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Meeting short- and long-term sustainability goals

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9.1   Introduction

The challenges to improving food security and agricultural sustainability in Africa are great and multifaceted. The first green revolution failed in Africa, and roughly 50% of its population has remained in poverty (International Assessment of Agricultural Knowledge, Science and Technology for Development [IAASTD], 2009), despite the considerable resources invested in its implementation. This failure has been attributed to Africa's high agroecological variability, lack of infrastructure and irrigation (Toenniessen et al., 2008), and poor understanding of the important role of socioeconomic and cultural complexity (Sanginga, 2010). As Giller et al. (2010) pointed out, there are no silver bullets for improving agricultural productivity in Africa. For any set of approaches to be effective, it will need to take into account the tremendous diversity of local farming systems in the region and the variation in underlying resources and capacities within and between communities and improve livelihoods to increase nutritional self-sufficiency and reduce poverty. These approaches will also need to be sustainable, that is, to be able to maintain improvements into the foreseeable future.

Despite improvements in many other regions, sub-Saharan Africa has continued to experience a decline in food security and agricultural productivity per capita, leading to an increase in undernourishment since 1990 (Food and Agricultural Organization [FAO], 2006; Toenniessen et al., 2008). Biophysical challenges to food security include production-limiting constraints faced by resource-poor farmers, such as shrinking farm sizes and inequitable land distribution patterns, depleted soils and limited use of fertilizer and soil amendments, unreliable rainfall and lack of irrigation capacity, inadequate pest and disease control, and limited access to improved varieties and seed distribution systems (Diao et al., 2007).

These production challenges for agriculture in Africa are likely to be made even more difficult in the future by the effects of global climate change. Predicted changes for sub-Saharan Africa include increased rainfall variability, more frequent extreme events such as droughts and floods, and increased average temperatures (National Research Council [NRC], 2008; IAASTD, 2009). Only 4% of agricultural land in sub-Saharan Africa is irrigated, which means that more unpredictable rainfall will greatly impact the primarily rain-fed systems throughout the region. Biophysical production constraints are further aggravated by infrastructural issues such as poorly maintained roads and transportation systems, lack of access to regional or international markets, poor or nonexistent access to credit, problems with labor availability, unstable political systems, poor security, and warfare (Diao et al., 2007). Further, a lack of innovation networks and underinvestment by national governments and other institutions in the physical, institutional, and human capital needed to support sustainable agricultural intensification in Africa are widespread (NRC, 2010).

Against this backdrop, there have been a number of multistakeholder, international groups convened to develop strategic approaches to what has been termed either a second green revolution (InterAcademy Council, 2004; Toenniessen et al., 2008; African Green Revolution, 2009) or the sustainable intensification of African agriculture (NRC, 2010; IAASTD, 2009). Members of the African Union have created the Comprehensive Africa Agriculture Development Program (CAADP) to help African countries improve economic growth through agricultural development that "eliminates hunger, reduces poverty and food insecurity, and enables expansion of exports" (African Union Report, 2008). The road maps offered by these organizations vary but include use of improved crop varieties, increasing soil productivity, building more equitable access to input and product markets

(Toenniessen et al., 2008), and adopting new policies that encourage input use by farmers and fair prices for their produce (Sanginga, 2010). Some envisage a tripling of cereal grain yields through the use of inorganic and organic fertilizers and high-yielding crop varieties, farmer education and empowerment, and improved markets (Sanchez, 2010). Others emphasize the need for interdisciplinary and participatory system approaches that recognize the importance of socioeconomic and biophysical context, make effective use of local resources, use well-adapted crop varieties and livestock breeds, and involve judicious use of external inputs when needed (NRC, 2010; IAASTD, 2009).

9.2 Improving soil fertility in sub-Saharan Africa

Improving soil fertility is a central goal for sustainable agriculture in Africa (IAASTD, 2009; NRC, 2010). Although use of improved cultivars that are more productive, drought tolerant, and resistant to pests and diseases is an important intervention, it is clear that poor soil fertility is a major constraint to increased crop productivity (Sanchez, 2010). This has led some to argue that a primary focus on increasing fertilizer use, together with the use of improved crop varieties where possible, is needed to improve yields and livelihoods across many African cropping systems (Vanlauwe et al., 2010; Sanchez, 2010). Others caution that while fertilizer use may be an important component, an overreliance on purchased inputs makes resource-poor farmers vulnerable to what can be wide fluctuations in price and availability, and that high prices put fertilizer out of reach for resource-poor farmers (Denning et al., 2009; NRC, 2010; Sirrine, Shennan, Snapp, et al., 2010; Snapp et al., 2010). Systems that rely on and enhance locally available fertility resources also need to be sought. The reasons for low fertilizer use and the myriad challenges to increasing fertilizer use effectively in Africa, especially among the poorest farmers, were aptly described by Morris et al. (2007). Issues such as low value/cost ratios for fertilizer use, high price instability, high yield response variability, and high costs of or limited access to credit led the authors to suggest that low fertilizer use may in fact be a rational response to managing risk by African farmers (Morris et al., 2007).

Degraded soils are a severe problem in much of sub-Saharan Africa (Bekunda et al., 2010), and significant declines in soil organic matter (SOM) are well documented (Moebius-Clune et al., 2011; Joergensen, 2010; Lal, 2006). A review of organic matter in the tropics as a whole highlighted the lower levels of total soil carbon (C) and nitrogen (N) associated with arable farming as compared to forest and pastures, with even greater differences observed in microbial biomass C and N (Joergensen, 2010). Further, the amount of land converted from forest and savannah to cropland is still increasing in sub-Saharan Africa (Verchot, 2010), a problem exacerbated by degradation of cropland soils.

The loss of SOM affects not only nutrient availability but also other aspects of soil biological and physical functions that often cannot be rectified by use of fertilizers alone. SOM levels have an impact on soil physical structure and hence aggregate stability, water infiltration rates, and water-holding capacity. Indeed, in addition to fertility limitation, poor soil physical structure, reduced resistance to erosion, and reduced drought resistance are thought to be responsible for low crop yields observed in the region (Lal, 2006). Organic matter inputs to soil are also critical for supporting a diverse and active soil microbial community and macrofauna responsible for residue decomposition, carbon turnover, nutrient cycling, and other functions, such as disease and pest suppression (Joergensen, 2010; Akinnifesi et al., 2010; Shennan, 2008). While use of inorganic fertilizers can increase yields, when used alone they may not provide enough crop residue to affect SOM positively. Indeed, a meta-analysis concluded that organic resource additions

were necessary to increase soil organic C in maize-based systems (Chivenge, Vanlauwe, and J. Six, 2011).

There is an increasing recognition that integrated use of inorganic fertilizer together with technologies to improve SOM (such as use of legumes as cover crops, relay crops, managed fallows and other agroforestry (AF) systems, and recycling of manure and composts) may hold the greatest potential for both short-term livelihood gains and longer-term soil fertility improvements (Sileshi et al., 2008; Sanchez, 2010; Snapp et al., 1998, 2010; Vanlauwe et al., 2010; Bekunda et al., 2010; Chivenge, Vanlauwe, and J. Six, 2011). Integrated soil fertility management (ISFM) is now being widely promoted and can be defined as "a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs and improved germplasm, combined with the knowledge of how to adapt these practices to local conditions aimed at maximizing agronomic use efficiency of applied nutrients and improving crop productivity" (Vanlauwe et al., 2010, p. 17). In essence, this approach encompasses the use of any of the organic matter technologies listed, in conjunction with supplemental fertilizer, depending on the specific characteristics of the area. Conservation agriculture is also being promoted as a means to improve SOM levels and crop productivity, which brings in the added dimension of reduced tillage along with maintenance of permanent soil cover (by crop residues and cover crops) and diversified crop rotations or plant associations, including legumes (Meyer, 2009). This approach is proving to be successful in many regions globally, including sub-Saharan Africa (European Technology Assessment Group, 2009; Naudin et al., 2010), but there are challenges in some areas related to soil conditions, competing uses for crop residues, labor requirements for weeding, and access to herbicides (Gowing and Palmer, 2008; Giller et al., 2009).

9.3   *Legume-based systems*

To what extent can these various integrated approaches and organic matter technologies improve SOM levels, soil structure, and soil biology and thus sustainably support higher crop yields over the long term? Here, we focus on annual cropping system diversification with legumes and highlight important findings and areas needing more research, rather than attempt an extensive review of the literature. Various types of legume systems are being promoted for improved soil fertility and crop production in different contexts. These include improved fallows, AF, rotation, green manures, and intercropping systems (Akinnifesi et al., 2010). Most reviews of legume strategies emphasize the evidence for increased crop yields relative to current farmer practice.

A recent meta-analysis of 94 studies involving legumes concluded overwhelmingly that the response to legumes is positive, often resulting in two- to threefold yield increases in low to moderate-yielding sites (Sileshi et al., 2008). Addition of 50% of the recommended fertilizer dose further increased yields by more than 25% over legumes alone, indicating that legumes can significantly reduce fertilizer requirements. In a large on-farm trial in Malawi, Snapp et al. (2010) also demonstrated the benefits of diversification of cropping systems, with legumes combined with half the recommended fertilizer rates producing equivalent yields to fully fertilized monoculture systems and with lower yield variability. Similar conclusions of improved yields and reduced fertilizer requirements were reached in a review of the effects of various systems that incorporated leguminous trees and shrubs in maize systems of eastern and southern Africa (Akinnifesi et al., 2010).

There is a variety of mechanisms by which legumes can potentially improve crop production. These include increased N provision through biological nitrogen fixation (BNF), recycling of nutrients from deeper in the soil profile, improved soil structure and physical

properties due to increased organic matter inputs, and improved soil biological activity with associated increased nutrient availability and in some cases via enhanced disease or pest suppression (Akinnifesi et al., 2010; Franke et al., 2008).

BNF contributions vary considerably among species, growth habit, and by location, but amounts as high as 300 kg N ha^{-1} have been measured for some tree legumes (*Leucaena colinsii*) and in the range of 35–150 kg N ha^{-1} for shrubby species like fish bean (*Tephrosia vogellii*), common sesban or river bean (*Sesbania sesban*), and pigeon pea (*Cajanus cajan*) (Akinnifesi et al., 2010; Adu-Gyamfi et al., 2007). There is considerable variation in BNF and legume productivity from site to site, which can be related to soil nutrient limitations, especially P availability, water stress, or lack of appropriate or sufficient indigenous rhizobium inoculant (Bekunda et al., 2010). An assessment of indigenous soil rhizobia in eastern and southern Africa found that many soils had low populations and may benefit from the addition of inoculant, but inoculant use is presently low in the region (Bekunda et al., 2010). Some work suggests that inoculation with indigenous rhizobia can be more beneficial than with exotic strains (Makatiani and Odee, 2007), and that combined inoculation with arbuscular mycorrhiza (AM) (Mishra, 2008; Singh, 1996; Sekhon et al., 1992) or with endosphere bacteria (Rajendran et al., 2008) can improve nodulation and BNF compared to rhizobial inoculation alone. There clearly remains significant potential for improvement of legume growth and BNF to improve poor-quality soils through addition of appropriate fertility amendments or microbial inoculants.

While much of the crop response to legumes can be attributed to increased N supply, other effects may also be important (Franke et al., 2008; Yusuf et al., 2009). It is widely agreed that the use of legumes is an important strategy to help maintain soil quality (Lal, 2009; Akinnifesi et al., 2010; Bationo et al., 2007), but relatively few studies in the published literature have investigated changes in SOM or physical and biological properties directly. In some cases, integration of legumes was found to increase total soil C when used as intercrops (Beedy et al., 2010; Bationo and Buerkert, 2001), as improved fallows (Nyamadzawo et al., 2009; Bossio et al., 2005), or as cover crops (Barthes et al., 2004); others found that incorporation of high-quality legume biomass led to a decline in soil C, but less than when fertilizer was used alone or in the no input control (Mugwe et al., 2009). In another study, rotation with legumes did not affect total soil C after 2 years relative to continuous maize, but total soil N was increased by 23% and water-soluble carbon was increased by 79–106%, depending on the species and cultivar of legume used (Yusuf et al., 2009).

Snapp and Pound (2008) have argued that in some land-limited systems improvements in total soil C may not be observed given the relatively low levels of residue input possible with intercropping or relay intercropping, as compared with managed fallow or use of green manures. Instead, they asserted that it is more important to assess effects on nutrient availability mediated through changes in labile pools of soil C and N, microbial activity, and recycling of nutrients from deeper in the soil profile. Various measures of labile C and N pools provide indicators of readily available sources of nutrients for microbial activity and food sources for soil fauna, such as particulate organic matter (POM), microbial carbohydrates involved in aggregate formation (C extractable with hot water), nonspecific labile pools (permanaganate oxidizable), soil N supply capacity (N mineralization), and microbial biomass and activity, which provide a measure of cycling of organic matter and nutrients (Haynes, 2008). These measures can provide more sensitive indications of management impacts that relate to both nutrient cycling and improved soil physical properties.

There is some evidence that labile soil C pools are increased by legumes. For example, a gliricidia/maize intercrop increased POM more than total SOM and enriched the POM with N relative to maize alone (Beedy et al., 2010). Similarly, high-quality legume residue

incorporation increased labile C (measured as potassium permanaganate oxidizable) and mineralizable N in POM in a manner equivalent to manure application (Mtambanengwe and Mapfumo, 2008). In another study, total soil C, microbial biomass C (MBC), soil C mineralization, and soil-specific respiration were all higher in legume-treated soils, although the difference in MBC was not statistically significant (Kone et al., 2008). Total microbial biomass increased with legume fallows relative to continuous maize (Nyamadzawo et al., 2009; Bossio et al., 2005), and 16S ribosomal RNA (rRNA) gene and phospholipid fatty acid (PLFA) analysis demonstrated that shifts in the microbial community structure also occurred (Bossio et al., 2005). Seasonal changes in microbial biomass C and N and crop N uptake led Sugihara et al. (2010) to conclude that soil microbes serve as an important N source for crop growth during the grain-forming stage in dry tropical cropland in Tanzania.

The effect of residue incorporation on changes in soil C and N pools is complex and depends in part on soil and residue properties. In a clayey soil, adding organic residues, irrespective of quality, increased total soil C and N as well as macroaggregates, whereas residue inputs had little effect in a loamy, sandy soil (Gentile et al., 2010). Conversely, another study found that in a sandy soil a medium-quality residue (higher polyphenol content) led to greater amounts of residue-derived N being found in coarse POM as compared to high-quality residue (Chivenge, Vanlauwe, Gentile, et al., 2011), yet residue quality had no effect on C pools in a clayey soil in the same study. The reason for these differences across soil types is unclear. Also, soil quality measured as MBC and available P improved more rapidly at a higher-fertility site with cover crop use than when cover crops were used at a lower-fertility location (Kone et al., 2008b).

Even when there is no effect of residue quality on long-term soil C accumulation, it may affect short-term C and N release dynamics and hence synchrony between N release and crop demand. Another study found that residue quality did not affect long-term soil C accumulation, but it did affect short-term C and N release dynamics and interactions with fertilizer additions (Gentile et al., 2011). The combination of fertilizer and low-quality residue immobilized more fertilizer N than with a high-quality residue. Under field conditions, this temporary immobilization actually reduced N losses and led to a positive effect on crop N uptake (Gentile et al., 2011). Nitrogen mineralization rates are known to vary among legume residues of different qualities, with polyphenol content and N content being the major properties controlling N release (Baijukya et al., 2006). Improved understanding of seasonal dynamics of mineralization, microbial populations, and changes in labile pools of C and N, associated with incorporation of legume residues of different qualities and fertilizer use, is needed to enhance synchrony between nutrient availability and crop demand.

More work is also needed to relate changes in different SOM fractions and microbial populations noted to key soil physical properties, such as improved aggregate stability and reduced crusting, that are important for reducing soil erosion. Some work has shown improvements in water infiltration rates (Nyamadzawo et al., 2007), reduced bulk density, and improved aggregate stability (Sileshi and Mafongoya, 2006) following improved legume fallows, but little information is available for other systems.

While most research has focused on C and N dynamics, some studies have shown benefits of legume incorporation on crop growth and P uptake (Pypers et al., 2007; Akinnifesi et al., 2007; Alvey et al., 2001). This may be due to increased microbial mineralization of soil organic P (Randhawa et al., 2005), solubilization of inorganic P fixed by iron (Fe) and aluminum (Al) in the soil (Mweta et al., 2007), stimulation of AM infection (Bagayoko et al., 2000), or a combination of effects (Alvey et al., 2001). Given the low P status of many African soils, the effects of long-term legume use on P fertility warrant further study.

It is interesting to note that fields classified by farmers as productive versus poor differed in many of the same measures as discussed, with productive soils having higher total C and N, labile C, microbial biomass C and N, N mineralization, and soil respiration, as well as increased effective cation exchange capacity, exchangeable cations, and extractable P (Murage et al., 2000). By preferentially applying residues, manures, or fertilizers to their most productive fields, farmers ensured that at least some of their land had good SOM and fertility levels (Mtambanengwe and Mapfumo, 2008).

Clearly, legumes can have many beneficial impacts on soil quality, in large part by impacting nutrient cycling through soil microbial populations, but legume BNF and productivity are often suboptimal due to soil fertility or other limitations. There is considerable interest in whether soil microbial populations can be altered to enhance different functions such as BNF, or increase P availability, through the addition of beneficial bacteria or fungi. A publication summarized the current state of use of microbial soil amendments or biofertilizers in the tropics (Uribe et al., 2010). Most of the work on biofertilizers has focused on Latin America and Asia, with relatively few studies in Africa. The main types of materials being developed are inoculants of symbiotic BNF bacteria (rhizobia), nonsymbiotic BNF bacteria, phosphorus-solubilizing bacteria (Yarzabal, 2010), and AM fungi. All have had success in increasing yields of various crops in experimental trials but suffered from variable performance in field situations for a variety of possible reasons.

Challenges remain in the production of high-quality, low-cost inoculants, as well as a lack of understanding of species- and site-specific effects. These can include inoculant survival issues, competition from indigenous microorganisms, soil type and fertility effects, and differential interactions based on crop species and varieties. From the discussion, however, given the importance of legumes for helping improve African soils that are degraded and with low organic matter, further research on biofertilizers is warranted. One example of a product developed in Africa is PREP PAC, an inexpensive mix of urea, rock phosphate, legume seeds, and rhizobium, which is being tested in participatory on-farm trials (Okalebo et al., 2006).

9.4 A conceptual framework for assessing relative sustainability of production systems

In all probability, increased use of fertilizers, legumes, AF, ISFM, conservation agriculture, improved seed, and crop/livestock integration will all play a role in improving food production and soil quality in Africa (NRC, 2010), but no single technology package is likely to be broadly applicable across the diversity of systems in the region. Rather, it can be argued that a systems approach with interdisciplinary research that is participatory and grounded in the local context and needs is required to develop locally appropriate and sustainable solutions (NRC, 2010; InterAcademy Council, 2004; Pretty, 2008; IAASTD, 2009; Snapp and Pound, 2008). To identify what are the most locally appropriate and sustainable systems among different options requires us to think about how we assess "appropriateness" and sustainability.

Gains in agricultural production must be sustained into the future, yet what is involved in creating sustainable systems and what makes a system sustainable are complex questions that merit critical exploration. It is not simply about increasing yields; agricultural sustainability also encompasses other considerations, such as longer-term impacts on the environment and resource base (especially soil), as well as on farmers' livelihoods. As discussed in the NRC report *Sustainable Agricultural Systems in the 21st Century* (NRC, 2010),

agricultural sustainability is a complex concept that involves meeting broadly agreed-on societal goals into the future. Achieving these goals will require systems that are adequately productive; that use resources efficiently and protect or enhance the resource base; and importantly, that demonstrate robustness in the face of fluctuating conditions and unpredictable shocks (NRC, 2010).

Overarching sustainability goals revolve around the need to satisfy human food and fiber needs (in terms of amount and accessibility), while protecting or enhancing the resource base and surrounding environments and providing viable livelihoods and a good quality of life for farming communities (NRC, 2010). More specific goals are embedded within each of these general ones, and the relative importance given to each will vary depending on the system in question and the social context within which the system is embedded. For example, it can be argued that questions regarding the sustainability of contemporary agricultural systems in the United States and other developed countries have arisen in large part due to concerns about negative impacts of agricultural inputs on the environment, whereas primary questions of sustainability in sub-Saharan Africa revolve around the ability to produce sufficient and accessible food to alleviate hunger and poverty and regenerate degraded soils. Thus, while there is ultimately a need to balance each of the goals for long-term sustainability, in the more immediate term one goal may be given higher priority than another depending on the specific context.

The question of who decides the specific goals and priorities is critical since many parties have vested interests in agricultural sustainability and yet likely vary in the relative weight they place on different goals. As scientists, we cannot answer the question of what the goals and priorities should be; this is fundamentally a "social choice" that needs to be arrived at through negotiation and political process (NRC, 2010). In the case of Africa, this point is reflected in calls for African countries themselves to take the lead in development efforts to improve food production and sustainability (Interacademy Council, 2004; African Union Report, 2008; Flora, 2010) and for farmer voices to be heard in setting research agendas (African Farmers Organization, 2009).

What scientists can and must do is to inform this process of negotiation and decision making by providing answers to the "what is" and "what if" questions; that is, given what is known about the status quo, what are the likely outcomes and effects of choosing certain specific interventions over others? Investigations by agricultural researchers of the impacts of legumes, manure application, and fertilizers on crop yields, soil nutrients, and microbial communities address reasonable topics . However, to answer what-if types of questions most effectively, attention must be given to the socioeconomic and cultural context of systems being targeted and the needs and desires of the farm households in the region. These contextual factors will also determine sustainability outcomes and impacts of the different systems being tested. Further, consideration of context will increase the likelihood that any technologies or knowledge developed will be appropriate and meet the needs of farmers, be feasible given their circumstances, and thus be more likely to be adopted and adapted by farmers. Accomplishing this requires integration of different disciplinary approaches and a close connection with and participation of key stakeholders.

9.4.1   The importance of the time dimension

At a practical level, we suggest that the sustainability of existing or proposed agricultural systems is determined by their ability to meet immediate livelihood needs, provide reasonable stability in performance from year to year, and over the longer term to maintain or

improve the natural resource base on which the system depends. There is often a trade-off between maximizing immediate livelihood benefits and conserving or enhancing the soil resource (Bezner Kerr et al., 2007), yet to be sustainable over the longer term, the cropping systems must at least maintain or ideally improve soil fertility and quality. Resource-poor farmers may be more likely to adopt cropping systems that benefit them both immediately and consistently (i.e., show improved yields, income, or food supply and involve less risk on a year-to-year basis), however, rather than systems that are most optimal for long-term fertility improvement.

Thus, we suggest that the most sustainable cropping systems are likely to represent a compromise between short- and medium-term benefits to farmers' livelihoods and long-term maintenance or improvement of the natural resource base, as Ashby et al. (1996) also observed. Stoorvogel et al. (2004) discussed the trade-offs between desirable traits associated with agricultural systems that operate over various time and spatial scales and have employed trade-off analysis models to investigate environmental and economic impacts. We propose that the trade-offs between goals operating at different time frames will be based on unique local socioeconomic, cultural, and biophysical parameters, which emphasizes the importance of performing locally relevant research.

9.4.2 Socioeconomic variability, vulnerability, and distributional impacts

It is important to recognize that specific trade-offs (and their extent) are likely to vary among households within communities based on factors such as differential economic endowments and landholding sizes, location of landholdings (biophysical context), and even within households based on factors such as gender, age, and health status. For example, a system that improves yields but requires more labor may be of value only to wealthier farmers. Researchers have placed increasing emphasis on understanding the role of *social* vulnerability in risk-based analyses (e.g., Kelly and Adger, 2000; Wisner et al., 2004). While much of the research has focused on the impacts on climate change, hazards may also result from new technologies that have a potential to cause social, infrastructural, or environmental change (Oliver-Smith and Hoffman, 2002).

The sustainable livelihoods framework (Chambers and Conway, 1992; Department for International Development [DFID], 2001) emphasizes the importance of addressing vulnerability, defined as both the exposure to shocks, risk, and stress and the inability to cope without experiencing hardship. Vulnerability thus encompasses but looks beyond income-poverty, a concept typically quantified by per-capita wealth generation in that it considers individuals' security and well-being based on locally relevant, complex, and multidimensional factors (Chambers, 1995). Important factors include biophysical vulnerability based on risks related to soil type, slope, and landscape position, for example, and social vulnerability that relates to poverty, access to and dependency on purchased resources, diversity of income sources, and the social status of individuals or households within a community (Adger, 1999). As the risk introduced by new agricultural systems will likely vary based on farmers' socioeconomic resources and degrees of vulnerability, vulnerability-based analyses may help researchers determine the distributional impacts of new cropping systems among different community members. In fact, distributional economic analyses (Von Braun, 2003) have frequently determined that new agricultural technologies are most profitable, and at times only profitable, for better-resourced farmers, while fewer benefits have been realized for women and poor farmers. Sustainability assessments would therefore be improved by distributional analyses of cropping system impacts.

In summary, we argue for a framework in which sustainability is assessed as the ability to meet a balance of immediate-term livelihood needs, acceptable food/income stability from year to year, and longer-term soil fertility improvement. Further, relative sustainability of different management strategies should be addressed in a distributional manner, that is, considering the variability in biophysical and socioeconomic resource endowments and vulnerability of different households. We illustrate this framework using data from an on-farm study in southern Malawi. Maize legume relay intercrop systems were being promoted as potential strategies for improving both short-term productivity and livelihoods while simultaneously helping to rebuild SOM in systems where land was limited (Chirwa et al., 2006; Snapp et al., 1998). The project compared the performance of different fertilizer and maize/legume relay intercrop systems established across a regionally representative range of smallholder farms.

9.5   Case study: legume maize relay cropping in Southern Malawi

Here, we use the conceptual framework developed in a case study from southern Malawi to illustrate a model for interdisciplinary and participatory research examining the relative sustainability of different maize/legume relay cropping systems. Sustainability is considered in terms of immediate-term livelihood benefits (crop yields, net income, and secondary food or income provision), stability (risk of low yields over time and space), evidence of potential and actual adoption of the system, and longer-term soil fertility impacts. Our analysis also addresses the implications of distributional impacts (among different socioeconomic groups, genders, and landscape positions) on the relative performance and desirability of the different cropping systems.

9.5.1   Study location and farmer selection

Malawi is a small, landlocked country in southern Africa with high levels of poverty and a history of chronic food insecurity (Chinsinga, 2005). Smallholder farmers comprise 85% of the population, and maize, the staple crop, is planted to roughly 85% of arable agricultural lands (Smale and Heisey, 1997). Southern Malawi is the most impoverished region in Malawi and has high population density, limited landholdings (National Economic Council [NEC], 2000), and few livestock.

The study was an on-farm, farmer-/researcher-designed and managed project initiated by researchers at the University of Malawi's Bunda College of Agriculture in 1994 and continued with our participation through 2004. Participating farmers were located in villages within the Songani watershed, located approximately 15–20 km north of Zomba in southern Malawi. This region is subject to a unimodal rainfall pattern, with the wet season occurring between October and May. Average annual rainfall in the study area is 1,150 mm (Kamanga et al., 1999). The soils are mainly classified as alfisols and ultisols (Eswaran et al., 1996). They are typically well-drained loamy sands, with N as the most limiting nutrient (Snapp, 1998). Since agriculture has increasingly spread onto hillsides and steep slopes in this region (Banda et al., 1994), our research included farmers with plots at three different landscapes: (1) dambo (less than 12% slope and poorly drained), (2) dambo margin (less than 12% slope and well drained), and (3) hillside (greater than 12% slope) (Kamanga et al., 1999).

Forty-eight farm families, or households, were recruited for the initial project, selected at random along six transects spaced 0.6 km apart. Eight households were no longer participating in the project by 2004, and six other participants were either too old or ill to consistently participate in all components of the socioeconomic data collection. The ethnicity of participating farmers was predominantly Yao, with a minority from Chewa and Ngoni ethnic groups. Forty-one percent of the households participating in the socioeconomic analyses were female-headed households (FHHs), defined as households where women were divorced, widowed, or separated from their husbands (Bezner Kerr, 2005).

9.5.2   Legume species

Prior to the project's initiation, University of Malawi, Bunda College of Agriculture researchers held community meetings to ascertain farmers' assessments of local agricultural constraints and opportunities. Soil fertility concerns predominated, and given high fertilizer prices at the time, limited landholding sizes in the region, and the lack of access to livestock manure, relay cropping of deep-rooted N-fixing legumes alongside maize was identified as a research priority. All three AF species in this study are short-lived deciduous shrubs of the family Leguminosae. *Sesbania sesban* generally grows between 4 and 8 m tall, while *Tephrosia vogelii* and pigeon pea (*Cajanus cajan*) are typically 1.3–3 m tall (Bunderson et al., 1995). Both *T. vogelii* and pigeon pea were cultivated in southern Malawi prior to the project's inception. Pigeon pea is also a perennial grain legume, and the seed is eaten to provide an important secondary protein source (Snapp, Blackie, et al., 2003). Pigeon pea is the most common intercrop with maize in southern Malawi (Chirwa et al., 2003). Farmers traditionally incorporated pigeon pea leafy biomass after the leaves had senesced and fallen, but researchers also incorporated any fresh leafy biomass that remained on the legume plants into the soil, leaving the woody portion to be used as fuel wood at farmers' request. *T. vogelii* contains a toxic compound called *tephrosin* and historically was used to poison fish for consumption but had not previously been used as a green manure. The farmers also had no prior experience cultivating *S. sesban*, but researchers chose to include it in the study because it produces large amounts of biomass, and the leaves can be used as green manure. The woody portions of all three legumes were used by farmers as fuel wood.

9.5.3   Experimental design and management

The project encompassed two distinct experimental designs: design 1 (D1) from 1995 to 2000 and design 2 (D2) from 2001 to 2004 (Figure 9.1). The designs primarily differed in the rate and timing of inorganic fertilizer application. In 1995, four rain-fed plots were established within each participating farmer's field; plots remained fixed in the same location and position for the remainder of the project. At the onset of rains (typically in late October or November), a maize hybrid was planted in each of the four plots and harvested the following year. As is traditional in Malawi, three maize seeds were sown together, in planting stations 90 cm apart on ridges also 90 cm apart. The legume species were planted directly between maize stations. *T. vogelii* and pigeon pea seeds were each relay cropped into one of the four plots within 2 weeks of maize planting, whereas due to a very low seed germination rate, *S. sesban* seedlings were grown in a nursery and transplanted into the third plot roughly 2 months after planting maize, one plant between each maize station. The fourth plot served as the maize-only control; however, farmers generally intercropped some plants in these plots.

Phase 1: 1999-2001		Phase 2: 2003-2004		
1) MZ+F	3) SS+F	1) MZ+F	2) SS+ 1/2FF	5) MZ-F
2) MZ-F	4) SS-F			
5) TV+F	7) PP+F	3) TV+ 1/2FF	4) PP+ 1/2FF	
6) TV-F	8) PP-F			

Figure 9.1 Project designs 1 (phase 1) and 2 (phase 2). Phase 1 treatments: (1) maize control plus full fertilizer (MZ+F); (2) maize control without fertilizer (MZ-F); (3) maize intercropped with *S. sesban* plus full fertilizer (SS+F); (4) maize intercropped with *S. sesban* without fertilizer (SS-F); (5) maize intercropped with *T. vogelii* plus full fertilizer (TV+F); (6) maize intercropped with *T. vogelii* without fertilizer (TV-F); (7) maize intercropped with pigeon pea plus full fertilizer (PP+F); and (8) maize intercropped with pigeon pea without fertilizer (PP-F). Phase 2 treatments: (1) maize plus full fertilizer (MZ+F); (2) maize intercropped with *S. sesban* plus the second fertilizer application (SS+1/2F); (3) maize intercropped with *T. vogelii* plus the second fertilizer application (TV+1/2F); (4) maize intercropped with pigeon pea plus the second fertilizer application (PP+1/2F); and (5) maize receiving no fertilizer (MZ-F). When sampling for phase 2, we always sampled from the center of the plot. In this way, we averaged the variation between previously fertilized and unfertilized plots.

During D1, one-half of each plot received an inorganic fertilizer treatment at a rate of 45 kg N ha^{-1} (see Figure 9.1 for cropping system abbreviations). As is typical for the region, fertilizer was applied twice during the cropping cycle: one-half at maize planting (formulated as 23N:21P:0K and 4S) and the other half as a side-dress of calcium ammonium nitrate when maize was roughly 60 cm in height. For D2, the experimental design was modified to determine if legumes could replace the first inorganic fertilizer application. At the time, few farmers were able to afford the full recommended rate of fertilizer as used in D1. Thus, in 2001 new treatments were superimposed over the same plots previously used; each legume treatment remained in the same location, but the plots were no longer split (Figure 9.1). The three legume systems did not receive the first inorganic fertilizer application, but each still received the second fertilizer application (22.5 kg N ha^{-1}). The entire maize control plot received the full rate of fertilizer (45 kg N ha^{-1}) at the two standard application timings. A fifth plot, MZ-F, was added at each farmer's field as the untreated control with maize alone. Based on this design, there was no true control to determine the impact of legumes versus fertilizer. Legume systems (SS+1/2F, TV+1/2F, and PP+1/2F) could only be compared to one another and again unfertilized or fertilized maize controls. Data from the 2001/2002 cropping cycle were not included in the analysis due to the recent change in the experimental design.

To fit within smallholder farming systems and minimize competition with maize, the perennial legume species were annually replanted. For both designs, nonwoody portions of the legumes were cut and incorporated into the soil, typically in late September or early October. Researchers applied fertilizer, provided much of the labor related to legumes (sowing, transplanting, and incorporation), and harvested maize from subplots. While this was done to ensure uniform management, it would have been preferable in retrospect to have farmers directly involved in these activities (see further discussion). Farmers performed land preparation, sowed maize, weeded, and harvested maize outside the experimental subplots. D1 data were collected by researchers at the University of Malawi, Bunda

College of Agriculture and are used here with permission from Dr. Kanyama-Phiri. D2 data were collected by us and local assistants employed by Bunda College of Agriculture for the complete duration of the project.

9.5.4   Maize yields

Mature maize was harvested from subplots at the center of each plot. For D1, grain yields were taken when plants had dried in the field, and 12% moisture content was assumed for the grain (Kamanga et al., 1999). For D2, we harvested maize slightly earlier as per farmers' requests and therefore calculated the actual dry weight based on a subsample of the fresh material. Although the study began in 1995, we only present phase 1 data from the 1999 and 2000 maize harvests and phase 2 data from the 2003 and 2004 maize harvests since these were years with the most complete data sets and greatest number of replicates available. Also, 2001–2002 was a transition period between the two designs. Maize yield data, as well as other forms of data, were not available for all farms in any given year for a variety of reasons. For instance, many farmers harvested maize early due to concerns of crop theft from their fields, and sometimes fields had been set ablaze by youth trying to capture mice as a protein source. Occasionally, some farmers applied small quantities of fertilizer in unknown quantities, precluding their inclusion in the analysis. These kinds of problems are to be expected in on-farm participatory work with resource-limited farmers, and we acknowledge that this poses challenges for data analysis. The resulting unbalanced data structure was considered throughout our statistical analyses in both our choice of methods and in evaluating the assumptions for each test. Data are presented for 29 farmers in 1999, 28 in 2000, 21 in 2003, and 14 in 2004. For each design, maize yields were evaluated using two-way analyses of variance (ANOVAs) (*$P < 0.05$), with cropping system and year as the main factors and maize yield as the response variable. For both D1 and D2, Tukey's post hoc tests (*$P < 0.05$) were employed to compare treatments.

9.5.5   Soil analysis

Soil was sampled from each treatment with the exception of D1 legume treatments receiving full fertilizer (the latter were not collected due to a variety of logistical constraints). A composite soil sample of six subsamples was collected from 0 to 10 cm depth in 1994 (prior to the establishment of treatments), 2000, and 2004. Soils were air dried, passed through a 2-mm sieve, and analyzed for pH, extractable Bray-P (Diamond, 1995), and percentage total C and percentage total N using a Carlo Erba 1108 elemental analyzer (Smith and Tabatabai, 2003). Soil data were analyzed from a subset of 12 farmers, balanced across the three landscapes. The same set of farmers was used for 1994, 2000, and 2004.

9.5.6   Maize foliar analysis

Foliar tissue testing was performed for D2 years 2003 and 2004. Samples were collected using a composite of 12 ear-leaf blades located immediately above the primary ear node (Jones and Eck, 1973) when maize was at peak tassel. They were then analyzed for percentage C, N, and S (Smith and Tabatabai, 2003) using high-temperature dry combustion. Foliar percentage P was determined using a nitric acid/hydrogen peroxide microwave digestion and analysis by inductively coupled plasma atomic emission spectrometry (Meyer and Keliher, 1992). Maize foliar data were collected from 21 farmers in 2003 and 12 farmers in 2004.

9.5.7 *Legume biomass and tissue analysis*

We did not collect D1 legume biomass data but determined D2 legume biomass by harvesting from a 5×5-mm subplot at the time of incorporation, which was October 2002 and ran from August to September in 2003 (the timing was changed due to farmers' requests). Foliar legume tissue samples, collected at time of incorporation, included a composite of green leafy materials from 12 plants. They were dried, ground, and analyzed for percentage N as described previously for maize foliar samples. Legume biomass data were collected from 13 farmers in 2002 and 17 farmers in 2003.

To determine the impact of legume treatments and landscapes, we performed separate two-way ANOVAs ($*P < 0.05$) using the following dependent variables: pH, extractable P, soil percentage C, soil percentage N, legume biomass, maize foliar percentage N, maize foliar percentage S, and maize foliar percentage P. Legume treatment and landscape were the two independent factors. Total N input was calculated by combining organic legume-based N contribution (legume biomass × legume foliar percentage N), when present, and inorganic N quantities. We were unable to transform total N input to achieve normality or homogeneity of variance and therefore could not perform ANOVAs. Instead, we performed nonparametric median tests for the independent variable cropping system ($*P < 0.05$) (Norušis, 2003).

9.5.8 *Economic analysis*

We performed a distributional cost-benefit analysis for the cropping systems in which we separately investigated costs and benefits for the wealthiest and poorest farmers because their marketing strategies varied substantially (see Sirrine, Shennan, Snapp, et al., 2010, for detailed methods). While wealthier and very impoverished farmers typically sell proportionally similar quantities of maize (10% of their yields), wealthier farmers often retain their maize to sell when prices are high, and highly impoverished farmers, in need of cash after the hungry season, generally sell when prices are low (Center for Regional Agricultural Trade Expansion Support [RATES], 2003; Peters, 2006). Due to substantial intra- and interannual fluctuations in costs and benefits (Sirrine, Shennan, Snapp, et al., 2010), we evaluated profitability separately for the two different design years. We were unable to present cost-benefit data for middle-income farmers because their marketing strategies were less well defined. Crop prices and input and labor costs used to estimate profitability can be found in the work of Sirrine, Shennan, Snapp, et al. (2010).

The methods for our participatory wealth-ranking exercise are described in detail in the work of Sirrine, Shennan, Snapp, et al. (2010). Briefly, farmers were placed into socioeconomic categories using a participatory wealth-ranking method described and validated by Adams et al. (1997), in which a few community members helped researchers place farmers into one of three categories: wealthiest, middle-income bracket, and poorest. Farmers were placed into these categories based on wealth and vulnerability indicators specific to the region, including selling their own labor (*ganyu*), hiring casual labor, ability to afford fertilizer, food availability throughout the year, and landholding size, among others. Indicators were chosen based on both locally based literature (e.g., Ellis, 1998) and key community members' perceptions. We later verified whether farmers had been placed in correct categories through household visits and interviews.

9.5.9   Socioeconomic data collection and analysis

Socioeconomic data were collected through farmer interviews and focus groups. For detailed methods, see the work of Sirrine, Shennan, and Sirrine (2010). Briefly, semiformal farmer interviews were carried out in 2001 to obtain demographic data and farmers' experience with the legumes and in 2003 to obtain farmers' assessments of the legume systems. For the latter, we then solicited information on farmers' preferred legume system(s) and farmers' perceptions of the legume systems' labor requirements, secondary benefits, impacts on food security, biophysical performance, and variability. Husbands and wives were interviewed separately for both interviews. From the 34 farm households still participating, 47 individual farmers were interviewed in 2001 and 51 in 2003, which represented 87% and 94% of the potential study population, respectively.

Adoption surveys were also performed in 2001 and 2003 to collect information on legume system adoption in farmers' fields. We carried out 34 surveys in 2001, interviewing husbands and wives together since they generally farm the same plots of land. In 2003, the adoption survey was combined with the preference survey; thus, we interviewed 51 farmers. Although heads of households were interviewed separately, data were only reported for each household. The first adoption survey also requested farmers to recall on-farm presence of any of the three legume species prior to the inception of the project's experimental phase in 1995. We analyzed legume system adoption and intensity of cropping chronologically using farmer recall for 1994 and actual adoption results for 2001 and 2003.

In 2004, we held four focus groups that included five to nine farmers each with the dual purpose of informing farmers of the research results and to obtain further insights into cropping system impacts on livelihoods. The composition of the focus groups was reflective of the overall population of farmers participating in the project and included men, women, FHHs, and a range of poor to wealthier farmers. Following the focus groups, we also held a training session focused on legume management.

9.6   Case study results and discussion

When averaged across all landscapes for D1, the highest yields were obtained in all treatments receiving inorganic fertilizer (F) (Table 9.1), with a consistent, but nonsignificant, trend toward higher average yields when legumes were present, especially *S. sesban*. In general, yields were lowest on the hillside and highest in the dambo margin, with similar patterns of response to fertilizer and legume treatments. Legume treatment differences were not significant, however, on the hillside, whereas they were in the dambo and dambo margin (Figure 9.2). In the last cases, the legumes with fertilizer treatment yields were all significantly higher than the unfertilized control, with the maize with fertilizer and legume-only treatment yields between the unfertilized control and the fertilized legumes. D1 and D2 fertilized maize control yields (Table 9.1) were substantially higher than those found by Harawa et al. (2006), Kamanaga, Waddington, et al. (2010), and Snapp et al. (2010) from other on-farm research trials in Malawi; but unfertilized maize yields from D2 were similar. Maize yields were found to increase by between 0.2 and 4 ton ha^{-1} when legumes were introduced in a similar study (Kamanga, Waddington, et al., 2010), which is in line with the increases observed in this study. Snapp et al. (2010) also observed improved fertilizer response with long-lived legumes, such as pigeon pea and *Tephrosia*, as was seen in D1 here.

Table 9.1 Mean Maize Yields and Profitability by Cropping System and Wealth Group

Cropping system	Mean maize yield (kg/ha)[1]	Wealth group[2]	Mean yield by wealth group: 1999 (kg/ha)[3]	Mean yield by wealth group: 2000 (kg/ha)[3]	Mean profitability by wealth group: 1999 (MKw/ha)[3]	Mean profitability by wealth group: 2000 (MKw/ha)[3]
D1/year			1999	2000	1999	2000
MZ+F	3,691[abc]	Wealthiest	4,476*	3,705*	28,098**	13,822*
		Poorest	1,470*	2,760*	5,532**	8,591*
MZ-F	2,407[ac]	Wealthiest	2,260	2,142	16,995	8,359
		Poorest	1,464	1,872	7,762	6,699
SS+F	4,422[bd]	Wealthiest	5,333***	4,837	33,182***	18,338
		Poorest	2,110***	4,230	8,830***	14,601
SS-F	2,795[ac]	Wealthiest	3,372***	3,180	21,006***	12,403
		Poorest	1,520***	2,785	6,928***	9,965
TV+F	3,811[ab]	Wealthiest	4,227*	4,577	25,982*	17,968
		Poorest	2,655*	3,820	13,637*	13,533
TV-F	2,279[c]	Wealthiest	2,452**	2,937	15,302**	12,238
		Poorest	1,570**	2,420	8,353**	9,239
PP+F	3,825[ad]	Wealthiest	4,451*	4,790*	34,233*	25,651*
		Poorest	1,593*	3,340*	12,725*	17,768*
PP-F	2,591[ac]	Wealthiest	2,624*	2,983	23,167*	19,074
		Poorest	1,363*	2,300	13,560*	15,247
D2/Year			2003	2004	2003	2004
MZ+F	4,201[a]	Wealthiest	4,457	4,183*	38,388	47,948*
		Poorest	3,256	2,283*	23,956	22,694*
MZ-F	1,233[c]	Wealthiest	1,786	885	14,685	7,868
		Poorest	1,104	1,055	6,941	10,225
SS+1/2F	3,150[ab]	Wealthiest	2,785	2,194	21,815	22,137
		Poorest	2,751	2,409	19,787	25,176
TV+1/2F	3,046[ab]	Wealthiest	3,029	2,776	25,361	30,929
		Poorest	2,874	2,028	22,000	21,057
PP+1/2F	1,756[bc]	Wealthiest	2,509	1,876	26,564	25,356
		Poorest	1,443	1,120	14,639	15,436

[1] Lowercase letters indicate statistical differences based on one-way ANOVAs ($P < 0.05$, Tukey's post hoc test).
[2] Profitability was not quantified for moderately wealthy farmers due to minimal information on their marketing strategies.
[3] The asterisks *, **, *** indicate significant *t*-test result comparing wealthiest and poorest farmers' yield or profitability for a single cropping system at $P < 0.05, 0.01, 0.001$, respectively. Data from Sirrine, Shennan, S. Snapp, et al. 2010.

When averaged across all landscapes in D2, the maize plus full fertilizer produced the highest yields, the legumes plus half fertilizer intermediate yields, and the unfertilized maize controls the lowest yields (Table 9.1). Once again, yields were lowest across all systems on the hillside and highest in the dambo margin (Figure 9.3). In a study in the same area, Harawa et al. (2006) also found that *S. sesban* and *T. vogelii* performed poorly on the hillside landscape, which had extremely rocky topography and shallow soils (Figure 9.4).
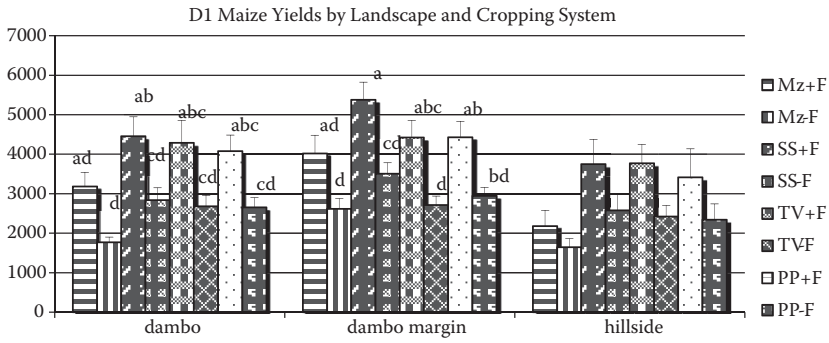
Figure 9.2 D1 (1999 and 2000 average) maize yields by treatment and landscape. Different letters indicate statistical significance at the *P* < 0.05 level.
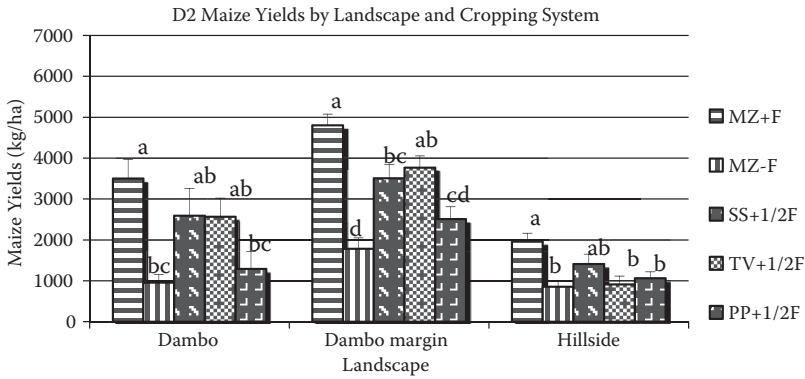

Figure 9.3 D2 (2003 and 2004 average) maize yields by treatment and landscape. Different letters indicate statistical significance at the *P* < 0.05 level.

Figure 9.4 Typical hillside field.

The greatest benefit of the legumes plus half fertilizer were apparent in the dambo margin and the dambo, where both *S. sesban* and *T. vogelii* with half fertilizer had higher yields than the unfertilized control, but less than the fully fertilized maize. When disaggregated in this way, pigeon pea plus half fertilizer did not yield significantly higher than unfertilized maize in any landscape. This indicates a more positive effect of *T. vogelli* and *S. sesban* on maize yields than pigeon pea since they received the equivalent quantities of inorganic fertilizer. In lab trials, Sakala et al. (2000) found that mixed pigeon pea and maize residues experienced prolonged net N immobilization greater than that predicted based on mineralization patterns of sole maize and sole pigeon pea. When there is no initial fertilizer application as in our D2 legume plus half fertilizer treatments, temporary N immobilization by the pigeon pea residue may have occurred. However, there was no evidence of immobilization by pigeon pea in the D1 period (Figure 9.2), when unfertilized pigeon pea yields were equal to or greater than the unfertilized no legume control across all landscapes. The reason for the different maize yield response to pigeon pea across the two designs is unclear but may have been related to poorer pigeon pea growth in the D2 years.

Both unfertilized and legume plus half fertilizer maize yields from D2 (Figure 9.3) were low relative to those of D1 (Figure 9.2) but were still in the range or higher than those reported by others for on-farm research in this region (Harawa et al., 2006; Kamanga et al., 2010; Snapp et al., 2010). It is interesting to note that maize yields in the legume treatments receiving half fertilizer were similar to those of D1 legumes receiving no fertilizer. The lack of initial fertilizer may have negatively affected early growth and nodulation of the legumes. Previous work has shown that small quantities of inorganic N fertilizer often have a stimulatory impact on legume growth, nodulation, and BNF (Giller and Cadisch, 1995), especially in low-N soils (Hardarson and Atkins, 2003). As Sirrine, Shennan, Snapp, et al. (2010) suggested, the legumes may perform best with an immediately available N input from inorganic fertilizer applied at maize planting to establish well and to avoid any nutrient immobilization following incorporation of the preceding legume residue. Further, small amounts of P fertilizer (20 kg P ha^{-1}) have also been found to improve pigeon pea growth (Kamanga, Whitbread, et al., 2010) and to improve nodulation in *S. sesban* and other legumes (Uddin et al., 2008). Even if the full recommended amount of fertilizer is unavailable, it may still be beneficial to apply at least some N and P fertilizer at maize planting rather than assuming that the previously incorporated legume biomass can replace the first application.

9.7   Legume yields and N input

Legume leafy biomass yields were low in D2 (mean = 472 kg ha^{-1} in 2002 and 204 kg ha^{-1} in 2003) but in line with those obtained by Snapp et al. (2010) for on-farm trials in this region (430 kg ha^{-1}). These numbers are lower, however, than others reported for the region by Harawa et al. (2006) and by Kamanga et al. (1999), particularly for *S. sesban* and *T. vogelii*. The difference may relate to the amount of woody biomass included in the measurement; here, only leafy biomass was incorporated according to farmers' requests. In this study, there was no difference in the quantity of leafy biomass produced by the different legume species (Table 9.2). Yet, despite the relatively low biomass amounts, subsequent maize yields were positively associated with legume biomass in both years (simple regression $P < 0.01$; Table 9.3), suggesting that legumes were still playing a role in improving maize productivity.

Nitrogen is limiting in this region (Snapp, 1998), and total N input (which combines inorganic fertilizer and legume N sources) was also strongly correlated with maize yields in both years (simple regression $P < 0.001$, 30% of yield variation in 2003 and 44% in 2004)

Table 9.2 Mean Legume Biomass and Total N Input[1] for 2002 and 2003

Cropping system	2002		2003	
	Legume biomass (kg/ha)	Total N input (kg/ha)	Legume biomass (kg/ha)	Total N input (kg/ha)
MZ+F	NA	45[a]	NA	45[a]
MZ-F	NA	0[b]	NA	0[b]
SS+1/2F	360	31[c]	208	27[c]
TV+1/2F	628	38[c]	197	27[c]
PP+1/2F	409	34[c]	208	28[c]

[1]   Total N input combines organic and inorganic N sources. NA, not applicable. Lowercase letters indicate statistical differences based on nonparametric median tests ($P < 0.05$). Absence of letters indicates the factor was not significant.

Table 9.3 D2 Simple Regressions of Foliar Nutrient Content, Legume Biomass, and N Input with Maize Yields from 2003 and 2004

Variable	2003				2004			
	Beta	R^2	*P* value	N	Beta	R^2	*P* value	N
Foliar %N	0.489	0.239	0.000***	103	0.507	0.257	0.000***	60
Foliar %S	0.509	0.259	0.000***	103	0.513	0.263	0.000***	55
Foliar %P	NA	NA	NA	NA	0.233	0.054	NA	45
Legume biomass[1]	0.442	0.190	0.003**	45	0.531	0.282	0.003**	30
Total N input[2]	0.544	0.296	0.000***	79	0.662	0.438	0.000***	50

Note: Beta, slope of the regression line when predictor and independent variables are standardized (indicates the direction of the relationship); R^2, proportion of variability in the dependent variable attributable to the regression equation; *P* value, significance level, with *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$. N, total number of cases; NS, not significant; WS, whole soil; LF, light fraction.

[1]   Legume biomass does not include MZ+F or MZ-F treatments.
[2]   Total N includes both organic and inorganic fertilizer sources; also includes all five treatments.

(Table 9.3). Others have also found maize yields to be linearly related to the amount of N recycled from *Sesbania* and pigeon pea fallows (Ndufa et al., 2009) or to the total amount of inorganic and organic N sources applied (Mtambanengwe and Mapfumo, 2006). Kamanga, Waddington, et al. (2010) suggested that to have a positive impact on maize yields, legume dry matter biomass should be at least 2,000 kg ha⁻¹, but here we found that much smaller quantities of legume biomass combined with modest amounts (22.5 kg N ha⁻¹) of inorganic N provided benefits for farmers with access to limited quantities of fertilizer. It is also possible that there are cumulative benefits from annual legume relay cropping since 1996 on overall soil quality that contribute to enhanced maize yields, even though we were unable to demonstrate changes over time in major soil nutrients with legume use (see Section 9.7.1). Others have suggested that long-term soil quality benefits accrue from repeated legume use (Kamanga, Waddington, et al., 2010a; Franzel and Scherr, 2002).

A focus on improving legume biomass production in combination with the use of moderate amounts of fertilizer clearly has the potential to greatly improve maize yields in this region. Efforts are needed both to improve agronomic management of the legumes and to better understand the mechanisms by which legumes improve maize yields. Legume density and planting arrangement can have major effects on intercrop performance (Mucheru-Muna et al., 2010; Snapp and Silim, 2002), and timing of incorporation will affect residue quality, which will in turn affect N release dynamics. If residue quality

is high, N will be released more quickly, whereas residue with a lower N content would decompose more slowly (Baijukya et al., 2006). If released too quickly, N will be vulnerable to leaching losses, whereas early maize growth could be reduced if it is released too slowly. Phiri et al. (1999) found that *S. sesban*, a moderate-quality residue, mineralized slowly in southern Malawi, with the strongest correlation between biomass N added and soil mineral N occurring 85 days after incorporation. Release dynamics from residues are also affected by fertilizer additions (Gentile et al., 2011; Kwabiah et al., 1999).

Increased N provision is obviously an important mechanism by which legumes improve maize yields. High rates of nodulation and nitrogen fixation are desirable, and one study found that more than 93% of the nitrogen in pigeon pea plants in farmers' fields in Malawi came from fixation (Adu-Gyamfi et al., 2007), and that annual rates of fixation ranged between 37 and 117 kg N ha^{-1}. This is greater than the total N content of pigeon pea harvested in D2 here, suggesting that growth and nodulation were relatively poor in most fields in these 2 years. Similarly, the biomass N from *T. vogelii* and *S. sesban* were well below amounts found in some other studies (Akinnifesi et al., 2010). As discussed previously, it may be beneficial to apply even small amounts of N and P fertilizer, if available, at maize planting to help stimulate early legume root growth and nodulation (Hardarson and Atkins, 2007; Kamanga, Waddington, et al., 2010; Kamanga, Whitbread, et al., 2010). It would also be useful to measure levels of viable rhizobia in the soil and degree of nodulation to determine if inoculant additions would be beneficial.

In addition to N input through BNF, there is evidence that deep-rooted legumes, such as those used here, can recycle nitrogen that has leached deeper in the soil profile back into surface soils on incorporation (Akinnifesi et al., 2010; Snapp et al., 1998). Interestingly, pigeon pea has also been found to improve water availability for associated maize plants by accessing deep water and subsequently releasing water back into the soil through its shallower roots (Sekiya and Yano, 2004). Enhanced soil moisture could also benefit the soil microbial community and hence nutrient mineralization. Further, Makumba et al. (2009) found that decomposing pigeon pea roots contributed substantially to mineral N in the soil profile; *T. vogelii* and *S. sesban* roots could possibly have similar effects.

Maize tissue percentage N levels were highest in both 2003 and 2004 in the full-fertilizer treatment, followed by similar but lower levels in the various legume plus half fertilizer treatments, and were lowest in unfertilized control (Table 9.4). Maize yields were positively correlated with both tissue percentage N and percentage S (Table 9.3). While nitrogen is the most commonly limiting nutrient in the region (Snapp, 1998), Weil and Mughogho (2000) found that maize yields in Malawi responded to sulfur applications in scenarios in which adequate N was available. Further, extensive S deficiency has been observed in farmer fields in West Africa (Nziguheba et al., 2009) and elsewhere (Scherer, 2009).

Table 9.4 Maize Foliar %N and %S by Treatment and Landscape for 2003 and 2004

Cropping system	2003		2004		
	%N	%S	%N	%S	%P
MZ+F	2.473[a]	0.188[a]	2.038[a]	0.210[a]	0.311
MZ−F	1.342[b]	0.121[b]	1.262[b]	0.133[b]	0.250
SS+1/2F	1.828[c]	0.145[bc]	1.715[c]	0.156[b]	0.248
TV+1/2F	1.852[c]	0.150[c]	1.723[c]	0.149[b]	0.264
PP+1/2F	1.769[c]	0.139[bc]	1.711[c]	0.153[b]	0.277

Note: Lowercase letters indicate statistical differences based on one-way ANOVAs ($P < 0.05$, Tukey's post hoc test). Absence of letters indicates the factor was not significant.

Interestingly, we observed higher tissue S levels in the legume plus half fertilizer treatments as compared to unfertilized maize, suggesting that the legumes enhanced S availability in the soil since the fertilizer applied with the legumes in D2 did not contain any S (whereas that applied to the full fertilizer MZ+F at planting did). If microbial activity were increased in the legume treatments, this could have resulted in greater mineralization of organic S pools in the soil. Studies have shown that crops acquire the majority of their S from organic forms, even in the presence of sulfate fertilizer (Boye et al., 2010). Alternatively, it is possible that sulfate leached deeper in the soil profile was accessed by the legumes and recycled into the upper soil layers. Interactions between legume use and S dynamics warrant further investigation. There is also some evidence that inclusion of legumes in rotations can benefit crop P nutrition through the stimulation of AM infection (Bagayoko et al., 2000; Alvey et al., 2001) or by increasing soil P availability (Randhawa et al., 2005; Mweta et al., 2007; Alvey et al., 2001). However, we found no evidence for legume-mediated effects on maize tissue percentage P here (Table 9.4) or soil-available P (see next section).

9.7.1 Soil fertility

Neither treatment nor landscape position resulted in measurable changes in pH and total soil percentage N in 2000 or 2004 (Table 9.5), which is perhaps not surprising given the high variability across sites and the low replicate numbers for soil analysis (12 farmers). Interestingly, soil percentage C was significantly lower in the dambo margin than on the hillside in 2000 (Table 9.6), although there were no percentage C treatment effects on maize yields in 2000 or 2004. The trend toward higher percentage C on the hillside may be related to the small number of replicates or the more recent transition of agriculture to the hillside (Banda et al., 1994), whereas the dambo margin has historically been the prime agricultural land in highly populated southern Malawi. Furthermore, the hillside landscape was often highly rocky, and farmers pushed together boulders to collect pockets of soil in which to crop maize (see Figure 9.4), which may have resulted in higher soil C levels in these pockets than in the surrounding soil.

To address the variability issue, we also looked at the percentage change over time of each parameter for a given plot, and even then there were no discernible changes over time in either soil percentage C or percentage N or effects of treatment or landscape. Furthermore, despite the range of soil C and N contents present across the sites, there was no correlation between maize yields and either percentage C or percentage N (Table 9.7). Snapp et al. (2010) also did not detect changes in soil C in Malawi trials of long-lived legumes that included pigeon pea, noting the long time frame necessary to detect changes

Table 9.5 Two-Way ANOVA Results for Long-Term Soil Indicators for D1 and D2

| | D1-2000 | | | | D2-2004 | | | |
| | Legume treatment | | Landscape | | Legume treatment | | Landscape | |
Variable	F	*P* value	F	*P* value	F	*P* value	F	*P* value
pH	1.15	NS	1.6	NS	1.48	NS	3.15	NS
Extractable P (ppm)	0.07	NS	20.2	0.000***	0.2	NS	9.65	0.001**
%C-WS	1.13	NS	3.39	0.042*	0.43	NS	2.064	NS
%N-WS	1.41	NS	1.95	NS	0.356	NS	1.47	NS

Note: The asterisks *, **, *** indicate significance at $P < 0.05$, 0.01, 0.001, respectively. NS, not significant.

Table 9.6 Whole-Soil %C and %N, pH, and Extractable P (ppm) for Baseline, 2000, and 2004 Soils

	pH	Whole-soil %C	Whole-soil %N	Extractable P (ppm)
Baseline				
Average	5.76	1.20	0.091	13.90
By landscape				
Dambo	5.68	1.60	0.122	2.60
Dambo margin	5.83	0.90	0.067	12.37
Hillside	5.78	0.97	0.076	26.73
D1				
Cropping system				
MZ+F	5.83	1.13	0.079	13.21
MZ-F	5.71	1.20	0.089	13.70
SS-F	5.74	1.18	0.087	12.00
TV-F	5.61	0.87	0.063	14.03
PP-F	5.70	1.22	0.086	19.68
By landscape				
Dambo	5.73	1.29[ab]	0.095	1.89[a]
Dambo margin	5.64	0.91[a]	0.068	13.31[b]
Hillside	5.78	1.23[b]	0.083	28.38[b]
D2				
MZ+F	5.60	1.01	0.076	26.71
MZ-F	5.80	1.00	0.071	19.85
SS+1/2F	5.52	1.11	0.083	27.64
TV+1/2F	5.49	1.14	0.084	21.46
PP+1/2F	5.64	0.98	0.073	23.73
By landscape				
Dambo	5.49	1.29	0.085	5.16[a]
Dambo margin	5.58	0.90	0.068	15.64[a]
Hillside	5.76	1.13	0.082	50.55[b]

Note: Lowercase letters indicate significant differences based on one-way ANOVAs ($P < 0.05$ Tukey's post hoc test).

in soil percentage C. Even without changes in total percentage C or percentage N, it is possible that changes in more labile fractions of SOM may have occurred as discussed previously. We attempted to isolate the more labile light fraction of the SOM using a size density fractionation method (Meijboom et al., 1995; Barrios et al., 1996) but were unable to isolate sufficient quantities of soil from the initial size fractionation to complete the density fractionation, despite using the recommended 500 g of soil.

Some studies have shown benefits of legume incorporation on soil P availability due to increased mineralization of organic P (Randhawa et al., 2005) or solubilization of inorganic P fixed by Fe and Al in the soil (Mweta et al., 2007). Here, no legume effects on available

Table 9.7 Simple Regressions of Long-Term Soil Quality Indicator Variables and Maize Yields for D1 and D2

Soil indicators	D1				D2			
	Beta	R^2	P value	N	Beta	R^2	P value	N
pH	0.150	0.000	NS	23	−0.261	0.068	NS	24
Extract P (ppm)	−0.449	0.164	0.032*	23	0.097	0.009	NS	24
%C-WS	0.930	0.090	NS	38	−0.237	0.056	NS	34
%N-WS	0.085	0.007	NS	38	−0.180	0.032	NS	34

Note: Beta, slope of the regression line when predictor and independent variables are standardized (indicates the direction of the relationship); R^2, proportion of variability in the dependent variable attributable to the regression equation; P value, significance level, with *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$. N, total number of cases; NS, not significant; WS, whole soil; LF, light fraction.

Bray-extractable soil P were observed; however, soil P was highly variable across sites and time, with averages across treatment and year ranging between 2 and 51 ppm (Table 9.6). The trend was for the dambo to have the lowest levels and the hillside the highest, with the dambo margin intermediate (Tables 9.5 and 9.6). Soil P was significantly lower in the dambo than the other landscapes in 2000 and lower in the dambo and dambo margin than the hillside in 2004 (Table 9.6). Low extractable P levels in the dambo (Table 9.3) may be consistent with P fixation by iron and aluminum complexes, which occurs as seasonally flooded soils dry (PPI, 2005). Soil P may have built up on the hillside due to low maize productivity (Figures 9.2 and 9.3), the practice of creating pockets of soil between rocks for planting maize, or related to landscape geology, but more extensive sampling is needed to determine how robust and widespread this pattern is. Harawa et al. (2006) performed research in a nearby location and found P levels to be lowest in the dambo and hillside and highest in the dambo margin. Snapp et al. (1998), however, found a very high level of variability in soil P among smallholder farms in Malawi.

9.7.2   *Distributional economic analysis*

Yields varied depending on the wealth status of the farmers (Table 9.1), with a strong trend for wealthier farmers to have the highest yields in most cropping systems, and significantly higher yields in 1999, and in the fully fertilized treatments in 2003 (*t* tests $P < 0.05$). This difference likely reflected the preponderance of poor farmers cultivating on the marginal hillside soils, the frequency of poorer farmers selling their labor during critical periods in the maize cropping cycle (Sirrine, Shennan, Snapp, et al., 2010; Alwang and Siegel, 1999), and differences in prior field management practices, including history of fertilizer use. Kamanga, Waddington, et al. (2010) also found that better-resourced farmers in central Malawi experimenting with maize-legume intercrops had higher yields than poorly resourced farmers, attributing differences to disparate field management practices prior to the project's inception.

Given that the wealthier farmers could afford to wait for higher prices when selling maize (see Sirrine, Shennan, Snapp, et al., 2010b), these differences in yield resulted in even greater disparities in profitability for each system for wealthy versus poor farmers (Table 9.1). Design 1 legume-based systems were generally more profitable than the sole maize systems receiving equivalent fertilizer quantities, with pigeon pea systems typically the most profitable. Under D2, the legume effect could not be isolated, but the different legume plus half fertilizer treatments were more profitable than the unfertilized

control and less than the full fertilizer treatment (Table 9.1). In a study conducted in the area, Snapp et al. (2010) ran an economic analysis that varied fertilizer input prices and found that as input prices increased, diversified legume-based systems maintained their value, while the profitability of fertilized maize monocultures decreased. Interestingly, the profitability of D1 fertilizer-based systems was diminished for the poorer farmers compared to wealthier ones (Table 9.1), and a similar pattern was seen for fertilized maize in 2004. This raises concerns about the distributional impacts of fertilizer subsidies for farmers from different resource groups.

9.7.3   Legume system adoption and preference

A detailed discussion of adoption and preference for the different legume systems can be found in the work of Sirrine, Shennan, and Sirrine (2010). Here, we present a brief synopsis of the findings to illustrate the importance of addressing the socioeconomic context when developing and recommending alternative production strategies. In 2003, farmers were asked which of the three legume species they preferred to intercrop with maize. The majority of farmers (55%) stated a preference for pigeon pea, primarily due to its versatility. Farmers valued it as a secondary food source, as a source of firewood, and for soil improvement. The farmers who preferred *T. vogelii* (26%) referred to its ability to improve soil quality, its secondary use as a fish poison, and its low labor demand. The remaining 19% preferred *S. sesban* for its capacity to enhance soil quality, increase maize yields, and perceived larger growth compared to the other two legumes.

We also asked farmers what they actually planted on their own land to determine if stated preferences were reflected in actual adoption. At the onset of the project, essentially all farmers recalled growing some pigeon pea, and 16% grew some *T. vogelii* (none grew *S. sesban*). Farmer recall data on pigeon pea presence and *S. sesban* absence coincide with that reported in the regional literature. Regional cropping history of *T. vogelii* is less well known in terms of quantity, although interviews consistently clarified it had been used in the region as a fish poison for quite some time. In 2003, pigeon pea was still grown on 97% of farms, and *T. vogelii* planting had risen to 20% (Figure 9.5). Only 6% of farmers had adopted *S. sesban* by 2003, with the additional labor demands (including growing it in a nursery, transplanting it during a time of peak agricultural labor needs, and cutting the larger trunks it tended to produce) and poorly understood germination requirements being stated as impediments to its adoption.

Patterns of both preference and adoption varied among farmers depending on wealth ranking, gender, landscape position, and other factors. We hypothesized that the poorest farmers would have the strongest preference for pigeon pea due to the immediate livelihood benefits it had as a food source, but while the poorest farmers did have a strong preference for pigeon pea, farmers in the middle-income bracket had an even stronger preference (Figure 9.5). Interestingly, 40% of the poorest farmers preferred *T. vogelii* due to the immediate livelihood benefit it offers by selling or using the biomass as a fish poison. Clearly, short-term considerations were critical to the poorest farmers who only planted pigeon pea or *T. vogelii* on their own land (Figure 9.5). Bezner Kerr et al. (2007) also found that immediate food security concerns were more influential than soil quality in dictating northern Malawian farmers' cropping system preference. Here, the wealthiest farmers were most likely to prefer, and the only ones to adopt, *S. sesban*, indicating they were best positioned to accommodate the higher labor requirements necessary to benefit from yield gains and the longer-term soil quality improvement likely to accrue over a number of years (Franzel and Scherr, 2002).
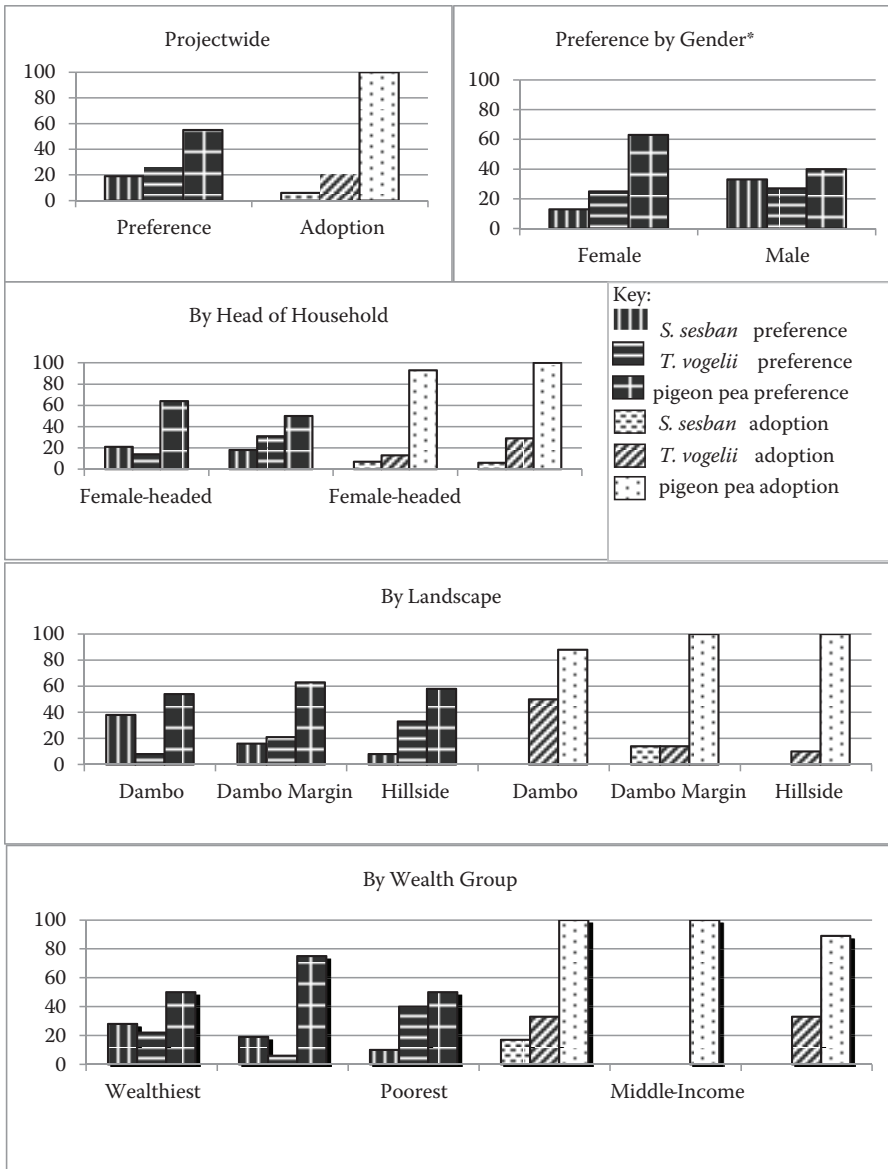
Figure 9.5 Percentage farmer adoption and preference of the legume species in 2003, both project-wide and disaggregated by gender, head of household, wealth rank, and landscape. (Data from Sirrine, D., C. Shennan, and J.R. Sirrine. 2010. Comparing agroforestry systems' ex ante adoption potential and ex post adoption: on-farm participatory research from southern Malawi. *Agroforest. Syst.* 79(2):253–266.)

We found that pigeon pea was often stereotyped as women's and children's food in this region, so it was not surprising that females were more likely to prefer pigeon pea than males (Figure 9.5). Women spoke of its role as an additional food source, and a few mentioned the ability to sell excess seed and retain the money themselves for household purchases. Conversely, many men said they did not like to consume pigeon pea but rather preferred to consume meat and fish. FHHs were also more likely to prefer pigeon pea than

were male-headed households (MHHs) (Figure 9.5). Indeed, FHHs are disproportionately poor (NEC, 2000; Simtowe, 2010; Takane, 2009) and likely in greater need of short-term livelihood support in the form of food. Nonetheless, although many men voiced their dislike of pigeon pea's taste, all MHHs planted pigeon pea (Figure 9.5). Some FHHs had a difficult time saving seeds for subsequent planting due to food insecurity, which may explain why a few FHHs did not plant pigeon pea in 2003. Likewise, Ferguson (1994) found that Malawian land-limited, resource-poor females struggled to save seed from season to season as they either consumed it or sold it shortly after harvest.

We had expected pigeon pea preference to be highest on the hillside, the landscape with the highest concentration of the poorest farmers. In actuality, pigeon pea preference was highest at the dambo margin and slightly lower for farmers on the hillside and dambo (Figure 9.5). Hillside farmers explained that baboons from the adjacent forest stole pigeon pea from their fields, and as a result they had low yields, making *T. vogelii* more attractive. Nonetheless, pigeon pea adoption was still much higher than *T. vogelii* and *S. sesban* across all three landscapes (Figure 9.5), suggesting that it continues to play an important role for hillside farmers despite theft by baboons.

9.8   Assessing sustainability

Using the framework outlined, we can examine sustainability as the ability to meet a combination of goals, including immediate-term livelihood needs, food/income stability over time, and long-term improvement of soil quality. In addition, the distributional dimension to sustainability must be considered since the sustainability of each system clearly depends on the socioeconomic status of the farmers, their gender, and their position across the landscape.

Short-term livelihood concerns relate not only to maize yields but also to immediate benefits such as provision of a secondary food or income source, as is the case with pigeon pea and *T. vogelii*, and untimely labor requirements associated with managing *S. sesban*, which limited its use to a few wealthier farmers. In terms of short-term livelihoods, for the most vulnerable farmers the unfertilized pigeon pea system provided the best option among the D1 treatments in the period 1999–2000 based on its high returns and provision of a secondary food or income source for women. The fertilized *T. vogelii* system gave similar returns, but it is unlikely that the poorest farmers would be able to purchase the necessary amount of fertilizer. For the wealthier farmers, fertilized pigeon pea gave the highest returns in both years, but all fertilized systems performed well.

Among the D2 treatments, the highest returns even for the poorest farmers came from the fully fertilized system, which appears to represent the best option but may be unrealistic for most farmers, especially poorer farmers, for two reasons. First, until the government's recent fertilizer subsidy programs, initiated in 2005, only roughly 25% of smallholders in southern Malawi could afford to purchase inorganic fertilizers (Minot et al., 2000), and many applied quantities far smaller than the recommended rate (Dorothy Sirrine, personal observation, 2002–2004). Second, southern Malawian smallholders, even wealthier smallholders, rarely monocrop maize due to limited landholdings. Thus, for the poorest farmers either *T. vogelii* plus half fertilizer or pigeon pea plus half fertilizer was a promising option, providing they could afford a smaller amount of fertilizer. While *S. sesban* plus half fertilizer gave good returns, poorer farmers would be unlikely to have the necessary additional labor available for growing *S. sesban* since poorer households in general sell their own labor, especially during the peak agricultural season, as a livelihood

strategy (Alwang and Siegel, 1999). This is especially true for many FHHs, further reducing the time they can dedicate to their own plots of land (Simtowe, 2010; Takane, 2009).

Interestingly, there is evidence that in addition to providing short-term livelihood benefits, legumes help reduce the risk of very low yields. Sirrine, Shennan, Snapp, et al. (2010) measured risk of low yields as 75% lower confidence limits (LCLs), which is measured as a one-in-four chance of yields falling below this level. Systems receiving fertilizer had higher LCLs than those with no fertilizer, but notably, they also found that the maize/legume intercrops had consistently higher LCLs than the equivalent nonlegume controls. That is, in both the presence and absence of fertilizer, legumes reduced the risk of low yields. Similar patterns of relative risk have been found in two other studies in Malawi. Kamanga et al. (2009) also looked at risk using LCLs and found that addition of fertilizer reduced risk, but that maize intercropped with pigeon pea had the lowest risk of any system. In another study, spatial variability in yields was consistently higher in unfertilized than in fertilized maize (Snapp et al., 2010), and yet superior yield stability as measured by coefficients of variation was observed in maize/shrubby grain legume rotations. Greater yield stability with legumes also translates into more stability of returns since using legumes either avoids (if no fertilizer is used) or reduces the vulnerability of farmers to fluctuations in fertilizer pricing (Snapp et al., 2010).

Overall, from livelihood, maize yield, and risk perspectives, we found that relay intercropping pigeon pea with maize offered the most sustainable and low-risk, low-cost option for the poorest farmers to improve production and food supply. If fertilizer is available at low cost, even limited amounts could improve the pigeon pea system for these farmers. In contrast, the wealthier farmers have many more options. They are well positioned to benefit from the fertilizer and legumes due to their flexible marketing strategies, higher-quality landholdings, access to labor, and the ability to afford inputs. Based on net returns, under D1 the full fertilizer, followed by *S. sesban* plus full fertilizer, were the most promising systems, whereas under D2 the fully fertilized maize gave the highest returns. When the reduced risk associated with legumes is taken into account, as well as their soil improvement potential, any of the legumes together with fertilizer are good options for wealthier farmers. Again, pigeon pea with full fertilizer may be the best option given the value placed on it by women and the potential for women to gain control over any money generated from pigeon pea sales—a point that was raised in our focus groups, where women spoke of the importance of having income that they could use to purchase household necessities.

In terms of long-term soil quality improvement, we were unable to detect significant changes in soil percentage C or percentage N over time under any of the systems tested, so we cannot use these indicators to differentiate among the systems. More nuanced indicators of nutrient cycling and SOM dynamics were needed to better assess legume impacts on soil fertility. One challenge is coming up with indicators, especially biological indicators that are low cost and feasible, to measure at multiple field sites distant from laboratory or cooling/freezing facilities, as in this case. Yet, it is critical to collect this kind of data under realistic field conditions and not only at experiment stations, where legume productivity tends to be much higher (Mafongoya et al., 2006). Moebius-Clune et al. (2011) argued for a suite of relatively low-cost soil quality indicators that reflect a combination of soil physical, chemical, and biological properties, each linked to important ecosystem processes. These include a range of macro- and micronutrient levels, water-stable aggregates, available water capacity, penetrometer resistance, and biologically active soil carbon measured with a very dilute potassium permanganate method and a handheld colorimeter. Penetrometer resistance was measured in the field, and the remaining measurements were made using sieved

dried soil, making them appropriate for sampling large numbers of fields in distant sites. It would be interesting to see if this suite of indicators effectively captures management impacts on soil quality across a range of locations and if the permanganate measure proves to be a good indicator of soil biological changes.

It is interesting to note that there is close correspondence between the systems recommended and what farmers actually adopted during the course of the study. Essentially all farmers planted some pigeon pea with their maize, about 20% planted *Tephrosia*, and only 6%, all wealthier farmers, planted *Sesbania*. Overall, our results concur with others (Snapp et al., 2010; Kamanga, Waddington, et al., 2010; Kanyama-Phiri et al., 1998), which shows that legumes could play an important role in increasing sustainability of maize production systems in Malawi, but that the benefits of using legumes were greatly enhanced by their use in combination with moderate amounts of inorganic fertilizer (Table 9.1, Figure 9.2). The higher productivity under D1 as compared to D2 suggests that farmers should ideally use as much fertilizer as they can afford up to the recommended amount and, if possible, apply it in two applications as done in D1. However, it is unclear at this point when to recommend application of more limited amounts of fertilizer or indeed at what stage it is best to incorporate the legume biomass. Our understanding of the dynamics of N release from different age legume residues is currently limited, as is our understanding of effects of amounts and timing of fertilizer application on growth and nitrogen fixation by different legume species.

Legume productivity was less than optimal in these on-farm trials given the low biomass obtained (Table 9.2) relative to other values in the literature, suggesting there is considerable potential to further improve system productivity. There is a real opportunity for researchers or extension agents to work with farmers in an iterative and adaptive way to optimize legume management for different landscape positions and resource levels (Shennan, 2008). Research is needed on basic agronomic questions (optimizing seeding rates, planting arrangements, fertilizer amounts and timing, timing of biomass incorporation, etc.), assessment of rhizobium levels and BNF, and the use of improved legume and maize cultivars as suggested by Snapp, Blackie, et al. (2003). Work is also needed to better understand legume and fertilizer effects on labile organic matter pools, microbial activity, and patterns of mineralization/immobilization from different age residues to optimize legume management.

Focus groups held at the end of the project showed that farmers had ideas for improving legume management and suggestions to make the system work better in terms of timing of labor demands. Farmers frequently suggested earlier incorporation of the legumes so that the biomass was further along in decomposition and would not interfere with land preparation (creating ridges) for the upcoming cropping season. Sirrine, Shennan, and Sirrine (2010) noted that this would require farmers to forgo a small second harvest of dry pigeon pea but would also incorporate residue earlier before the leaves begin to senesce, perhaps minimizing N loss from decomposing leaves. Farmers also suggested that less woody material be incorporated because they felt it decomposed too slowly, which was primarily an issue for *S. sesban*, which has smaller leaves and stems that were more challenging to thresh. As discussed, changing the timing and composition of residue incorporation will impact N release dynamics and perhaps increase vulnerability to leaching losses. Reducing total biomass inputs by not incorporating woody material may also have an impact on long-term SOM changes. These trade-offs would need to be evaluated along with the economics of the different incorporation strategies.

In many on-farm projects, farmer involvement is limited, as in this one, due to the trade-off between including farmers in all facets of cropping system management and

maintaining standard management practices across farmers' treatments. With hindsight, we think that greater farmer involvement in project management could have provided results that reflected realistic farmer management strategies and provided more opportunities for social learning to occur among researchers and farmers during the project. Other work has demonstrated the benefits of facilitating farmer innovation in adapting legume (Snapp, Jones, et al., 2003), alley cropping (Kanmegne and Degrande, 2002), and tree mulch (Stoate and Jarju, 2008) systems to better meet their needs and constraints.

In terms of social learning, it would also have been beneficial for farmers to be apprised of the research results at regular intervals throughout the duration of our on-farm projects. We held focus groups at the end of the project to present findings to farmers; these findings were understood well and resulted in many additional suggestions and invaluable feedback. A subsequent training session on legume management clearly demonstrated missed opportunities to both educate and collaborate with farmers on improved legume management.

Nonetheless, farmers provided us with a vivid picture of the limitations and constraints they face when trying to adopt and continue the legume systems being tested. This feedback was extremely valuable in helping us understand how to improve the sustainability of the current cropping systems and underscored the socioeconomic and cultural heterogeneity that will determine whether the next green revolution attempts will be met with success or failure. The aim of tripling cereal grain yields to achieve a green revolution (Sanchez, 2010) and improving soil fertility appears to make sense. However, in the case of FHHs and poorer households in southern Malawi, a strong focus on improving maize yields without an understanding of how diversified cropping systems with pigeon pea can contribute to food security and reduce risk might overlook a critical goal: that of alleviating hunger for the most vulnerable populations. That is, it is essential that a new green revolution be comprehensive and inclusive, encompassing considerations of food security, vulnerability, nutrition, and gender dimensions (Negin et al., 2009).

We cannot emphasize enough the importance of careful investigation of the distributional impacts of proposed changes to production systems, coupled with an understanding of the need to balance short- and long-term sustainability goals. This is particularly true for the neediest farmers, often FHHs. In this regard, the frequently diminished effectiveness of fertilizer on maize yields and profitability for the poorest farmers (Table 9.1) raises concerns about the impacts of fertilizer subsidies for Malawi's neediest farmers. Moreover, inorganic fertilizer prices are both volatile and increasing in the world market (Woods et al., 2010). Malawi's current input subsidy program represents a substantial part of the national budget (Snapp et al., 2010) and may not be sustainable even into the immediate future. While legume/maize relay crops benefited from the addition of inorganic fertilizers (Table 9.1), given the important role legumes played in production risk reduction, household food security, and maintaining maize yields, increased emphasis should also be placed on improving their use and effectiveness through agronomic and soil microbiological research, extension, and potentially even subsidies for acquiring legume seeds.

The conceptual framework we present for evaluating cropping system sustainability emphasizes the importance of identifying trade-offs across time frames and distributional impacts of modifying cropping systems on those potentially impacted. It can accommodate assessment of spatial impacts and could be applied at larger spatial scales than used here. The fundamental framework could equally well be applied in developed nations, using appropriate measures of differential social and biophysical vulnerability within and among communities and incorporating additional indicators of environmental impacts as sustainability measures. As in the developing world, a nuanced understanding of land-

scape, social, and cultural heterogeneity will also influence the ability to transition to more sustainable cropping systems.

9.9   Conclusion

There is ample evidence that the use of legumes, ideally in conjunction with some fertilizer, provides significant benefits in terms of improved crop productivity in a variety of sub-Saharan Africa cropping systems. Less widely documented are measures of changes in different aspects of soil quality, especially in terms of impacts on soil C and N pools and microbial ecology, and how these relate to crop growth and nutrient cycling. It is also apparent that there is great variability in the performance of legumes in different systems and locations, leaving significant opportunities for improved management to increase BNF and biomass production. Improved understanding of residue quality and decomposition dynamics would also help to synchronize N release dynamics better with crop demand.

The question of how to assess the relative sustainability of different management options was discussed, framing sustainability as the ability to meet a combination of goals, including immediate-term livelihood needs, food/income stability over time, and long-term improvement of soil quality. This framing makes it clear that in addition to understanding system impacts on the biophysical components of an agroecosytem, it is critical to consider the socioeconomic and cultural contexts where a system is targeted. These arguments were illustrated through a case study of legume relay cropping in Malawi.

The case study provided a realistic assessment of the performance and sustainability of different fertilizer and legume relay intercropped systems by testing them across a representative range of smallholder farms in this region of Malawi. We used a framework that examined sustainability as a combination of short-term livelihood benefits measured as crop yields and net returns, farmer preference, adoptability, risk, and longer-term soil fertility impacts, although we were limited in our ability to differentiate among the treatments in terms of changes in soil fertility. While presenting some logistical challenges, the project design allowed us to consider the effects of different landscape positions, resource endowments, and gender on the desirability and sustainability of each system tested. By considering variability across time and space, we obtained information on the risks of low yields associated with each system. The incorporation of surveys, interviews, participant observation, and focus groups provided insights on the socioeconomic and cultural realities of the participating farmers and their opinions of the systems being tested and enabled a distributional assessment of performance to be made.

We found that relay intercropping maize with pigeon pea offered the most sustainable low-cost, low-risk option of the systems tested for improving food production and net income for the poorest farmers. However, further improvements are needed to move these farmers to greater food security. In contrast, any of the legumes plus a moderate amount of fertilizer offered higher returns and benefits for wealthier farmers. Pigeon pea, however, has the advantage of being a secondary food and a potentially valuable source of income specifically for women.

For this, and other legume-based systems, a focus on improving legume management to increase growth and BNF together with a better understanding of the dynamics of residue decomposition, nutrient cycling, and SOM changes could greatly enhance system productivity and sustainability. More effective use of legumes can help reduce risk and vulnerability to fertilizer price fluctuations by reducing fertilizer requirements and improving soil quality over the long term. The choice of systems to recommend needs to reflect

socioeconomic and cultural considerations, as well as biophysical performance, and take into account food security and livelihood needs of farmers with different resource levels.

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