concept (Figure 1), to facilitate the visualization of their potential influence on the use of legume technologies by the farmers in terms of the potential socio-ecological niches. In addition, the farmer legume production objectives were determined (Table 3). Monthly surveys were also conducted at five selected markets in each study site, for a period of one year, to assess periodic fluctuations in legume prices. The socio-economic data was used in conjunction with the biophysical data, on legume adaptability, grain yield, N_2-fixation and net N inputs, and economic benefits, to explore socio-ecological niches for legume technologies in abstract farms constructed in the three study sites.

Farmer stratification and construction of abstract farms

Farmers were grouped into high resource endowment (HRE), medium resource endowment (MRE) and low resource endowment (LRE) to facilitate the analysis of the socio-economic circumstances under which they undertake their production activities. Nine abstract farms were then constructed in the three study sites on the basis of biophysical data derived from on-farm experimentation, and socio-economic surveys (Table 4a). Farms in AEZ1 and AEZ2 are similar in some characteristics (Figure 2), but differ in family and farm size (Table 4a). The principal characteristics used in the stratification included next to farm and family size, also livestock ownership, labour availability and income. Presented values are the median for each resource endowment group.

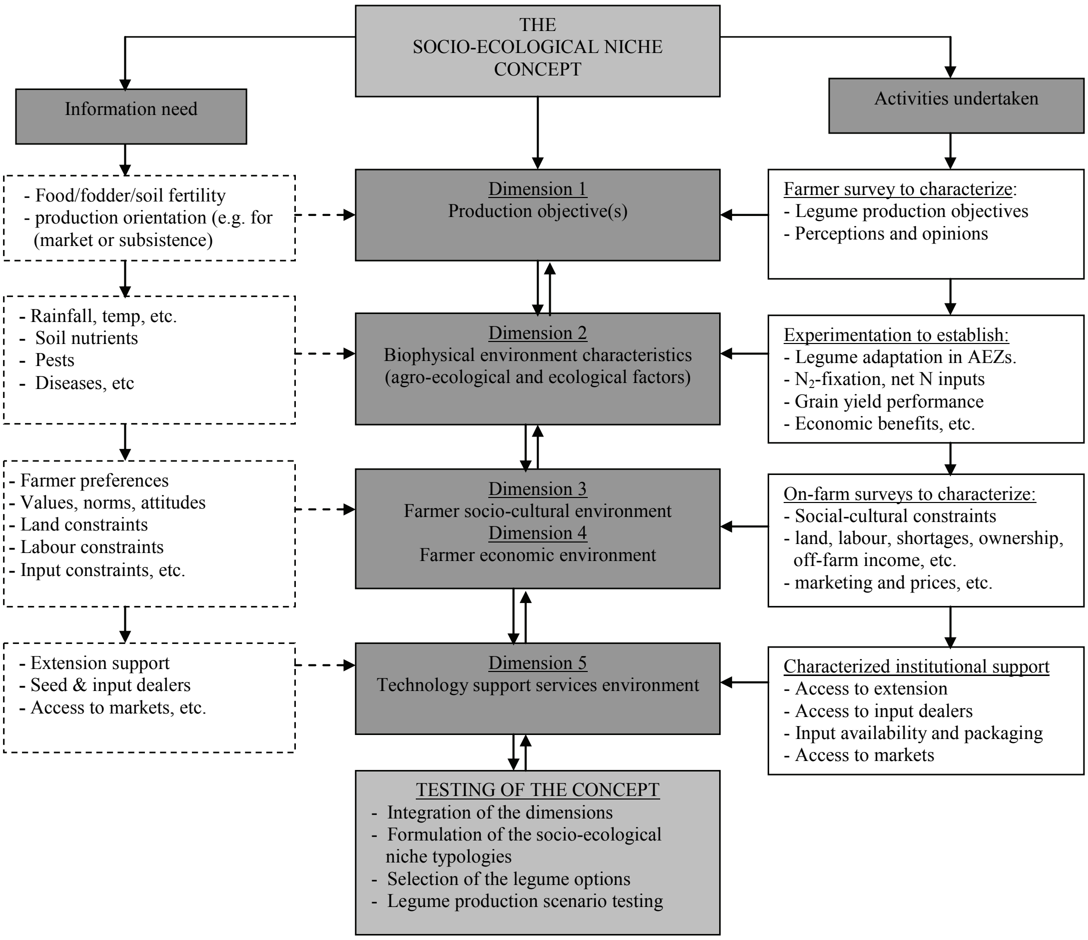


Figure 1. Diagram showing the methodology used in testing the utility of the socio-ecological niche concept, including the activities undertaken to fill the information gaps.

Baseline data for the abstract farms

The abstract farms were constructed on the basis of baseline data (Table 4a) derived from the legume screening experiment conducted on-farm in the three agro-ecological zones (Figure 1), socio-economic surveys, and other relevant literature. The major baseline parameters were farm size, family size, field typology and the area available for production for each field, mean maize and bean grain yield for each field typology, and area of farm required for maize and bean production to ensure food security. Farm size is considered excluding the areas occupied by the homestead and the home garden and family sizes are based on household demographic characteristics of the three study sites (see Table 1). Field typology is based on farmer classification of the relative fertility of their fields. Three fertility classes were recognized by farmers in each study site; Field 1 (high fertility), field 2 (medium fertility) and field 3 (low fertility). The fertility rating is on a relative scale. Area of different field types was estimated based on observations made on the trial farms, and on data from a previous on-farm survey (Tittonell et al., 2005a). Field 1 is 15% of the farm area; field 2 is 40%, while field 3 was estimated at 45% of the total farm area. For food security, a household requires 170 kg of grain per person annually (Shepherd and Soule, 1998).

Table 2. Major production constraints cited by farmers in detailed on-farm surveys in the three study sites, organized according to the four dimensions of the socio-ecological niche concept

	% farmers		
Constraint	Kakamega (AEZ 1)	Vihiga (AEZ 2)	Bondo (AEZ 3)
Biophysical:			
Noxious weeds (*Striga hermonthica*)	9	43	70
Severe soil erosion	43	50	35
Pest and diseases	53	24	22
Low soil fertility	41	48	32
Inadequate moisture	15	17	67
Variability in soil fertility	47	45	38
Socio-cultural:			
Theft of farm produce	30	63	7
Crop damage by livestock	35	29	46
Preference for different legumes than available	52	56	51
Weakening community institutions	49	56	43
Low interest in agriculture by the youth	52	35	40
Economic:			
Land shortage	20	75	5
Insufficient labour	33	19	47
Inadequate on-farm storage facilities	38	25	32
Lack of off-farm income	45	55	70
Lack of remittances	57	50	70
Institutional:			
Lack of certified legume seed	31	43	40
Inadequate extension support	40	10	50
Low access to input dealers	23	18	39
Concern for adulteration of inputs	39	32	29
Inappropriate input type/packaging	48	56	62
Poor condition of roads (input/output delivery)	35	33	45
Exorbitant levies by market authorities	58	61	59

Table 3. Farmers' legume production objectives based on on-farm surveys in three agro-ecological zones in Western Kenya.

Production objective	% farmers		
	Kakamega (AEZ 1)	Vihiga (AEZ 2)	Bondo (AEZ 3)
Food only	24	0	15
Livestock only	0	0	0
Soil fertility only	0	0	0
Food and livestock	12	41	2
Food and soil fertility	2	7	19
Livestock and soil fertility	3	3	2
Food, livestock and soil fertility	46	49	63
Unsure	12	0	0
n =	41	54	54

It was assumed that maize forms 55% of the grain requirement, and bean 45%. Based on this information, the annual grain requirement for each household for food security was computed by multiplying the maize and bean requirements by the number of individuals in the household. Data on maize grain yield in each field type is based on results of experiments on 27 farms in the study sites (Chapter 5), and on-farm survey data (Tittonell, et al., 2005b).

The current legume production situation

The analysis of the current legume production situation (Table 4b) was done using the abstract farms as discussed above. In each AEZ, three abstract farms (HRE, MRE and LRE) were utilized. The analysis assumes maize is grown intercropped with bean, both during the long and the short rains seasons. This is the common practice by the majority of the farmers in the study sites (e.g. Tittonell et al., 2005b). Since maize and bean are the principal crops for food security, they are preferentially allocated to the most fertile field in the farm (field 1). However, the farmers use as much land as possible to achieve food security, so if food security is not attained by utilizing field 1, field 2 is used for maize and bean production, and if food security is still not achieved, field 3 is also used for maize and bean production. For HRE (high resource endowed) and MRE (medium resource endowed) farm types, due to greater farm size, only 50% of fields 2 and 3 is required for production of maize, bean and other grain legumes that may be introduced, leaving the remainder for other uses, including pasture, fodder, woodlots, etc. For LRE, all the area under fields 2 and 3 is available for introduced grain legumes. However, due to labour and cash constraints, the MRE farmer can only utilize a maximum of 1.5 ha of land each season, and the LRE farmer a maximum of 1.0 ha^{-1} each season. Maize grain yield is different between the long and short rains seasons. In AEZs 1 and 2, the short rains maize yield is 60% of the long rains yield, while in AEZ 3, the short rains maize yield is 45% of the long rains yield. These estimates are based on grain yields of 27 on-farm experiments in the study sites during a normal rainfall year (Chapter 5). Surplus maize and bean is sold for cash at prevailing prices at the local markets. Mean maize price per kg is US$ 0.24 (AEZs 1 and 3) and US$ 0.23 (AEZ 2), while mean bean price per kg is US$ 0.41 (AEZ 1), US$ 0.60 (AEZ 2), and US$ 0.35 (AEZ 3). These figures are based on monthly price surveys in seven selected local markets in each study site for a period of one year (Chapter 5).

Alternative legume production scenario

Since the identification of the socio-ecological niche for legumes requires integrated analysis of the socio-economic and the biophysical environments of the farmer, the notion of socio-ecological niche typology (Figure 3), was formulated to facilitate this integration. Socio-ecological niche typology is an extension of farm typology, which is normally based mainly on resource endowment. However, resource endowment constitutes only one (economic) dimension of the socio-ecological niche, although it is acknowledged that the socio-ecological niche factors may not always operate completely independent of each other. For example, distance to the nearest market (institutional) may influence farmer income (economic), etc. However, by explicitly incorporating the biophysical, socio-cultural, and economic factors into the analysis, socio-ecological niche typology allows integrated assessment of these factors to be performed, and hence has advantage over farm typology alone (Chapter 2).

In the alternative production scenario, the socio-ecological niche typologies of the abstract farms are used to guide selection of possible legume production options for each farm (Table 5). Maize and bean intercrop is maintained in field 1, as in the current production situation. However, in fields 2 and 3, a grain legume (GL) is introduced in rotation with maize. The choice of GL varies according to the socio-ecological niche typology of the farm, and the performance of legumes in response to biophysical factors (Table 6). In AEZ 1, GL is groundnut in all fields and for all resource endowment groups, due to greater net N input and returns to land, even though grain yield was comparable to soyabean. In AEZ 2, groundnut and soyabean have comparable grain yields, net N input and returns to land, but groundnut was chosen on the basis of food preferences, which makes it more marketable as a cash crop. In AEZ 3, soyabean is introduced in field 2 on the basis of greater returns to land, and groundnut in field 3 based on greater net N input. In the short rains season, GL is allocated to 50% of the area of fields 2 and 3, for HRE and MRE farmers, and to 100% of the area of fields 2 and 3, for LRE farmers. In the long rains season, maize intercropped with bean is grown in fields 2 and 3, where GL had been. Best management practices are applied, hence differences in yield between HRE, MRE and LRE, due to seed quality, plant density, weeding, etc, are eliminated, and rainfall and inherent soil properties are the only major factors causing differential performance.

Results

A majority of smallholder farmers in the sites studied in Western Kenya are unable to produce sufficient maize and bean to meet their household requirements, and as a result, experience food insecurity for periods of up to eleven months (Table 1). Productivity is constrained by a number of factors, including scarcities of land, labour and capital. In the lower potential agro-ecological zones, e.g. AEZ 3, soil moisture is an additional constraint, due to low and less reliable rainfall. Generally, food insecurity decreases with increase in farmer resource endowment. Introduction of appropriate legume species can improve the productivity of the farming systems and food security, especially for the MRE and LRE farmers. This was assessed in an analysis of the alternative production scenario (Table 4), using maize and bean self-sufficiency (food security), and income from surplus production as indicators. For the purpose of illustration, the analysis is confined to grain legumes, although other legumes, e.g. fodder and green manure also affect productivity, where they fit into the available socio-ecological niches.

Current (maize-bean) production situation

In the current production situation (Table 4b), maize and bean are produced intercropped, during the long and short rains seasons. In AEZ 1, only the HRE farm, with a household size of eight and 3.0 ha of land, was completely food secure, with 655% maize self-sufficiency, and 220% bean self-sufficiency. Using all area under field 1 (0.45 ha), and 50% of the area of fields 2 and 3, a total of 4.90 Mg of maize farm^{-1}year^{-1}, and 1.34 Mg of bean farm^{-1}year^{-1} was produced, against an annual requirement of 0.75 Mg for maize and 0.61 Mg for bean. This resulted in a surplus maize production of 4.15 Mg and 0.73 Mg of bean year^{-1}, with total gross value of US$ 1297. In contrast, the MRE farm, with a household size of nine and farm size of 1.5 ha, had a self-sufficiency of 162% for maize and only 54% for bean (Table 4b). A total of 1.36 Mg of maize and 0.37 Mg of bean were produced farm^{-1} year^{-1}, against an annual maize requirement of 0.84 Mg and 0.69 Mg for bean, leading to a surplus production of 0.52 Mg for maize year^{-1} and no surplus bean production. The total value of surplus maize was US$ 125, which was remarkably less compared with US$ 1297 for HRE. The LRE farm, with a household size of nine and only 0.8 ha of land, was not able to attain self-sufficiency in either maize or bean. Maize self-sufficiency was 96% and bean only 36%, consequently, there was no surplus production.

In AEZ 2, the HRE farm, similar to AEZ 1, was self-sufficient in both maize and bean (Table 4b). With a household size of eight and a farm size of 2.5 ha, total maize production was 4.26 Mg farm^{-1}year^{-1}, and that of bean 1.15 Mg farm^{-1}year^{-1}, against an annual requirement of 0.75 Mg, for maize, and 0.61 Mg, for bean. This resulted in maize self-sufficiency of 570% and 188% for bean. Surplus maize production was 3.51 Mg year^{-1} and that of bean 0.54 Mg year^{-1}, with a total gross value of US$ 1063. For the MRE farm, with a large household size of ten individuals, and a farm size of 1.5 ha, a total of 1.44 Mg of maize, and 0.38 Mg of bean was produced per year, against an annual requirement of 0.94 Mg, for maize, and 0.77 Mg, for bean. This resulted in 154% self-sufficiency in maize, and only 50% self-sufficiency in bean. Surplus maize production was 0.50 Mg year^{-1}, with a gross value of US$ 116. In comparison, the LRE farm, with a household size of ten and a farm size of only 0.5 ha, was only 58% self-sufficient in maize and 17% self-sufficient in bean, and therefore had no surplus production.

In AEZ 3, despite relatively greater land availability, MRE and LRE farmers were unable to produce enough maize and bean to be fully food secure (Table 4b). This was attributed to poorer maize and bean yields in AEZ 3, due to lower rainfall. However, the HRE farm was self-sufficient in maize (566%), and bean (205%). Although farm size was large (6.0 ha), the farmer had the capacity to utilize only a maximum of 3.0 ha, due to labour and cash constraints, resulting in a production of 3.70 Mg of maize year^{-1} and 1.10 Mg of bean year^{-1}. Against an annual requirement of 0.65 Mg for maize and 0.54 Mg for bean, surplus maize production was 3.05 Mg year^{-1}, and that for bean 0.56 Mg year^{-1}, with gross total value of US$ 962. For the MRE farm, with a household size of eight persons, and a farm size of 3.0 ha, and a capacity to utilize only a maximum of 1.5 ha per season due to labour and cash shortages, total maize production was 1.33 Mg year^{-1} and that of bean 0.36 Mg year^{-1}, resulting in maize self-sufficiency of 178% and only 59% for bean. Surplus maize production was 0.58 Mg year^{-1}, with a gross value of US$ 140. The LRE farm, with eight individuals in the household, and 1.0 ha of land, could not attain food self-sufficiency, even when all the land was utilized for maize and bean production. Maize self-sufficiency was 89% and bean 34%.

Alternative legume production scenario

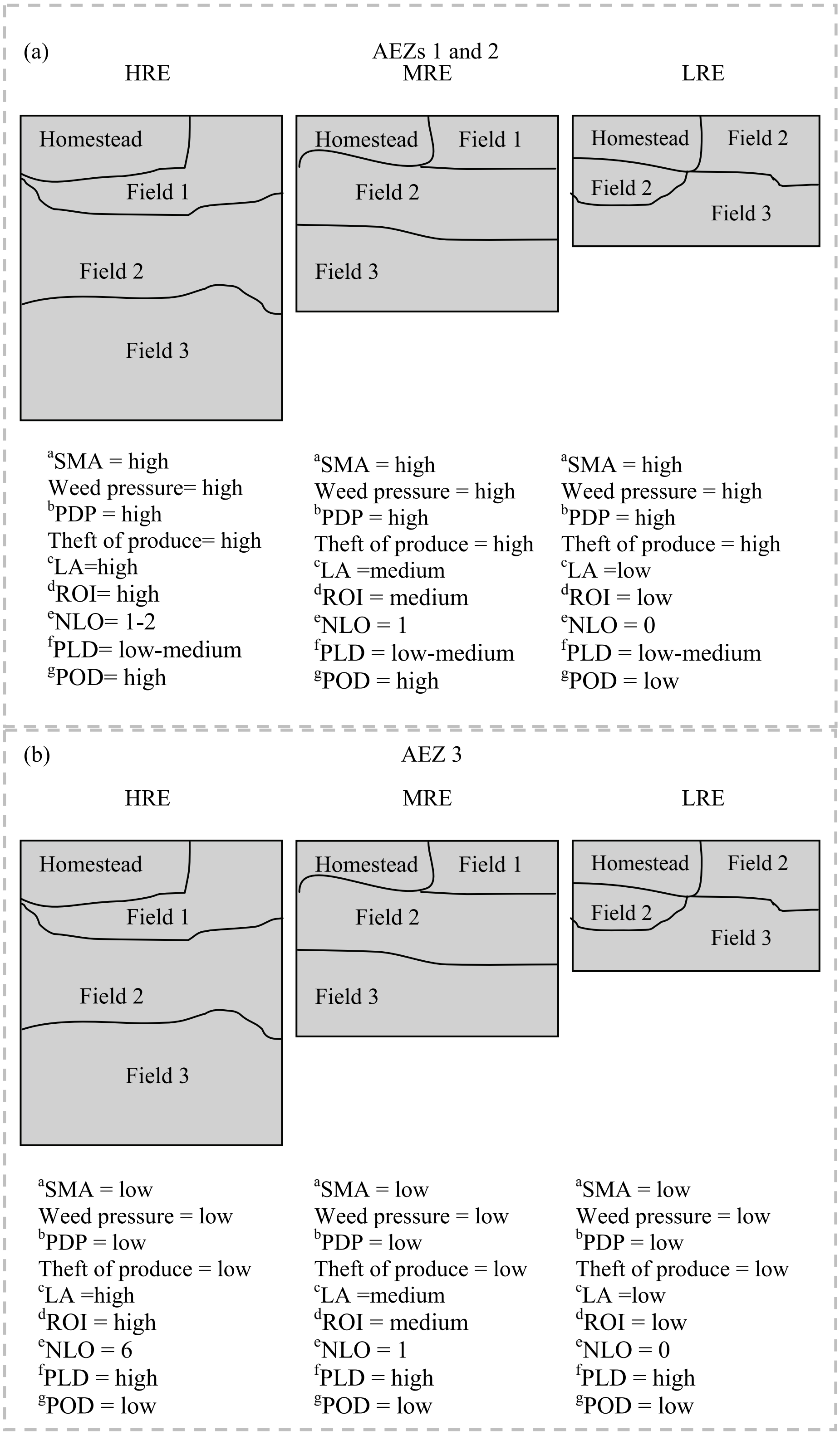
In the alternative legume production scenario, maize intercropped with bean was maintained in field 1 during the short and the long rains seasons (as in current production situation), a grain legume was grown in fields 2 and 3, according to availability of space, and in the long rains season, maize intercropped with bean was grown in fields 2 and 3. The grain legume was chosen on the basis of the socio-ecological niche typology of the farmer. For the HRE farmer in AEZ 1 (Table 4c), groundnut was introduced in fields 2 and 3, based on grain yield, net N input and returns to land (see Table 6). The introduction of groundnut in fields 2 and 3 resulted in a total of 0.75 Mg of groundnut grain, and improvement in the production of maize and bean in the long rains season. Total maize production (fields 1, 2 and 3) was 5.61 Mg year^{-1}, compared with 4.90 Mg year^{-1} under current production situation, while total bean production was 1.39 Mg year^{-1}, compared with 1.34 Mg year^{-1}under current production situation. As a result, maize self-sufficiency increased from 655% under current production scenario, to 750%, while bean self-sufficiency increased from 220% to 227%. Groundnut has a higher value of US$ 0.75 kg^{-1} in AEZ 1, compared with US$ 0.41 kg^{-1}, for bean, hence total gross value of surplus production increased by US$ 752, from US$ 1297 to US$ 2049. In the MRE farm, substituting groundnut for bean in fields 2 and 3 during the short rains season produced 0.38 Mg of groundnut, and increased total maize production from 1.36 Mg to 2.33 Mg, and that of bean from 0.37 Mg to 0.54 Mg. This increased maize self-sufficiency from 162% to 277%, and that of bean from 54% to 79%, while the total gross value of surplus production increased from US$ 125 to US$ 640. For the LRE farm, maize self-sufficiency increased from 96% to 186%, and that of bean from 36% to 39%. In contrast to current production situation where there was no surplus production, the farmer produced a surplus of 0.28 Mg of groundnut, and 0.72 Mg of maize, with a total gross value of US$ 382.

In AEZ 2, similar to AEZ 1, field 1 was reserved for maize and bean during the short and the long rains seasons. Groundnut was grown in fields 2 and 3, during the short rains season, followed by maize and bean intercrop, during the long rains season. Groundnut was chosen on the basis of greater grain yield and returns to land (Table 6). As a result, in HRE farm, 0.55 Mg of groundnut grain was produced in fields 2 and 3 during the short rains season, and total maize output of the farm increased from 4.26 Mg to 4.45 Mg, while that of bean decreased by 0.15 Mg. Maize self-sufficiency increased from 570% to 595%, while that of bean decreased slightly, from 188% to 164%. However, the gross value of total surplus production increased by 37%, from US$ 1063 to US$ 1664. In comparison, the MRE farm produced 0.33 Mg of groundnut, and total maize production, as a result of incorporating groundnut into the cropping system, increased from 1.44 Mg to 2.24 Mg, while that of bean increased from 0.38 Mg to 0.46 Mg. Maize self sufficiency increased from 154% to 239%, while that of bean increased from 50% to 60%. Even though there was no surplus bean production, the 0.33 Mg of groundnut and 1.30 Mg surplus maize produced increased the total gross value of surplus production by 82%, from US$ 116 to US$ 646. For the LRE farm, the benefits were relatively small due to severe land shortage. Maize self-sufficiency increased from 58% to 72%, and bean from17% to 20%. However, the 0.11 Mg of groundnut obtained from field 2 had a gross value of UD$ 116, which was an improvement, compared with the current production situation.

In AEZ 3 (Table 4c), unlike AEZs 1 and 2, soyabean was selected for field 2, on the basis of net N input and returns to land (see Table 6). For field 3, however, groundnut was selected, based on greater net N input than soyabean, and greater value as a grain legume for food than lablab, which had a similar net N input. For the HRE farm, the introduction of groundnut and soyabean into the cropping system resulted in a total production of 0.39 Mg (groundnut and soyabean grain combined). Total maize production increased from 3.70 Mg to 3.96 Mg, while that of bean decreased slightly, from 1.1 Mg to 1.0 Mg. However, maize self-sufficiency increased from 566% to 606%, while that of bean decreased slightly from 205% to 186%. Total surplus maize production was 3.31 Mg, and that of bean 0.46 Mg, and total value of surplus products was US$ 1245, which was 23% higher compared with the current production situation. For the MRE farm, maize self-sufficiency increased from 178% to 228%, and that of bean decreased from 59% to 58%. However, the total gross value of surplus products (maize, groundnut and soyabean) was US$ 395, which was64% higher compared with US$ 140 in the current production situation. For the LRE farm, the introduction of groundnut and soyabean into the cropping system resulted in total production of 0.22 Mg (groundnut and soyabean), and increased total maize output from 0.66 Mg to 0.92 Mg, and that of bean only marginally, from 0.21 Mg to 0.24 Mg. As a result, maize self-sufficiency increased from 89% to 124%, while that of bean only showed a marginal increase, from 34% to 39%. However, total gross value of surplus production was US$ 210, compared to zero, for the current production situation.

Table 4. Baseline production data and analysis of current situation and alternative legume production scenarios of abstract farms belonging to high resource endowment (HRE), medium resource endowment (MRE) and low resource endowment (LRE) typologies in three agro-ecological zones in western Kenya.

a) Baseline data	Kakamega (AEZ 1)			Vihiga (AEZ 2)			Bondo (AEZ 3)		
	HRE	MRE	LRE	HRE	MRE	LRE	HRE	MRE	LRE
Family size	8	9	9	8	10	10	7	8	8
Maize requirement (Mg year^{-1})	0.75	0.84	0.84	0.75	0.94	0.94	0.65	0.75	0.75
Bean requirement (Mg year^{-1})	0.61	0.69	0.69	0.61	0.77	0.77	0.54	0.61	0.61
Farm size (ha)	3	1.5	0.8	2.5	1.5	0.5	6.0	3.0	1
Area field 1 (ha)	0.45	0.23	0.12	0.38	0.23	0.08	0.9	0.45	0.15
Maize grain yield field 1 (Mg ha^{-1})	2.5	1.2	0.8	2.4	1.2	0.9	1.5	0.8	0.6
Area field 2 (ha)	1.2	0.6	0.32	1.0	0.6	0.2	1.1	1.05	0.4
Maize grain yield field 2 (Mg ha^{-1})	1.5	0.9	0.7	1.8	1.1	0.9	1.1	0.7	0.6
Area field 3 (ha)	1.35	0.68	0.36	1.13	0.68	0.23	1.0	0	0.45
Maize grain yield field 3 (Mg ha^{-1})	1.0	0.6	0.5	0.9	0.5	0.4	0.5	0	0.2
b) current production scenario									
Field 1 maize production (Mg farm^{-1} year^{-1})	1.80	0.43	0.15	1.44	0.43	0.11	1.96	0.52	0.13
Field 1 bean production (Mg farm^{-1} year^{-1})	0.56	0.13	0.05	0.45	0.13	0.03	0.67	0.18	0.04
Field 2 maize production (Mg farm^{-1} year^{-1})	1.98	0.59	0.36	1.98	0.73	0.29	1.33	0.81	0.38
Field 2 bean production (Mg farm^{-1} year^{-1})	0.45	0.13	0.11	0.45	0.16	0.09	0.30	0.18	0.12
Field 3 maize production (Mg farm^{-1} year^{-1})	1.12	0.34	0.30	0.84	0.28	0.15	0.42	0	0.15
Field 3 bean production (Mg farm^{-1} year^{-1})	0.34	0.10	0.09	0.25	0.08	0.01	0.12	0	0.04
Total maize production (Mg farm^{-1} year^{-1})	4.90	1.36	0.81	4.26	1.44	0.55	3.70	1.33	0.66
Total bean production (Mg farm^{-1} year^{-1})	1.34	0.37	0.25	1.15	0.38	0.13	1.10	0.36	0.21
Maize self-sufficiency (%)	**655**	**162**	**96**	**570**	**154**	**58**	**566**	**178**	**89**
Bean self-sufficiency (%)	**220**	**54**	**36**	**188**	**50**	**17**	**205**	**59**	**34**
Surplus maize production (Mg farm^{-1} year^{-1})	4.15	0.52	0	3.51	0.50	0	3.05	0.58	0
Surplus bean production (Mg farm^{-1} year^{-1})	0.73	0	0	0.54	0	0	0.56	0	0
Total gross value of surplus production (US$)	**1297**	**125**	**0**	**1063**	**116**	**0**	**962**	**140**	**0**
c) Alternative production scenario									
Field 1 maize production (Mg farm^{-1} year^{-1})	1.80	0.43	0.15	1.44	0.43	0.14	1.96	0.52	0.13
Field 1 bean production (Mg farm^{-1} year^{-1})	0.56	0.13	0.05	0.45	0.13	0.04	0.67	0.18	0.04
Field 2 GL production (Mg farm^{-1} year^{-1})	0.46	0.23	0.12	0.33	0.20	0.07	0.23	0.22	0.08
Field 2 maize production (Mg farm^{-1} year^{-1})	2.31	1.16	0.62	1.78	1.07	0.36	1.24	1.19	0.45
Field 2 bean production (Mg farm^{-1} year^{-1})	0.50	0.25	0.13	0.35	0.21	0.07	0.18	1.17	0.07
Field 3 GL production (Mg farm^{-1} year^{-1})	0.29	0.15	0.15	0.23	0.14	0.05	0.16	0	0.14
Field 3 maize production (Mg farm^{-1} year^{-1})	1.50	0.75	0.80	1.24	0.74	0.25	0.76	0	0.34
Field 3 bean production (Mg farm^{-1} year^{-1})	0.33	0.17	0.09	0.21	0.12	0.04	0.15	0	0.13
Total maize production (Mg farm^{-1} year^{-1})	5.61	2.33	1.57	4.45	2.24	0.74	3.96	1.71	0.92
Total bean production (Mg farm^{-1} year^{-1})	1.39	0.54	0.27	1.00	0.46	0.15	1.00	0.35	0.24
Maize self-sufficiency (%)	**750**	**277**	**186**	**595**	**239**	**79**	**606**	**228**	**124**
Bean self-sufficiency (%)	**227**	**79**	**39**	**164**	**60**	**20**	**186**	**58**	**39**
Surplus GL production (Mg farm^{-1} year^{-1})	0.75	0.38	0.28	0.55	0.33	0.11	0.39	0.22	0.22
Surplus maize production (Mg farm^{-1} year^{-1})	4.86	1.49	0.72	3.70	1.30	0	3.31	0.96	0.18
Surplus bean production (Mg farm^{-1} year^{-1})	0.78	0	0	0.39	0	0	0.46	0	0
Total gross value of surplus production (US$)	**2049**	**640**	**382**	**1664**	**646**	**116**	**1245**	**395**	**210**



NB: The HRE, MRE and LRE farms in AEZs 1 and 2 are shown together. Apart from farm size, the other socio-ecological variables are quite similar. The farm diagrams are not to scale. Field 1= high fertility, Field 2= medium fertility, Field 3= low fertility [a]SMA= soil moisture availability [b]PDP= plant diseases pressure [c]LA= labour availability [d]ROI= relative off-farm income [e]NLO= number of

Figure 2. Diagram showing the abstract farms constructed in the three agro-ecological zones (AEZ) in western Kenya: (a) AEZs 1 and 2; and (b) AEZ 3, and the major factors determining their socio-ecological niche typologies for legume technologies.

Discussion

Productivity of the abstract farms

The analysis comparing the current legume production situation with an alternative legume production scenario showed large differences in the capacity of the farmers to produce sufficient maize and bean to satisfy household food needs. Food (maize and bean) self-sufficiency decreased with agro-ecological potential and resource endowment (Table 4). Under the current production situation (Table 4b), the HRE farms were maize and bean self–sufficient in all the agro-ecological zones, while MRE farms were self-sufficient in maize in all AEZs but were unable to produce enough bean to meet their food security needs. In comparison, the LRE farms were not self-sufficient in either maize or bean, or both, in any of the AEZs, even when all the land was utilized for production. This shows that for the LRE farmers, even though many factors ultimately contribute to the decision on adoption of legume technologies, land is the primary consideration in their legume technology rationalization process, since they would have to substantially change their production strategy to fit in the legumes. However, farmers are often reluctant to change their production systems unless they have expectations of greater economic returns.

The analysis of the current production situation showed that the benefits of legumes vary according to agro-ecological conditions, field typology (soil fertility) and farmer resource endowment (land, labour and capital). Improvements in farm productivity, obtained by fitting in alternative legumes (groundnut and soyabean) into the cropping systems, varied depending on the levels of these critical factors (Table 4c). In terms of food security, the impact of the alternative legumes was greatest for MRE and LRE farms, across the agro-ecological gradient.

In AEZ 1, maize self-sufficiency for the MRE improved by 29% and bean self-sufficiency by 32% (Table 4c), while for the LRE farm, maize self-sufficiency improved by 52% and bean self-sufficiency by 8%. For the HRE, where yields were already high, due to better current management and greater use of inputs, maize self-sufficiency improved by 13% and that of bean by only 3%. The trend was generally similar for AEZs 2 and 3. However, the LRE farm in AEZ 2 was not able to achieve self-sufficiency in either maize or bean due to severe land constraints, while the LRE farm in AEZ 3, despite lower rainfall, was able to achieve self-sufficiency in maize due to the relatively greater farm area available for legumes (Table 4a). This implies that legume technologies, such as the ones introduced, are unlikely to have much impact on the food security of smallholder farms severely constrained by land availability.

However, the alternative legumes had greater impact on the income of HRE farms than on that of the MRE and LRE farms. The change in gross income (alternative minus current scenario) from surplus production increased with rainfall and farmer resource endowment. In AEZ 1, the change in gross value of surplus production was US$ 752 for HRE farm, compared with US$ 512 for MRE and 382 for LRE, while in AEZ 2, the change was US$ 601 for HRE, US$ 530 for MRE, and US$ 116 for LRE. In AEZ 3, the change in gross income was remarkably less, US$ 283 for HRE, US$ 255 for MRE, and US$ 210 for LRE. These results indicate that farmers in high rainfall environments, and with high levels of resource endowment, stand to benefit more from legume technologies than those in low rainfall environments, and low levels of resource endowment.

Selection of legumes for the alternative production scenario

Food security is an important consideration in the decision concerning adoption of new technologies by farmers. Therefore, maize and bean, the food security crops, are likely to be given first priority. This means that any legume technology that can potentially be adopted can only be considered for fields 2 and 3, and must compete with other crops for the limited land, labour, and other production resources available, especially in LRE farms. Selection of that technology according to the socio-ecological niche concept is bound to increase the chances of its sustainable use by the farmer. Land, labour, livestock ownership, production objectives, markets and preferences, e.g. for food, are the major socio-economic factors influencing the choice of legume technologies. When these factors are assessed in conjunction with the biophysical performance of the legumes, e.g. relative productivity in response to rainfall, diseases, soil fertility conditions, etc., socio-ecological niches can be identified. For example, the HRE farmer in AEZ 1 (Table 6), besides grain legume, has opportunity for growing a fodder legume, because of livestock ownership, relatively greater land and labour availability, and high dairy potential in the agro-ecological zone. Based only on biomass production (Table 5), any of the three fodder species (desmodium, siratro or stylo) would be appropriate. The HRE farmer can also fit in a green manure species in field 3, to improve soil fertility. The appropriate grain legume choice for HRE farmer in AEZ 1 is groundnut for field 2. Groundnut, soyabean and lablab had comparable grain yields and returns to land (Table 5). Lablab has greater net N input, and would have been the best choice if soil fertility improvement *per se'* was the most important legume production objective of the farmer. However, no farmer in any of the study sites had soil fertility improvement as the only legume production objective (Table 3). In field 3, groundnut, soyabean, lima and lablab had comparable grain yield and returns to land. However, lablab, whose net N input was greater, would have been the best choice. However, marketing of lablab is problematic, especially in western Kenya, where it is not a common component of the diet. Cowpea and green gram, more common grain legumes, were eliminated after the preliminary legume screening trials due to poor disease tolerance and low grain yield (Chapter 3). In contrast, the MRE farmer may fit in a fodder legume but not a green manure legume, due to land and labour constraints, while the LRE farmer can only manage to fit in a grain legume in fields 2 and 3.

The legume choices for AEZ 2 are basically similar, except that the HRE farmer may not fit in a green manure legume, due to land constraints, and the MRE farmer may not be able to fit a fodder legume due land constraints, despite high dairy potential. The grain legume choice for field 2 was groundnut, based on superior grain yield (Table 5). Although lablab had greater net N contribution to soil N fertility and returns to land comparable to groundnut, groundnut was selected because of marketing considerations, as discussed above. In field 3, both groundnut and soyabean were suitable, based on returns to land. However, groundnut was selected because of greater preference for food and greater marketability in western Kenya. However, if field 3 is a distance from the homestead, then the most appropriate choice would be soyabean. Theft of farm produce is a major production constraint in AEZ 2, where it affected 63% of the farmers interviewed (see Table 2). Farmers would therefore be reluctant to grow a high value food crop like groundnut far away from the homestead. Soyabean is less likely to be stolen because it is less readily usable as food.

In AEZ 3, production of grain legumes is the only technology likely to be embraced by HRE, MRE and LRE farms. The socio-economic conditions (infrastructure, markets) are unfavourable and agro-ecological conditions are less favourable for dairy hence fodder legumes have low priority. Only the HRE farmer, due to greater land and labour availability, may grow green manure in field 2 or 3, to improve soil fertility, control weeds, etc. Soyabean was selected for field 2 in the alternative production scenario analysis because of greater returns to land (Table 5), while for field 3, since all the grain legumes had comparable grain yield, groundnut was selected on the basis of greater contribution to soil N fertility.

Table 5. Performance of the legume species across the agro-ecological and soil fertility gradients in Western Kenya (nd = not determined; n/a = not applicable).

	Species	High fertility field (field 1)				Medium fertility field (field 2)				Low fertility field (field 3)			
		[a]Biomass (Mg ha^{-1})	[b]Grain (Mg ha^{-1})	[c]Net N input (kg ha^{-1})	[d]Returns to land (US$ ha^{-1})	[a]Biomass (Mg ha^{-1})	[b]Grain (kg ha^{-1})	[c]Net N input (kg ha^{-1})	[d]Returns to land (US$ ha^{-1})	[a]Biomass (Mg ha^{-1})	[b]Grain (kg ha^{-1})	[c]Net N input (kg ha^{-1})	[d]Returns to land (US$ ha^{-1})
AEZ1	Bean	*	**	*	***	*	**	*	**	*	*	*	*
	Groundnut	**	***	***	***	**	**	***	***	*	**	**	**
	Soyabean	**	***	**	****	**	**	*	***	**	**	**	**
	Lima	*	*	**	***	*	**	**	**	*	**	**	**
	Lablab	*****	**	****	***	******	**	****	***	****	**	***	**
	Cowpea	*	*	nd	nd	nd	nd	nd	nd	*	*	nd	nd
	Green gram	*	*	nd	nd	nd	nd	nd	nd	*	*	nd	nd
	Velvet bean	****	n/a	****	**	****	n/a	****	**	****	n/a	****	**
	Jackbean	***	n/a	***	**	**	n/a	**	**	***	n/a	***	**
	Crotalaria	****	n/a	*****	**	***	n/a	*****	**	***	n/a	****	*
	Desmodium	***	n/a	***	n/a	***	n/a	***	n/a	***	n/a	***	n/a
	Siratro	***	n/a	***	n/a	***	n/a	**	n/a	***	n/a	**	n/a
	Stylo	***	n/a	***	n/a	***	n/a	***	n/a	***	n/a	***	n/a
AEZ2	Bean	*	**	*	***	*	**	*	*	*	*	*	*
	Groundnut	**	***	*	*****	*	***	*	*****	*	**	*	****
	Soyabean	**	***	*	*****	**	**	*	*****	**	***	*	****
	Lima	**	*	*	***	*	**	**	***	*	*	*	**
	Lablab	*****	***	**	*****	****	**	****	*****	*****	**	***	***
	Cowpea	*	*	nd	nd	nd	nd	nd	nd	*	nd	nd	nd
	Green gram	*	*	nd	nd	nd	nd	nd	nd	*	nd	nd	nd
	Velvet bean	****	n/a	*****	****	*****	n/a	*****	***	****	n/a	*****	***
	Jackbean	***	n/a	****	***	**	n/a	***	***	***	n/a	****	***
	Crotalaria	***	n/a	*****	***	*****	n/a	*****	***	***	n/a	*****	***
	Desmodium	****	n/a	***	n/a	***	n/a	***	n/a	***	n/a	***	n/a
	Siratro	*****	n/a	***	n/a	***	n/a	***	n/a	***	n/a	**	n/a
	Stylo	***	n/a	***	n/a	***	n/a	***	n/a	***	n/a	***	n/a
AEZ3	Bean	*	*	*	*	*	*	*	*	*	*	*	*
	Groundnut	*	**	**	**	*	*	**	*	*	*	**	*
	Soyabean	*	**	*	**	*	*	*	**	*	*	*	*
	Lima	*	**	*	*	*	*	*	*	*	*	*	*
	Lablab	*	*	**	**	**	*	**	*	*	*	**	*
	Cowpea	*	*	nd	nd	nd	*	nd	nd	*	*	nd	nd
	Green gram	*	*	nd	nd	nd	*	nd	nd	*	*	nd	nd
	Velvet bean	***	n/a	**	**	***	n/a	**	*	**	n/a	**	*
	Jackbean	***	n/a	**	**	***	n/a	**	*	**	n/a	**	*
	Crotalaria	***	n/a	**	**	***	n/a	***	*	**	n/a	***	*
	Desmodium	*	n/a	**	n/a	**	n/a	**	n/a	**	n/a	**	n/a
	Siratro	**	n/a	**	n/a	**	n/a	**	n/a	**	n/a	**	n/a
	Stylo	**	n/a	**	n/a	**	n/a	**	n/a	**	n/a	**	n/a

[a]: < 2 = *, 2-3 = **, 4-5 = ***, 6-7 =****, >8 = *****
[b]: <0.5 = *, 0.5-1.0 = **, > 1.0 = ***
[c]: < 25 = *, 25-50 = **, 60-90 = ***, 100-150 = ****, > 150 = *****
[d]: <150 = *, <150-300= **, 400-600 = ***, 700-900 = ****, > 900 = *****

Table 6. Potential legume technologies for the alternative production scenario, based on farmer socio-ecological niche typologies.

	Resource endowment	Short rains season			Long rains season		
		Field 1	Field 2	Field 3	Field 1	Field 2	Field 3
AEZ1							
	HRE	M+B	GL, FL	GL, FL, GM	M+B	M+B, FL	M+B, FL
	MRE	M+B	GL	GL, FL	M+B	M+B, FL	M+B, FL
	LRE	M+B	GL	GL	M+B	M+B	M+B
AEZ 2	HRE	M+B	GL, FL	GL, FL	M+B	M+B, FL	M+B
	MRE	M+B	GL	GL,	M+B	M+B	M+B, FL
	LRE	M+B	GL	GL	M+B	M+B	M+B
AEZ 3	HRE	M+B	GL, GM	GL, GM	M+B	M+B	M+B
	MRE	M+B	GL	GL	M+B	M+B	M+B
	LRE	M+B	GL	GL	M+B	M+B	M+B

[a]The socio-ecological niche typologies are indicated in Figure 2.
HRE = high resource endowment, MRE = medium resource endowment, LRE = low resource endowment.
Field 1= high fertility field, Field 2 = medium fertility field, Field 3 = medium fertility field.
M+B = maize + bean.
M+GL = maize+grain legume
GL = Grain legume.
GM = green manure legume.
FL = Fodder legume.

The utility of the socio-ecological niche concept

The results of this study demonstrate that the socio-ecological niche concept can be used to facilitate the assessment of legume technologies with potential for sustainable improvement of smallholder productivity. The alternative legume production scenario discussed above shows that socio-economic factors (land, labour, livestock ownership, production objectives, markets and food preferences, etc), and biophysical factors (rainfall, soil fertility, diseases, etc., and the relative productivity of the legumes in response to these factors) influence the choice of appropriate legume technologies for smallholder farmers. The notion of socio-ecological niche typology (Figure 3) is useful for the practical application of the socio-ecological niche concept. Socio-ecological niche typology can be viewed as an extension of farm typology, which is often employed in classification of farmers for a variety of purposes. Resource endowment is often used to classify farmers into various typologies for a variety of applications. Typically, a household wealth assessment include economic variables relating to assets such as land ownership, expenditure and income (Adams et al., 1997), which should be selected on the basis of relevance to the purpose of classification (Abubakr, 1999). However, the tendency is to rely on variables that avail themselves to quantification, and exclude those that do not (Adams et al., 1997) or those that cannot be readily assessed. In the context of the socio-ecological niche concept, resource endowment mainly addresses the economic dimension of the socio-ecological niche concept (see Figure 1), although some degree of interrelationship between the factors might be expected. However, by explicitly incorporating the biophysical, social and the institutional factors into the technology innovation and targeting process, the socio-ecological niche typology has advantage over a typology based only on resource endowment.

The socio-ecological niche concept can assist researchers and extension agents to identify and analyse the complex biophysical and socio-economic factors that define the smallholder production environment. This will hopefully lead to integration of the critical variables into the technology innovation process. However, for the socio-ecological niche concept to be applied successfully to technology innovation processes, closely partnership with farmers is required from the start (Figure 4). The scientists must learn from the farmers, while at the same time harnessing the most useful inputs from outside the local knowledge system, based on their own experience.

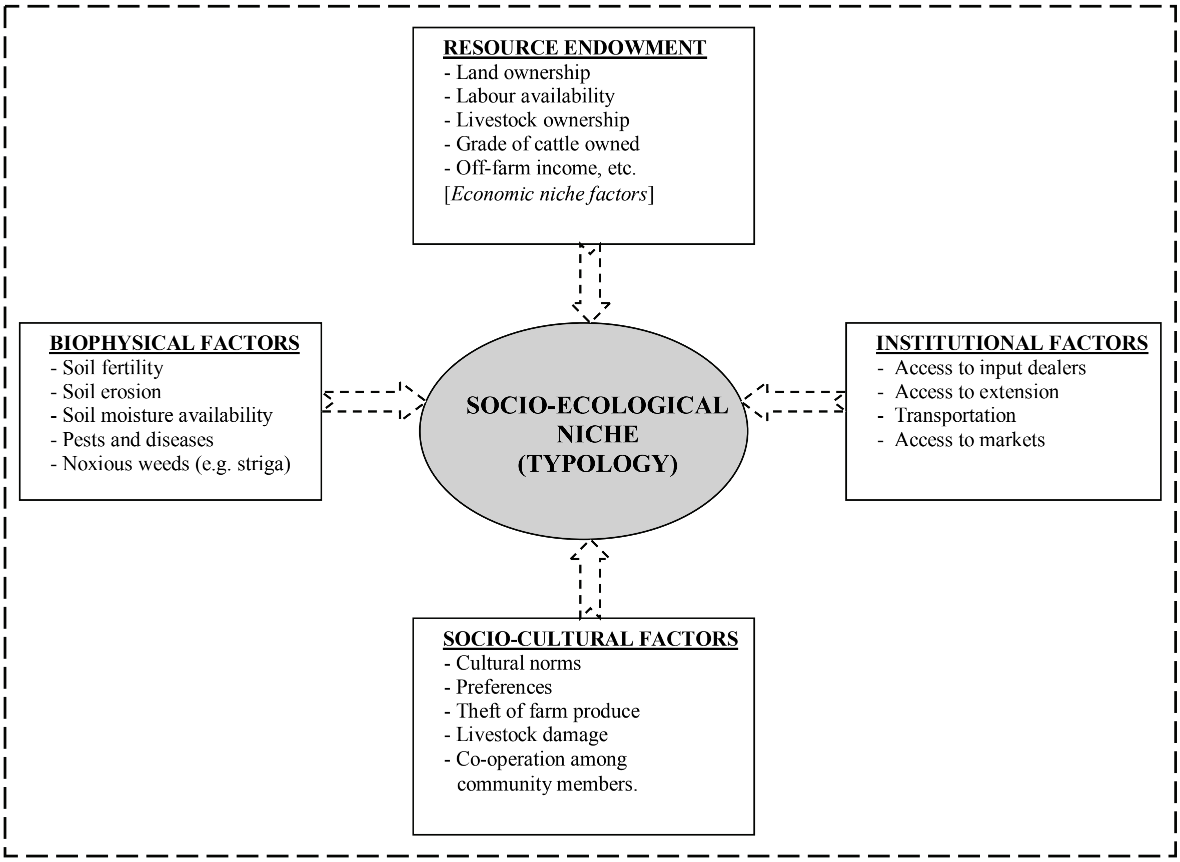


Figure 3. Diagram showing how resource endowment (farm typology), which is often based only on the economic socio-ecological niche factors, can be broadened by including biophysical, socio-cultural and institutional constraints, to derive a socio-ecological niche typology, on the basis of which appropriate legume technologies can be assessed.

Application of the socio-ecological niche concept

The socio-ecological niche concept can be used by researchers and extension agents to improve the value of the products and services they deliver to farmers. Researchers can make use of the concept at the project planning stage to predefine the options they intend to introduce to farmers, or the treatments they wish to test, to ensure that these are compatible with the biophysical and socio-economic realities on the ground. In this regard, the socio- ecological niche concept can be used as a framework for performing an *ex-ante* assessment of the potential of the options being considered for testing. Factors, such as farmer legume production objectives, land and labour availability, livestock ownership, extension support, access to inputs (seed, fertilizer, etc.), markets for farm produce, prices and price fluctuations, farmer preference, potential for livestock damage, theft of farm produce, and farmer organizations (e.g. for labour or seed bulking), can be taken on board in the planning of research projects. This would provide valuable insight into which legumes should be included in the project execution phase and which ones should be eliminated, greatly increasing research efficiency and impact. Used in this manner, the socio-ecological niche concept would lead to greater participation by farmers even in the early stages of technology development, instead of the current practice in which farmers are only involved when they host on-farm trials or when extension agents use their fields for demonstrating new technologies. This would result in a significant reduction in the number of technologies sitting on the shelves, or those that get rejected because they do not adequately address farmers' needs. Although this thesis has focused on legume technologies, the socio-ecological concept can be used for other agricultural technologies as well.

Farmers' interest in legume species and varieties

Farmers were exposed to a large number of legume species and varieties during the implementation of this thesis and were able to select some grain, green manure and forage legumes that they found useful and wanted to incorporate into their cropping systems. Bean is a major crop for food security but the farmer varieties were relatively more susceptible to diseases, hence improved bean varieties KK15 and KK20, which showed relatively greater tolerance to diseases, were selected by farmers for production. Farmers also showed interest in soyabean and groundnut, which had greater grain yield and disease tolerance than bean. Soyabean varieties SB17 and SB20, and groundnut varieties ICGV-12911 and ICGV-12988 were selected. A group of enterprising farmers in Bondo (AEZ3) foresaw the demand for

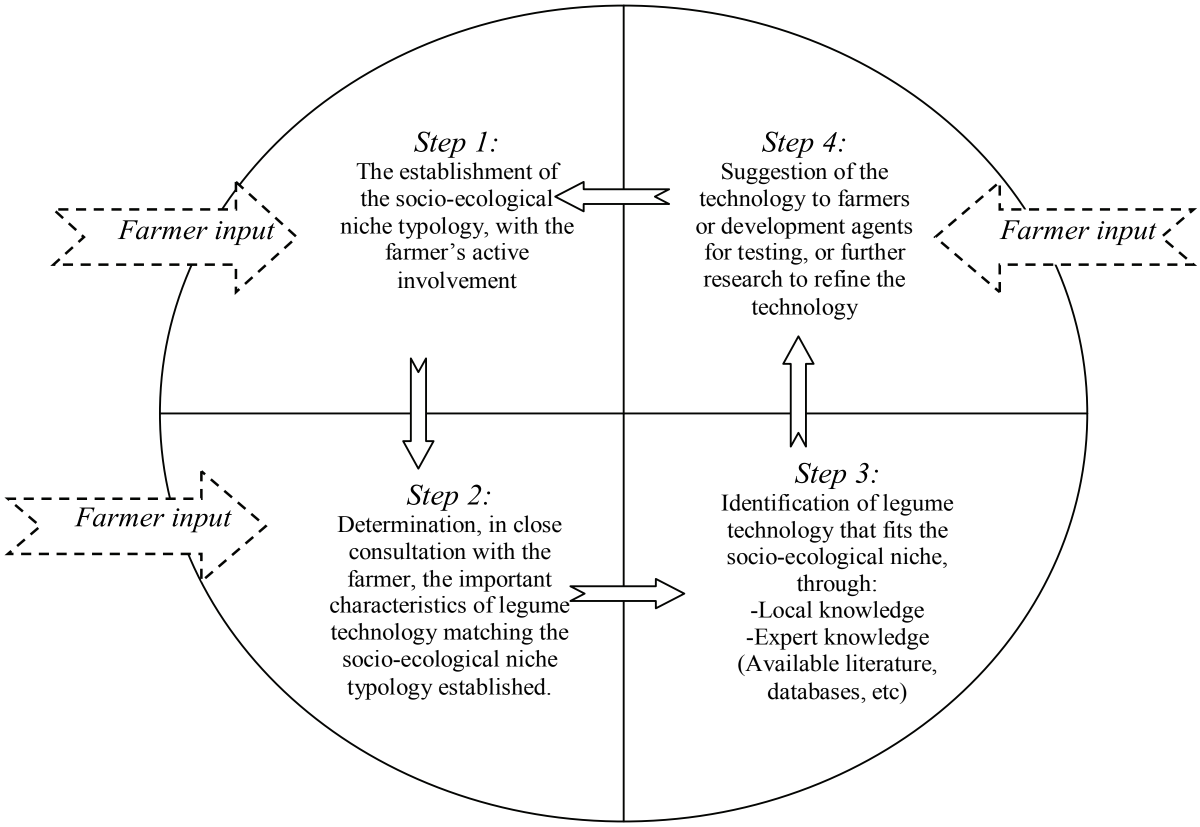


Figure 4. A four-step procedure for matching legume technologies to appropriate socio-ecological niches.

legume seed and formed a group to produce legume seed to satisfy the expected demand. With a little technical backstopping from researchers, they managed to produce 1 Mg of soyabean and groundnut seed in their first season of operation.

Further scenario testing using models

A more comprehensive legume production scenario testing using models is required to fully understanding the roles legumes can play in the improvement of productivity in the heterogeneous smallholder farming systems of western Kenya. This thesis only tested one alternative legume production scenario for each farmer resource endowment group in each AEZ. Using models, however, different scenarios of land and labour availability, livestock ownership, input and output prices, and legume production objectives, can be tested, for a more comprehensive understanding of the options available, to better fit legumes to the socio-ecological niches.

Conclusions

This study demonstrates the utility of the socio-ecological niche concept in facilitating the identification of legume technologies that can fit within the broad biophysical and socio-economic heterogeneity of the smallholder farming systems in western Kenya, to contribute to productivity improvement. The major variables influencing the choice of appropriate legume are production objectives, food preference, land, labour, livestock ownership, markets, rainfall, soil fertility, and plant diseases. The results show that the benefits of legumes vary, decreasing with rainfall, soil fertility and farmer resource endowment. Land scarcity is a major factor determining the potential contribution of the legumes to the improvement of farm productivity hence farmers with severe land constraints are unlikely to benefit from legume technologies. However, use of legume technologies leads to greater increases in productivity in MRE and LRE farms than HRE farms, whose management is already good due to greater resource endowment. Production scenario analysis shows that legume technologies can benefit the MRE and LRE farmers through improvement of food security situation and provision of extra income, while for HRE farmers who are already food secure, legumes can greatly improve income. Further legume production scenario analysis using models is required for a more comprehensive understanding of the options available and to better fit legumes to the socio-ecological niches.

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Summary

The western Kenya smallholder farming systems are characterized by low crop and livestock productivity. Poor soil fertility is the most important factor responsible for the low productivity. Although legumes have the potential for improving productivity through inputs of fixed atmospheric N_2, a high level of biophysical and socio-economic heterogeneity constrains their sustainable use by western Kenya smallholder farmers. A variety of biophysical factors (e.g. rainfall, soil fertility, incidence of pests and diseases, etc.) and socio-economic factors (e.g. land and labour availability, livestock ownership, legume production objectives, income, preference, etc.) have significant influence on the choice of legume technologies for smallholder farmers. The integration of these factors into the legume technology innovation process is essential for identification of legume technologies with potential for fitting into the broad biophysical and socio-economic heterogeneity of smallholder farming systems. The socio-ecological niche concept was proposed as framework for facilitating this integration. The concept is an extension of that of the "ecological niche" of an organism in classical ecological theory, to include socio-cultural, economic and institutional factors that have significant influence on technology adoption.

The objective of this thesis was to test, through on-farm experimentation and socio-economic surveys, the utility of the socio-ecological niche concept. The on-farm experiments were conducted in three different agro-ecological zones (AEZ), with rainfall decreasing from AEZ 1 to AEZ 3. Within each AEZ, experiments were laid out in fields of different soil fertility status, to assess the effect of the within-farm soil fertility variability on the productivity of a range of grain, green manure and forage legumes. Legume emergence, survival, tolerance to diseases, nodulation, biomass production, grain yield, N_2-fixation capacity and net N input to the soil were assessed. Economic benefits of growing grain and green manure legumes in rotation with maize were also determined. Socio-economic surveys characterized farmers' legume production objectives, as well as socio-cultural, economic and institutional factors with potential influence on legume use by smallholder farmers.

Results of the on-farm experiments showed that rainfall and soil fertility had significant influence on the productivity of the legumes. The emergence, survival, disease tolerance, nodulation and grain and biomass production of the species varied with rainfall and soil fertility. Performance of legumes was in general better in higher rainfall zones and richer soils. Incidence of diseases had greater effect on legume productivity in AEZ 1, compared with AEZs 2 and 3. The legume species and varieties also differed significantly in their tolerance to diseases. These results indicate

that opportunity exists for selection of species with greater potential for improving productivity by selecting different species of grain, green manure and forage legumes and different varieties of those species for different biophysical and socio-economic environments. Total dry matter (TDM) production varied from 0.1 Mg ha^{-1} to 13.9 Mg ha^{-1}, and generally the grain legumes produced less TDM than the green manure legumes and fodder legumes. However, soyabean and groundnut produced up to 4.6 Mg ha^{-1} TDM, indicating their great potential for soil fertility improvement, in addition to contributing to household food and cash needs. The study indicated that application of P is essential for enhancing the productivity of the legumes.

All the grain, green manure and fodder legume species tested showed ability to form viable nodules with naturally occurring rhizobia, and to fix atmospheric N_2 under the different agro-ecological and soil fertility conditions. This is particularly significant, given that the infrastructure for artificial inoculation does not exist in Western Kenya, as in most parts of sub-Saharan Africa. However, the results indicated differential capacities of the grain, green manure and fodder legume species to fix atmospheric N_2, hence different potential contributions to soil fertility improvement. Generally, the species fixed 23-90% of their N requirements in AEZs 1 and 2, compared to 7-77% of their N requirements fixed in AEZ 3. While N_2-fixation by the green manure species (29-232 kg N ha^{-1}) was remarkably greater than that of the grain legume species (3-172 kg N ha^{-1}), farmers are unlikely to adopt green manure technology in a significant way, unless they can provide other useable products. Farmers are not interested in legumes for the purpose of soil fertility improvement *per sé*, as was revealed by the survey of farmer legume production objectives. This implies that the multi-purpose green manure species, e.g. velvet bean, which can also be used as fodder for livestock, or crotalaria, which is also used as vegetable, especially in AEZ 3, have potential for finding suitable socio-ecological niches in smallholder farming systems. However, grain legumes, due to their food value and the potential for generating extra income for the household needs, have a greater chance of fitting into the smallholder farming systems.

The grain legumes, especially groundnut, soyabean and lablab, have the potential to make a significant contribution to smallholder productivity through grain and N inputs to the soil. However, for the grain legumes to contribute meaningfully to the maintenance of soil N fertility, a correct balance between grain yield and net N input is necessary, since grain yield is negatively correlated with net N input to the soil. For example, analysis of grain yield and net N input to the soil by grain legumes in AEZ 1 indicated that on average, 128 kg N is traded-off for every 1 Mg of grain harvested, and net N input becomes negative for grain yields above 1 Mg ha^{-1} in AEZ 1 and 0.5 Mg ha^{-1} in AEZ 3. This indicates that although high yielding grain legumes are beneficial to farmers, they have greater potential to mine soil N, defeating a main objective of their incorporation into the smallholder farming system.

Incorporation of legumes into the smallholder cropping systems in rotation with maize resulted in significant economic benefits, indicating that successful integration of legumes into the smallholder farming systems can have significant impacts on productivity. However, the benefits decreased with rainfall and soil fertility. Total maize productivity (short and long rains crops) decreased by 47%, from AEZ 1 to AEZ 3, and by 33%, from high to low soil fertility fields. Consequently, economic benefits were significantly less in AEZ 3, and became negative when the legumes were grown in the low fertility field. Although continuous maize fertilized with both N and P had the best total maize productivity, returns to land and labour were greatest with grain legume-maize cropping systems. In AEZ 2, where moisture was not limiting during the experimentation period, mean returns to land for grain legume-maize cropping systems were US$ 879 ha^{-1}, compared with US$ 533 for green manure-maize, and US$ 459 for continuous maize with N and P. Since labour is a scarce resource in smallholder farming systems, technologies that enhance labour productivity stand a better chance of acceptance by farmers. Mean returns to labour for grain legume-maize option were US$ 1.60 day^{-1}, compared with US$ 1.30 day^{-1} for green manure-maize and US$ 1.26 day^{-1} for continuous maize fertilized with N and P, both of which were below the local official daily wage rate of US$ 1.33 day^{-1}.

This study confirmed the utility of the socio-ecological niche concept in facilitating the integration of biophysical and socio-economic factors into the technology innovation process, to identify legumes that can potentially fit into the broad biophysical and socio-economic heterogeneity of the smallholder farming systems to improve productivity. Rainfall, soil fertility and incidence of diseases (biophysical) and land, labour availability, livestock ownership, production objectives, markets and farmer preferences (socio-economic) were identified as the most important socio-ecological niche factors influencing the choice of appropriate legumes for the smallholder socio-ecological niches. The analysis of the current legume production situation showed that the low resource endowed farmers were food insecure due to a combination of land and labour scarcity but could improve their maize self-sufficiency by 21-48%, and generate some additional income for household needs by growing alternative legumes selected on the basis of socio-ecological niche concept.

Samenvatting

Gewassen en vee in de bedrijfsystemen van kleine boeren in West Kenia kennen een lage productie. De belangrijkste factor verantwoordelijk voor deze lage productie is de geringe bodemvruchtbaarheid. Hoewel stikstofbindende gewassen in potentie de productiviteit zouden kunnen verbeteren door de inbreng van uit de atmosfeer gebonden stikstof, beperkt de grote mate van heterogeniteit in bio-fysische en sociaal-economische factoren tussen en in deze bedrijven de duurzame toepassing van deze technologie. Een palet van bio-fysische (bv. regenval, bodemvruchtbaarheid, voorkomen van ziekten en plagen, enz.) en sociaal-economische factoren (bv. beschikbaarheid aan land en arbeid, bezit aan vee, tegenstrijdige doelen bij gebruik van stikstofbindende gewassen, inkomen, voorkeur, enz.) beïnvloeden in sterke mate de keuze van de kleine boeren voor een bepaalde technologie en dus ook die voor stikstofbindende gewassen. De integratie van al deze factoren in een innovatie proces is van belang voor het identificeren van technologieën, die de potentie hebben om in deze kleine bedrijven te kunnen worden ingepast. Voor deze integratie is het concept van de sociaal-ecologische niche ontwikkeld. Dit concept is een uitbreiding van het ecologische niche concept van een organisme in de klassieke theorie van de ecologie beschreven, en behelst naast biofysische ook sociaal-culturele, economische en institutionele factoren; alle factoren samen kunnen van invloed zijn op de adoptie van een technologie.

De doelstelling van deze studie was het testen van het nut van dit concept door middel van veldproeven bij en enquêtes met boeren. De proeven zijn gedaan in drie verschillende agro-ecologische zones (AEZ) waarin de jaarlijkse regenval afneemt van AEZ1 tot AEZ3. In elke AEZ zijn proeven uitgelegd op velden met verschillende bodemvruchtbaarheid om het effect van deze verschillen op de productie van een serie stikstofbindende gewassen, te bepalen. Deze gewassen kunnen worden geteeld als graan-, voedergewas of als groenbemester. In de proeven zijn de volgende kenmerken van het gewas bepaald: kieming, vestiging en overleven van planten, tolerantie voor ziekten, vorming van wortelknolletjes voor stikstof binding, de biomassa en graanproductie, capaciteit voor stikstof binding, en de netto bijdrage aan stikstof in de grond. Daarnaast is het economische gewin van rotaties bepaald. In deze rotaties wordt het stikstofbindende gewas, geteeld als graangewas of als groenbemester, opgevolgd door maïs. Via enquêtes is bij boeren gepeild wat hun productiedoelen zijn en welke sociaal-culturele, economische en institutionele factoren zij ervaren die van invloed kunnen zijn op hun keuze voor het telen van stikstofbindende gewassen.

Resultaten van de veldproeven geven aan dat regenval en bodemvruchtbaarheid een significante invloed hebben op de productiviteit van stikstofbindende gewassen.

Kieming, vestiging en overleving, tolerantie voor ziekten, vorming van wortelknolletjes voor stikstofbinding en graan- en biomassa productie van de soorten varieerden met regenval en bodemvruchtbaarheid. De prestatie van de stikstofbindende gewassen was in doorsnee beter bij hogere regenval en betere bodemvruchtbaarheid. Aantasting door ziekten was groter in AEZ1 en had een groter effect op de productiviteit dan in de twee andere gebieden. De mate van tolerantie voor ziekteaantasting verschilde significant tussen de soorten en variëteiten. Deze resultaten geven aan dat er mogelijkheden zijn voor selectie van soorten en variëteiten die een grotere potentie voor productiviteit verbetering hebben als rekening wordt gehouden met de verschillen in biofysische factoren. Totale drogestof productie (TDP) varieerde tussen 0.1 Mg ha^{-1} tot 13.9 Mg ha^{-1}, en in doorsnee, produceerden de stikstofbindende gewassen geteeld voor graan minder dan de stikstofbindende gewassen die geteeld worden als groenbemester of voor veevoer. Sojabonen en pinda's, echter, produceerden tot 4.6 Mg ha^{-1} TDP, wat aangeeft dat zij een grote potentie hebben om bij te dragen aan de verbetering van de bodemvruchtbaarheid, aan vervulling van behoefte aan voedsel voor het huishouden en aan contant geld. Ten slotte gaven de resultaten van de veldproeven aan dat de bemesting met fosfor essentieel is voor een goede productie van stikstofbindende gewassen.

Alle stikstofbindende soorten die getest zijn bleken levensvatbare wortelknolletjes met van nature voorkomende rhizobia te vormen waardoor zij atmosferische stikstof konden binden bij de heersende, verschillende, agro-ecologische en bodemvruchtbaarheidcondities. Dit is vooral belangrijk, omdat de infrastructuur voor kunstmatige inenting met rhizobia niet bestaat in West Kenia, net als in de meeste gebieden in Afrika ten zuiden van de Sahara. Uit de resultaten bleek dat alle soorten stikstof binden maar dat de gebonden hoeveelheden verschilden tussen de soorten die graan-, voedergewas of groenbemester zijn. Daardoor verschillen zij ook in hun potentie tot bijdrage aan verbetering van de bodemvruchtbaarheid. In de AEZ1 en 2, binden de soorten tussen 23 en 90% van hun stikstofbehoefte uit de atmosferische stikstof, terwijl dat tussen 7 en 77% ligt in AEZ3. Hoewel de stikstofbinding van groenbemesters beduidend beter was (29-232 kg N ha^{-1}) dan die van stikstofbindende gewassen die als graan worden verbouwd (3-172 kg N ha^{-1}), is het onwaarschijnlijk dat boeren de technologie van groenbemesters zullen gaan toepassen, tenzij deze groenbemesters ook nog een ander bruikbaar product opleveren. Boeren zijn niet *per sé* geïnteresseerd in stikstofbindende gewassen omdat zij de bodemvruchtbaarheid verbeteren. Dit bleek uit de enquêtes waarin boeren konden aangeven waarom zij stikstofbindende gewassen zouden willen verbouwen. Dit betekent dat alleen groenbemesters die voor meerdere doeleinden kunnen worden gebruikt, een potentiële sociaal-ecologische niche kennen in de bedrijfsystemen van kleine boeren. Dit zijn bijvoorbeeld velvet bonen die ook als veevoer kunnen worden gebruikt, of crotelaria die, in het bijzonder in AEZ3, ook als groente wordt gebruikt. Echter, stikstofbindende gewassen geproduceerd voor hun graan hebben een grotere kans om binnen de bedrijfsystemen te passen, omdat zij naast hun waarde als voedsel voor het huishouden ook extra inkomen kunnen generen.

De stikstofbindende gewassen die voor hun graan worden verbouwd, in het bijzonder pinda's, sojabonen en lablab, hebben de potentie in zich om een significante bijdrage te leveren aan de productiviteit van de bedrijven door hun graan productie én hun stikstof bijdrage aan de bodem. Echter, deze stikstofbindende gewassen kunnen alleen een betekenisvolle bijdrage leveren aan de bodemvruchtbaarheid als een goede balans wordt gevonden tussen graanopbrengst en de netto bijdrage van stikstof aan de bodem; de graanopbrengst is negatief gecorreleerd met de netto bijdrage van stikstof aan de bodem. Bijvoorbeeld, de analyse van graanopbrengst en netto bijdrage van stikstof aan de bodem van graanproducerende stikstofbindende gewassen in AEZ1 geeft aan dat gemiddeld 128 kg stikstofbijdrage aan de bodem wordt uitgeruild tegen 1 Mg graan die wordt geoogst. De bijdrage van stikstof aan de bodem wordt negatief als de graanopbrengst meer dan 1 Mg ha^{-1} is. Dit betekent dat hoewel hoogproducerende stikstofbindende graangewassen een voordeel zijn voor boeren, de tweede doelstelling, te weten verbetering van bodemvruchtbaarheid, te niet wordt gedaan en in potentie tot uitputting van de bodem kan leiden.

Het opnemen van een stikstofbindend gewas in de rotatie met maïs leidt tot significante verbetering van het economische profijt, aangevend dat succesvolle integratie van een dergelijk gewas in het bouwplan van deze kleine boerenbedrijven de productiviteit in belangrijke mate kan verbeteren. Echter, dit profijt neemt af met afnemende regenval en slechtere bodemvruchtbaarheid. De maïsproductie over twee seizoenen (het korte en lange regenseizoen in een jaar) neemt met 47% af gaande van AEZ1 naar AEZ3, en met 33% van velden met hoge naar lage bodemvruchtbaarheid. Het economische profijt is daardoor in AEZ3 significant lager, en wordt in die zone zelfs negatief bij de stikstofbindende gewassen die op velden met lage bodemvruchtbaarheid worden geteeld. Hoewel de maïsproductie het hoogst is wanneer in opeenvolgende seizoenen alleen maïs met voldoende bemesting van stikstof en fosfor (kunstmest) wordt verbouwd, is de economische opbrengst uitgedrukt in geld per eenheid land of per eenheid arbeid het grootst als wordt gekozen voor stikstofbindende gewassen geteeld voor graan in rotatie met maïs. In AEZ2, waar gedurende de proeven geen watertekort was, waren de economische opbrengsten voor rotaties van maïs met stikstofbindende gewassen geteeld voor graan 879 US$ ha^{-1}, vergeleken met 533 US$ ha^{-1} voor rotaties met groenbemesters en 459 US$ ha^{-1} voor systemen waarbij maïs (met stikstof en fosfor bemesting) in continue monocultuur wordt verbouwd. Omdat arbeid in de bedrijfsystemen beperkt aanwezig is, zullen technologieën die de arbeidsproductiviteit verhogen een betere kans hebben om te worden geaccepteerd door boeren. De gemiddelde opbrengst per eenheid arbeid voor de rotaties van maïs met stikstofbindende gewassen die graan produceren was 1.69 US$ dag^{-1}, vergeleken met 1.30 US$ dag^{-1} voor rotaties met groenbemesters en 1.26 US$ dag^{-1} voor systemen waarbij maïs als continue monocultuur met stikstof en fosfor kunstmest wordt geteeld. De arbeidsproductiviteit van de laatste twee gewassystemen ligt onder het niveau van het officiële dagloon (1.33 US$ dag^{-1}) dat lokaal wordt betaald.

De studie bevestigt het nut van het concept sociaal-ecologische niche om de biofysische en sociaal-economische factoren die in een technologisch innovatieproces een rol spelen te integreren. In deze studie gaat het om de identificatie van stikstofbindende gewassen die in potentie de productiviteit van bedrijven van kleine boeren kan verbeteren. Regenval, bodemvruchtbaarheid en aantasting door en tolerantie voor ziekten (biofysische factoren), en beschikbaarheid aan land en arbeid, bezit van vee, productiedoelen, markten en de voorkeur van boeren (sociaal-economische factoren) werden geïdentificeerd als de meest bepalende socio-ecologische niche factoren die de keuze bepalen welke stikstofbindende gewassen het beste passen bij welke niches. De analyse van de huidige situatie toont aan dat boeren met weinig middelen voedselonzekerheid kennen door een gebrek aan land en arbeidskrachten. Echter, zij kunnen hun voedselzekerheid in maïs met 21 tot 48% verbeteren en daarnaast nog enig inkomen voor het huishouden generen door de juiste alternatieve stikstofbindende gewassen te kiezen, waarbij dan gebruik wordt gemaakt van het sociaal-ecologische niche concept.

Curriculum vitae

John Okeyo Ojiem was born in Kendu Bay, Kenya, on October 6, 1958. He had his primary and secondary education at Starehe Boys' Centre and School in Nairobi, then joined The Kenya Polytechnic for his Advanced Level Certificate of Education. Upon completion, he was awarded a cultural exchange scholarship to study for a BSc degree in Agriculture at Punjab Agricultural University in Ludhiana, India, graduating in 1984. The following year he joined Kenya Agricultural Research Institute (KARI) and was based at the Regional Research Centre in Embu, eastern Kenya. In 1987 he attended a six-month training in crop management at the International Centre for Maize and Wheat Improvement (CIMMYT) in Mexico, and soon after that, in 1989, received a USAID scholarship to study for MSc degree in Soil Science at Kansas State University, USA. After completing his MSc training, he worked briefly in Embu before being transferred to the Regional Research Centre, Kakamega, in 1993. In 1995 he attended a brief course on the control of parasitic weeds at the University of Hohenheim in Stuttgart, Germany. Between 1995 and 2002, he worked on various projects in western Kenya addressing soil fertility improvement, including the African Highlands Initiative, an eco-regional project on integrated natural resource management, of which he was the Site Coordinator for western Kenya. In August 2002, he joined Wageningen University for PhD training on a scholarship from the Rockefeller Foundation.

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- Enhancing soil productivity in East and Southern Africa. The Rockefeller Foundation (2004)
- Integrated natural resource management in practice. AHI/ICRAF (2004)

Funding

Financial support for this thesis was received from the Rockefeller Foundation through a grant to the author. Additional financial support came from Dr. Judith Zwartz Foundation, and the EU, through AfricaNUANCES**.** The author is grateful to these institutions for their generous support

Cover design and photos by the author.