EFFECTS OF MAIZE COWPEA INTERCROPPING ON YIELD STABILITY AND PRODUCTION RISK IN CENTRAL MALAWI: A MODELING STUDY

By

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ABSTRACT

EFFECTS OF MAIZE COWPEA INTERCROPPING ON YIELD STABILITY AND PRODUCTION RISK IN CENTRAL MALAWI: A MODELING STUDY

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Smallholder farmers in Malawi face growing challenges from increasingly variable weather and scarce resources. We used the Agricultural Production Systems Simulator (APSIM) to investigate yield stability and production risk in maize cowpea intercrop and maize and cowpea monocrop systems at three locations in central Malawi. This was done as part of an ongoing farmer participatory research project, with a household survey and field trials providing context for the modeling study. Models were calibrated and validated based on field trials, and cropping systems were simulated for 26 seasons. Simulations were run in two soils at each site, under unfertilized conditions and with the addition of 69 kg N / ha. We determined calorie and protein yields of intercrop and monocrop systems in relation to household needs, and used stability analysis to contrast yields across a range of environmental conditions.

Calorie and protein yields tended to be higher in intercrops than in monocrops, except at one location where unfertilized maize yields were suppressed in intercrop with cowpea. Calorie and protein yields of intercrops also tended to be more variable than monocrops, largely due to the high performance of intercrops under favorable conditions. Maize cowpea intercrop systems demonstrated a greater chance of meeting household calorie and protein needs than maize and cowpea monocrops in 83% of cases. This suggests that maize cowpea intercropping is generally advantageous for smallholder farmers in Malawi, but yields may be suppressed in environments where cowpea is a strong competitor with maize. This study is unique in that it addresses risk to farmers and compares system performance across a range of growing conditions and seasons.

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LIST OF ABBREVIATIONS and SYMBOLS

APSIM: Agricultural Production Systems Simulator

C: Carbon

N: Nitrogen

P: Phosphorus

P (as used in probability notation): Probability

$\cap$ (as used in probability notation): And

INTRODUCTION

Climate variability, food security and agricultural intensification in Malawi

Smallholder farmers practicing rain fed agriculture in sub-Saharan Africa must cope with present-day insecurity and a future rife with uncertainty. Many rural households are currently food-insecure, and food demand is expected to increase in coming decades due to a growing population and changing patterns of food consumption (Thornton *et al.*, 2011). At the same time, climate change will alter patterns of temperature and rainfall in sub-Saharan Africa, and may cause many areas to develop climate regimes with no present-day analogue. Without adaptation in maize (*Zea mays*) based agriculture, yields of this principal food crop are expected to grow less stable in coming decades (Lobell *et al.*, 2008; Thornton *et al.*, 2011).

With the threat of climate change and increasing demands placed on agroecosystems, farmers will need to adapt to new conditions and stresses. Farmers practicing rain fed agriculture have already developed strategies for coping with present-day climate stresses, and these strategies can serve as a starting point for adapting to an uncertain future (Thomalla *et al.*, 2006). However, smallholder farmers tend to have very limited access to resources, and this may force them to prioritize short-term food production over investments in longer-term agroecological stability (Snapp *et al.*, 2002b). This highlights the importance of working with farmers to develop adaptation strategies that fit within the context of farmers' needs and constraints (McDougall and Braun 2003, Snapp et al. 2003). By supporting adaptation strategies intended to improve crop production and food security under present-day environmental variability and stresses, we can support farmers' capacity to continue adapting in an uncertain future (Thomas and Twyman, 2005; Twomlow *et al.*, 2008).

Due to chronic food insecurity in sub-Saharan Africa and the threats of climate change and population growth, there have been frequent calls for a new African green revolution

(Toenniessen *et al.*, 2008; Snapp *et al.*, 2010). The first green revolution, which combined fertilizer-responsive hybrid grains with the intensive use of fertilizers, herbicides and pesticides, met with little success in Africa. Per-capita food production in Africa has actually declined in recent decades, while increasing in most other regions of the world (Toenniessen *et al.*, 2008). This is due at least in part to the high cost of agricultural inputs in Africa, in conjunction with incomes of less than $1 / day for many smallholder farmers (Kerr and Kolavalli, 1999). If future efforts at intensification are to meet with greater success, they must be commiserate with the serious constraints faced by many smallholder farmers in Africa.

Proposals for the form that this new green revolution should take are varied. Some proponents focus on the increased use of fertilizers and other inputs, made possible by heavy government subsidies (Denning *et al.*, 2009). However, exclusive reliance on subsidized inputs can prove problematic when those subsidies dry up due to changes in national policy (Chirwa *et al.*, 2006). It has therefore been argued that, in order to provide sustainable benefits to smallholder farmers, the African green revolution must be founded on ecological intensification and agricultural biodiversity (Snapp *et al.*, 2010). Efforts in this direction have focused mainly on the incorporation of legumes and organic amendment into cereal cropping systems, along with the modest use of fertilizers and other inputs (Vanlauwe *et al.*, 2010). Most legumes provide a supplemental source of fertility through biological nitrogen fixation, and can benefit subsequent grain crops (Chikowo *et al.*, 2004). When used in conjunction with modest fertilizer applications, legumes can increase the benefit from each kilogram of N applied (Snapp *et al.*, 2010). Intensification efforts based on the integration of legumes into cereal cropping systems may therefore prove more accessible to resource-constrained smallholder farmers.

Smallholder farmers in Malawi must cope with severe constraints as they adapt their agricultural systems to present and future conditions. Slightly over half of all Malawians earn less than a dollar a day, and a similar proportion of Malawian children are stunted due to malnutrition (Wood and Mayer, 2006). In drought years farmers can face partial or total crop failure, rendering them unable to meet household food needs through their own production (Kamanga *et al.*, 2010). Soil fertility is typically low, limiting the productivity of low-input agriculture (Snapp, 1998). The effects of these biophysical constraints are compounded by shrinking landholdings, high food prices, eroding social support networks, and the deterioration of natural areas that rural people rely upon to buffer food supplies in times of scarcity (Chinsinga, 2004; Scholes and Biggs, 2004; OECD/FAO, 2012). Nevertheless, many Malawian farmers continuously experiment with new cropping patterns and other agricultural strategies to make the most of the resources available to them (Peters 2002).

Farmers in Malawi have traditionally planted cereal and legume crops together in intercrop systems, and this practice remains prevalent in smallholder fields (Shaxson and Tauer, 1992; Peters, 2002). Intercropping systems, like other forms of crop diversification, spread risk among multiple crops, so that the failure of a single crop does not mean a failure to produce any food or income (Trenbath, 1999). Smallholder farmers frequently cite intercropping and other forms of mixed cropping as an important strategy for coping with climate variability (Hassan and Nhemachena, 2008; Ozor and Cynthia, 2010). Intercropping systems can be particularly attractive to farmers in Malawi because they ensure that a large portion of their limited arable land can be devoted to production of the staple crop, maize (Shaxson and Tauer, 1992; Snapp *et al.*, 2002b). In Malawian smallholder agriculture, crops are planted into ridges constructed with hand hoes. In traditional cropping systems planting ridges tend to be spaced relatively widely, but in recent years more intensive spacing has been heavily promoted and widely adopted by farmers (Denning *et al.*, 2009). This represents a widespread transition from a relatively conservative traditional approach, to an approach intended to maximize maize production. This transition may be paralleled by a decline in intercropping, as a recent nationwide survey (Jones *et al.*, 2014) reports decreased rates of intercropping compared with past surveys (Ngwira *et al.*, 1990).

Despite the continuing prevalence of intercropping in Malawi and across sub-Saharan Africa, many major research efforts have focused almost exclusively on crop rotation as a means of integrating legumes into cereal-based systems (Giller *et al.*, 2009). Similarly, agricultural extension agencies in sub-Saharan Africa have tended to discourage intercropping (Byerlee and Heisey, 1996), though extension in Malawi has included intercropping treatments in some large-scale trials (Snapp *et al.*, 2010). Critical evaluation of the risks and benefits of intercropping in African smallholder systems can shed light on the place of this practice in efforts towards agricultural intensification.

One of the chief aims of legume based intensification is to improve soil fertility over time through the production of N-rich biomass (Snapp *et al.*, 1998; Thierfelder *et al.*, 2012). However, farmers experiencing chronic food insecurity may be forced to prioritize immediate survival over long term considerations (Bryceson and Fonseca, 2006). Farmers in Malawi have expressed concern about any loss of maize production due to legumes, and while soil fertility is cited as a concern, it comes after food production and crop sales (Snapp *et al.*, 2002b). Food insecurity can force farmers to use cropping practices that are known to degrade the soil when they believe that those practices are the best option for meeting their immediate food needs (Murage *et al.*, 2000). Therefore, when evaluating options for sustainable intensification in smallholder systems, it is important to prioritize short-term food production alongside long-term improvements in soil fertility.

The ecology of intercropping and evaluation of intercrop systems

A large body of ecological theory and research indicates that biodiversity tends to be linked to improved ecological productivity and stability (Hooper *et al.*, 2005). While much of this research has been conducted in natural systems, the same principals apply to cropping systems. Two general mechanisms can allow intercrops to be more productive than monocrops. The competitive production principal states that different species will exploit slightly different resource pools, making inter-specific competition less intense than intra-specific competition (Vandermeer, 1995). This is observed in cases where intercrops achieve greater water use efficiency by drawing water at different times in the year (Sileshi *et al.*, 2011), or from different depths in the soil profile (Ogindo and Walker, 2005). The competitive production principal also comes into play when one intercrop partner is capable of fixing N from the atmosphere rather than relying entirely on N from the soil (Fukai and Trenbath, 1993; Chikowo *et al.*, 2004). Furthermore, interplanted crops can actively facilitate the growth of their partner crops. This can occur through the provision of biologically fixed N in the form of N-rich crop residues (Snapp *et al.*, 1998), through the creation of microclimates that limit water loss (Morris and Garrity, 1993), and through the suppression of weeds and insect pests (Skovgard and Pats, 1996).

While crops grown together in intercrop can be subject to a number of productivity-increasing interactions, they are also subject to inter-specific competition. Intercrop partners compete with one another for limited resources including water, light, and nutrients. Competition for water can limit the productivity of intercrops in dry years, resulting in higher yield variability in response to climatic conditions (Fukai and Trenbath, 1993; Ollenberger, 2012). While biological N fixation limits the degree of competition for N in cereal legume intercrops, N fixing legumes can still be limited by N competition in intercrop systems (Ghosh *et al.*, 2006). Competition for light can also determine whether crop yields are suppressed in intercrop, particularly in cases where a short statured crop is grown with a tall-statured crop such as maize (Keating and Carberry, 1993). Due to the interplay of productivity-increasing and productivity-limiting interactions in intercrop systems, intercrops will only demonstrate a yield advantage over monocrops in situations where inter-specific competition is less intense than intra-specific competition, or where competition between crops is out-weighed by facilitative interactions (Vandermeer, 1995).

Intercropping can take numerous forms combining two or more annual crops, perennial crops, or some combination of the two. For intercrops involving two annual crops with similar growth periods, intercrop systems can be distinguished into two basic forms (Fukai and Trenbath, 1993). Intercrops can be substitutive, with crop plants of one species replaced with plants of another. Substitutive intercrops have a total plant density similar to the plant density of either crop in monoculture. Alternately, intercrops can be additive, with crop plants of both species planted at the same density that would be used in monocrop. Additive intercrops have a higher total plant density than either crop in monoculture. These differences in plant density can alter the intensity of competition in intercrop systems, affecting the dynamics of the system (Rusinamhodzi *et al.*, 2012) and its relative advantage over monoculture (Watiki *et al.*, 1993).

Additive intercropping is commonly practiced by smallholder farmers in Malawi, and is particularly prevalent among households with limited land per-capita (Shaxson and Tauer, 1992). Farmers in neighboring Mozambique reported a preference for additive intercrop systems over substitutive systems due to their higher yield potential (Rusinamhodzi *et al.*, 2012). This preference for additive systems is supported by a modeling study of maize cowpea intercrops, which found that additive or semi-additive systems produce optimal economic yields (Adiku *et al.*, 1998).

Intercropping cereals with legumes has been found to increase the productivity of cereal cropping systems across many locations and climatic conditions in sub-Saharan Africa (Waddington *et al.*, 2007; Snapp *et al.*, 2010; Thierfelder *et al.*, 2012). This is largely driven by legumes' capacity to meet a portion of their own N requirements through biological N fixation, and their production of N-rich biomass which can contribute to the N nutrition of subsequent cereal crops (Chikowo *et al.*, 2004; Vesterager *et al.*, 2008). However, cereal legume intercropping does not necessarily offer an advantage under all conditions. The benefits of legume intercrops may diminish in input-intensive cropping systems, where the N needs of cereal crops are supplied by mineral fertilizer (Searle *et al.*, 1981; Carberry *et al.*, 1996; Sileshi *et al.*, 2011). In contrast, legumes may also contribute little under excessively harsh growing conditions. Legumes grown in extremely poor soils may grow poorly and contribute little N-rich biomass to the soil (Chikowo *et al.*, 2007; Mhango *et al.*, 2012). Finally, some arrangements of crops in intercrop may produce a yield advantage over monocrops, while others do not (Watiki *et al.*, 1993). We must therefore carefully evaluate the appropriateness of intercrop systems on a situation by situation basis and improve our understanding of how the environment interacts with intercrop system performance.

When contrasting monocrop and intercrop systems, it is necessary to find a basis for comparison between a system with one crop and a system with two or more. The yield of a single crop cannot fully express the productivity of an intercrop system. Numerous methods are used for comparing the productivity of monocrops and intercrops. Perhaps the most commonly used index for comparison is the land equivalent ratio (LER), which is the ratio of the land necessary to produce a given yield of two crops in monocrop to the land necessary to produce those same yields in intercrop. Unfortunately, the LER may be biased in favor of intercrops in situations where the two intercrop partners differ in productivity, as in most maize legume systems (Connolly, 1986). Monocrop and intercrop productivity are also frequently compared in terms of economic yield (Lightfoot *et al.*, 1987; Adiku *et al.*, 1998), though the results are dependent on fluctuating crop prices. Total calorie and protein yield of the cropping system has been proposed as an alternative basis for comparing intercrops and monocrops (Trenbath, 1999). Calorie and protein yields are likely to be particularly relevant to smallholder farmers who produce some or most of their own food.

Yield stability from season to season is a vital factor to consider when evaluating smallholder cropping systems. Because smallholder farming households often produce barely enough to meet their subsistence needs, yield stability is likely to impact food security in a variable and changing climate (Giller *et al.*, 2006; Kamanga *et al.*, 2010). Whether intercropping systems are more or less stable than monocrops is a matter of debate, and may vary based on the crops involved (Fukai and Trenbath, 1993; Altieri, 2004). Relative yield stability may also depend on the arrangement of crops in the cropping system (Shumba *et al.*, 1990; Rusinamhodzi *et al.*, 2012).

Stability can be conceived of in several ways. Frequently, stability is thought of as the degree of variation around the mean, often expressed as the coefficient of variation (Waddington *et al.*, 2007). Stability can also be thought of as responsiveness to varying environmental conditions. This is seen in stability analysis or adaptability analysis, in which yields are plotted against an environmental index ranging from the most favorable to the least favorable conditions (Lightfoot *et al.*, 1987; Hildebrand and Russell, 1996). Yield stability is important, but it is not the only relevant criteria from a farmer's perspective. A cropping system that produces consistently low yields may be considered stable, but may be entirely undesirable for farmers. To reflect farmers' needs, criteria for evaluating cropping systems must account for both mean yield and variability (Hildebrand and Russell, 1996).

Measures of production risk take into account both farmers' need to achieve high average yields, and their need to produce yields that are stable over time. Risk analysis measures the chance that a cropping system will meet or exceed a minimum required outcome (Hildebrand and Russell, 1996). By measuring the frequency with which the minimum outcome has been met in years past, risk analysis gives the likelihood that the outcome will be met in the future. This minimum required outcome can be a minimum economic yield (Lightfoot *et al.*, 1987; Yamoah *et al.*, 2000), or the minimum food production required to meet household needs (Kamanga *et al.*, 2010). By measuring the chance that a farming household will produce enough to meet their needs, risk analysis provides a criterion that is directly relevant to food security and livelihood sustainability.

Maize cowpea intercrop systems

Cowpea (*Vigna unguiculata*) is an annual legume common to smallholder cropping systems in sub-Saharan Africa. It was brought into cultivation in Africa, and wild relatives can be found across the continent (Padulosi and Ng, 1997). Cowpea cultivars display a variety of growth habits, ranging from fully determinate to highly indeterminate. It is valued for its edible foliage as well as for its grain, and can serve as a food source in the hungry period before harvest time (Nielsen *et al.*, 1997). Cowpea is relatively drought tolerant, and is capable of extracting water from the soil at soil water concentrations below the lower limit for maize (Adiku *et al.*, 1998). Unfortunately, cowpea is also susceptible to many insect pests and diseases, and yields may be depressed unless pesticides or biological control methods are used (Jackai and Adalla, 1997). In African smallholder cropping systems, cowpea is typically grown in intercrop with maize, sorghum, pearl millet, and other cereal crops, though monocropped cowpea is common in some regions (Mortimore *et al.*, 1997).

Maize and cowpea exhibit complementary use of water and N resources in intercrop systems. Cowpea in intercrop with maize has been found to supply up to 72% of its N needs through biological N fixation, though this percentage is depressed under P limited conditions (Vesterager *et al.*, 2008). Maize cowpea intercrops have also been found to exhibit higher water use efficiency than either crop in monocrop (Hulugalle and Lal, 1986). In intercropping systems maize has been found to withdraw the majority of water under wet conditions, while cowpea is capable of withdrawing soil water under conditions too dry for maize, resulting in complementary water use (Adiku *et al.*, 2001).

The productivity of maize in intercrop with cowpea relative to maize in monoculture may depend on the fertility inputs applied to the system. Additive maize cowpea intercrops have been found to produce maize yields that are equivalent to maize monocrops, while also producing cowpea, when no N is added to the system (Ofori and Stern, 1987; Rusinamhodzi *et al.*, 2012). However, under fertilized conditions, maize yields in maize cowpea intercrops can be sharply depressed when compared with maize monocrops (Ofori and Stern, 1987; Watiki *et al.*, 1993) but see (Rusinamhodzi *et al.*, 2012). Similar trends have been found in other maize legume intercrops, including maize pigeonpea and maze leucaena (Kamanga *et al.*, 2010; Sileshi *et al.*, 2011).

Fertility inputs can also be a factor determining intercrop advantage when the productivity of the entire system is considered. Unfertilized maize cowpea intercrops have been found to produce an LER above 1.5 (an LER of one indicates that an intercrop and its respective monocrops are equally productive) (Ofori and Stern, 1987), and produce higher economic yields than their respective monocrops (Carberry *et al.*, 1996). These studies have found that when N is applied to the system, maize cowpea intercrops achieve an LER closer to one (Ofori and Stern, 1987) and lose their economic advantage over monocrops (Carberry *et al.*, 1996). The superior performance of maize legume intercrops under unfertilized conditions is likely due to biological N fixation by legumes, allowing them to remain productive in conditions where maize is N limited (Vesterager *et al.*, 2008). Intercrop advantage can also result from the deposition of N rich residues in the soil, and the availability of that N to subsequent maize crops (Chikowo *et al.*, 2004). This advantage could disappear under conditions where N is not limiting. However, it should be noted that intercrop advantage is not always restricted to unfertilized systems, and in some cases maize cowpea intercrops have been found to achieve maize yields similar to monocrop regardless of the N rate applied, while producing cowpea in addition (Rusinamhodzi *et al.*, 2012).

The productivity and yield stability of maize in intercrop with cowpea can also depend on the way that plants are arranged in the system. A long term study of substitutive maize cowpea intercrop systems in Zimbabwe found depressed maize yields in intercrop with cowpea, but improved yield stability (Waddington *et al.*, 2007). Likewise, in a comparison of additive and substitutive systems in Mozambique, maize in substitutive intercrop with cowpea yielded less than maize in monocrop in both favorable and unfavorable seasons (Rusinamhodzi *et al.*, 2012). However, maize in additive intercrop with cowpea produced yields equivalent to monocrop in a favorable season, but lower yields than monocrop in an unfavorable season. These studies suggest that substitutive intercrop systems may provide improved yield stability and experience decreased maize yields relative to monocrop, while additive systems can achieve comparable maize yields but may suffer reduced yield stability.

Where the productivity of the entire cropping system has been considered, the stability of maize cowpea intercrops relative to monocrops has varied from one study to another. In a long term modeling study of maize cowpea cropping systems, the economic yield of intercrops was found to be more stable over time than the yield of either monocrop (Adiku *et al.*, 1998). In contrast, both additive and substitutive maize cowpea intercrop systems in Zimbabwe demonstrated LERs below 1 in an unfavorable season, and LERs above 1 in a more favorable season, indicating reduced yield stability compared to maize monocrop (Shumba *et al.*, 1990). Furthermore, in sorghum cowpea systems in Botswana, intercrops produced higher economic yields than monocrops, while yield stability was similar in monocrop and intercrop systems (Lightfoot *et al.,* 1987). This emphasizes that stability alone is not a sufficient criterion for evaluating intercrop systems, and a system may be of greater benefit to farmers without being more stable.

Crop simulation modeling and the Agricultural Production Systems Simulator

Process-based crop simulation models offer the ability to explore the performance of cropping systems under a wide range of environmental conditions. These models are based on equations describing physical and biological processes such as the mineralization and immobilization of N and the movement of water through the soil profile (Probert *et al.*, 1998), and physiological processes involved in crop growth (Carberry *et al.*, 1989). Using climate and soil parameters measured in the field, along with crop parameters determined through experimental trials, they simulate the interaction of crops, soils, and the atmosphere from one day to the next (Keating *et al.*, 2003).

The Agricultural Production Systems Simulator (APSIM) was developed to simulate semi-arid rain fed cropping systems in Australia, and has since been used extensively in sub-Saharan Africa (Keating *et al.*, 2003). Based on the CERES maize model, it has been expanded to simulate a wide range of crops and cropping systems (Carberry *et al.*, 1989). The capacity of APSIM to simulate maize and cowpea has been extensively tested against data from tropical agroecosystems, including systems in sub-Saharan Africa (Carberry *et al.*, 1989; Adiku *et al.*, 1995; Keating *et al.*, 2003).

APSIM is relatively unique among process based crop simulation models in its capacity to simulate intercrop systems (Malezieux *et al.*, 2009). Though the model has no spatial component, it employs an arbiter routine to partition resources including light, water, and N between intercrop partners (Carberry *et al.*, 1996). Features relevant to the simulation of intercrop systems include simulation of water and nutrient uptake at different layers of the soil profile, simulation of light availability and the effects of shading, simulated plant residue deposition and subsequent N mineralization, and simulation of the effects of soil surface litter on soil water (Keating *et al.*, 2003). The ability of APSIM to simulate maize cowpea intercrops has been tested using field data from sub-Saharan Africa (Adiku *et al.*, 1995).

While models such as APSIM are powerful, they also have serious limitations. APSIM does not include many important ecological factors such as the action of pests and disease, spatial interactions between components of the agroecosystem, and the dynamic, responsive management of cropping systems by farmers (Keating *et al.*, 2003). Despite these limitations, APSIM and related models remain powerful tools which have been extensively used to evaluate risk in cropping systems (Nelson *et al.*, 2002), explore the possible effects of climate change (Asseng *et al.*, 2013), and evaluate agricultural technologies in collaboration with farmers (Whitbread *et al.*, 2010). APSIM has been used to simulate smallholder cereal legume cropping systems in Malawi (Robertson *et al.*, 2005; Ollenberger, 2012), and to simulate the chance that farming households will meet their food needs under a variety of cropping systems (Snapp *et al.*, 2014).

In order to ensure that models provide a credible representations of actual systems, it is necessary to compare the behavior of simulated cropping systems to the behavior of actual systems (Xiong *et al.*, 2008). This is typically achieved through the process of calibration and validation. In model calibration, coefficients are adjusted to cause simulated yields to conform to observed yields. Calibration must be undertaken with caution – if too many model parameters are adjusted, or if parameters are adjusted outside of reasonable bounds, this process calls into doubt the model's ability to simulate biological mechanisms (Sinclair and Seligman, 2000). Model validation is the use of a model to simulate an environment that it was not calibrated for, and the comparison of the model's behavior to observations from the field. Validation is strongest when performed across a range of environmental conditions that represent the full scope of interest for the investigation (Sinclair and Seligman, 2000).

Calibration and validation alone are not sufficient to ensure that crop models will play a constructive role in the development of intensified cropping systems that can benefit smallholder farmers (Cash *et al.*, 2003). To make the greatest contribution to the process of sustainable development, models must be salient (relevant to actual systems and situations) and legitimate (acceptable to stakeholders in those systems), as well as being credible (providing a good approximation of the behavior of actual systems). While credibility can be established by contrasting modeled and actual systems (Xiong *et al.*, 2008; Asseng *et al.*, 2013), salience and legitimacy depend on interactions between modelers and stakeholders in the systems being modeled (Cash *et al.*, 2003). To be of use to farmers, modeling must be conducted in a context where farmers and other stakeholders are involved in the research process, and therefore have a basis for trusting its results (van den Belt, 2004).

QUESTIONS AND HYPOTHESES

Questions

We used simulation modeling to explore yield stability and production risk in maize cowpea intercrop systems and maize and cowpea monocrops at three study locations in central Malawi. This study was conducted as part of a farmer participatory research project established in central Malawi in 2012, building on over a decade of research on legume-diversified maize cropping for sustainable intensification (Kamanga *et al.*, 2010; Snapp *et al.*, 2010). We addressed the following questions:

- Do maize cowpea additive intercrops show increased calorie and protein yields in their first year of establishment when compared with maize and cowpea monocrops? Is this influenced by N fertilization?

- Do maize cowpea intercrops show reduced yield stability across seasons and soils compared with maize and cowpea monocrops?

- Can maize cowpea intercrops increase a typical farming household's chance of meeting calorie and protein needs through their own production, compared with maize and cowpea monocrops?

Hypotheses

- Maize cowpea additive intercrops will show higher mean calorie and protein yields than maize monocrops in the absence of N inputs, but not under N fertilized conditions.

- Maize and cowpea calorie and protein yields will be less stable across seasons and soils in maize cowpea intercrop systems compared with maize and cowpea monocrops.

- We do not have enough information to predict whether intercrops will increase a typical household's chance of meeting calorie and protein needs through their own production.

MATERIALS AND METHODS

Research context

This study was conducted as part of the Africa RISING Malawi research initiative, exploring strategies for sustainable intensification of maize-based cropping systems in central Malawi based on long-term farmer participatory research in the country (Snapp *et al.*, 1998). Our modeling investigation involved three locations in central Malawi in the 2012 – 2013 growing season. These were selected to represent three agroecological zones: high elevation with high water availability, mid elevation with medium water availability, and low elevation with moderate to low water availability (Table 1).

Africa RISING utilized a participatory research framework known as the mother / baby trial design (Snapp *et al.*, 2002a). Mother / baby trials situate agronomic research on working smallholder farms and involve farmers in the research process in order to make the work as relevant as possible to farmers. At each study location, two clusters of villages were identified, and participation was solicited from farmers in those villages. Participating farmers worked together, along with local agricultural extensionists, to maintain a replicated "mother trial" contrasting a range of cropping systems. In addition, farmers tested two or more cropping systems on their own farms in unreplicated "baby trials," adapting the systems to their own needs and growing conditions. In total there were two agronomic trials (mother trials) per study location, accompanied by many baby trials. In this study we focus on the researcher-designed, farmer and researcher managed mother trials, employing them as a basis for crop simulation modeling.

Soils at the Kandeu study location are a mix of orthic ferralsols and chromic luvisols. Soils at Lintipe are ferric livisols, and soils at Golomoti are a mix of eutric fluvisols and eutric cambisols (Lowole, 1984). The surface soil at trial one at Kandeu was sandy loam, while the soil at trial two was sandy clay loam. At Lintipe, the surface soil at trial one was clay, and at trial two, clay loam. The surface soil at Golomoti trial one was loam (Table 2). The percent total carbon in surface soils at our study locations ranged from 2.3% at Lintipe trial one, to 0.6% at Kandeu trial two. Soil pH at our study locations was generally low, and surface soil pH ranged from 5.13 at Lintipe trial two to 4.5 at Golomoti trial one. Phosphorus content of soils varied drastically across our study locations, with Bray extractable P in surface soils ranging from 72.5 ppm at Kandeu trial one, to 4 ppm at Kandeu trial two.

Table 1: Study locations classified by water availability. Classification is based on an index of mean annual rainfall over 30 years at each site and mean annual temperature (Chikowo 2013, personal communication).

Site name:	District	Altitude	Water availability	Latitude	Longitude
Kandeu	Ntcheu	909 m	Medium	-14.6292	34.5975
Linthipe	Dedza	1236 m	High	-14.2058	34.1009
Golomoti	Dedza	554 m	Low	-14.4386	34.6039

Survey data collection

We collected data on household composition and farming practices in each study location through a survey conducted in the summer of 2013. At each location, the survey included at least 40 households participating in the Africa RISING project, at least 20 local control households who were not participating in Africa RISING but were co-located in the same villages with farmers who were, and at least 20 distant control households in villages 10 km or more from the intervention villages. The survey included 81 households at the Kandeu study location, 83 households at the Lintipe study location, and 80 households at the Golomoti study location. Farmers were asked to provide detailed information on cropping practices in each field they managed, including all inputs applied, all crops grown and their planting arrangement (intercrop or sole crop), and an assessment of soil fertility in each of their fields.

Agronomic trials

Five experimental trials grown in the 2012 – 2013 season were used to calibrate and validate models in this study. There were two trials at the Kandeu study location, two at Lintipe, and one at Golomoti. Each trial included up to 12 treatments, replicated three times each in 5 m x 5 m plots and arranged in a randomized complete block design. Treatments were selected for each location to reflect a mix of current farmer practice, along with sustainable intensification strategies judged to be appropriate for the local environment.

At trial one in Kandeu, treatments included unfertilized maize monocrop, maize monocrop receiving the current recommended fertilizer rate for maize in Malawi (a basal application of 23 kg N and 21 kg P / ha plus a topdress of 46 kg N / ha), maize cowpea intercrop receiving the recommended fertilizer rate, and cowpea monocrop receiving a reduced fertilizer rate (a basal application of 12 kg N and 11 kg P / ha). The maize variety planted in this trial was Sc403, and the cowpea variety planted was Sudan 1. Trial two at Kandeu included both maize treatments and the maize cowpea intercrop as above, but no sole cowpea. The maize variety planted at Kandeu two was DKC 8053, and the cowpea variety planted was IT82E-16. At Lintipe, trials one and two included unfertilized maize, maize at the recommended fertilizer rate, and sole cowpea at the reduced fertilizer rate. The maize variety planted at Lintipe trial one was PAN 53, and the cowpea variety was Sudan 1. At Lintipe trial two, the maize variety planted was DK 9089 and the cowpea variety was IT82E-16. At Golomoti trial one, treatments were the same as the Lintipe trials. Sc403 maize was planted at Golomoti, along with Sudan 1 cowpea. All varieties were sourced from development organizations active in Malawi. Insect pests were controlled in cowpea in all trials using dimethoate, an insecticide sometimes used by farmers.

All crops were planted in December 2012. Crops were planted on ridges formed by hand-hoe, following local practice. Maize densities ranged from 40,000 plants / ha to 67,000 plants / ha depending on the trial. Cowpea densities ranged from 67,000 plants / ha to 167,000 plants / ha, depending on the trial. Differences in plant population density between trials were due to local ridge spacing (between 0.6 and 1 meter apart), which differed in response to environmental yield potential, and variation in the spacing of cowpea on the ridge (between 10 and 15 cm apart). Maize was spaced at 25 cm along the ridge. While maize is less closely spaced in traditional intercrop systems, the "Sasakawa method" of 25 cm maize spacing is being actively promoted by extension and has been widely adopted by farmers in Malawi (Denning *et al.*, 2009). Intercrops were fully additive, such that in each trial where a maize cowpea intercrop was planted, maize density in intercrop was equal to maize density in monocrop, and cowpea density in intercrop equaled cowpea density in monocrop.

Soil sampling and analysis

We collected soil profile data from the first agronomic trial at each study location. Soil pits were dug to a depth of 120 cm approximately one month prior to the time of sampling. At the time of sampling, a new face was created using a spade. We then took samples from the fresh face at depths of 0 - 15 cm, 15 – 30 cm, 30 – 60 cm, 60 – 90 cm, and 90 – 120 cm. At each depth, we took one 98 cm^3 soil core, hammered into the side of the pit and carefully removed to keep the core intact. In addition, we took one sample of disturbed soil at each depth. At Kandeu, the pit could only be dug to a depth of 90 cm due to impenetrable clay subsoil, and 90-120 cm samples were not taken.

Additional samples were taken from three random points in all agronomic trials. Samples were taken with a hand hoe at three depths: 0 – 15, 15 – 30 and 30 – 60 cm. Samples from each depth were composited, resulting in one 0 – 15 cm, one 15 – 30 cm, and one 30 – 60 cm sample from each trial. At Lintipe trial two, hand hoe samples were taken at depths of 0 – 15 and 15 – 30 cm only.

We also sampled soils from fields belonging to farmers participating in the Africa RISING project and interviewed in the baseline 2013 household survey. Surveyed farmers ranked the soil in each of their fields as "very fertile", "somewhat fertile", or "not fertile". At each site, we purposively selected among fields located near the agronomic trials three fields that had been ranked as "very fertile" and three that had been ranked as "not fertile", for a total of six fields per location.

Samples were taken from three random points within each field at depths of 0 – 15 cm and 15 – 30 cm using a hand hoe. The three samples taken from each depth were composited, resulting in one sample from 0 – 15 cm and one from 15 – 30 cm from each field. At each field, we inquired which crops had been grown in the 2012 / 2013 season. We took GPS coordinates at all sampled fields using a Garmin eTrex 10 GPS unit.

All disturbed soil samples were passed through a 2mm sieve at the Bunda College of Agriculture soil lab, and rocks and large pieces of organic matter were discarded. Samples were air-dried, and a subsample was shipped to Michigan State University for physical and chemical analysis. Undisturbed soil cores were oven dried for 48 hours at 130^{o} C at the Bunda College of Agriculture, and dry soil from the cores was weighed to determine bulk density.

Soil texture was determined from sieved soil using the hydrometer method (Kellogg Biological Station LTER, 2008). Soil pH in distilled water at a 1:2 soil to water ratio was determined (Hendershot *et al.*, 1993), using a Metler Toledo SevenEasy S20 pH meter.

A subsample of each soil was pulverized using a shatter mill for chemical analysis. Total carbon and total nitrogen were determined from pulverized soil using a using a Carlo Erba NA1500 SeriesII Combustion Analyzer (Kellogg Biological Station LTER, 2003). Available P was determined from pulverized soil by the Michigan State University Soil and Plant Nutrition Laboratory using the Bray extraction method (Bray and Kurtz, 1945).

Table 2: Soil properties measured in experimental trials and used in subsequent modeling. Bulk density is given as BD; % C and % N indicate percent total C and N in the soil; Bray P indicates Bray-extractable phosphorus.

Depth (cm)	% Sand	% Silt	% Clay	BD (g/cm^3)	% C	% N	pH	Bray P (ppm)
Kandeu trial 1								
0-15	75	17	9	1.5	1.0	0.09	5.0	72.5
15-30	74	13	13	1.4	0.7	0.06	5.4	42.5
30-60	68	17	16	1.3	0.8	0.06	5.2	27.5
60-90	40	20	40	1.4	1.5	0.12	4.9	9.5
Kandeu trial 2								
0-15	59	12	29	NA	0.7	0.06	5.0	4.0
15-30	50	10	40	NA	0.4	0.05	4.8	2.0
30-60	47	11	43	NA	0.2	0.04	4.9	2.0
Lintipe trial 1								
0-15	22	29	48	1.4	2.3	0.13	4.9	13.5
15-30	19	26	55	1.5	2.2	0.12	4.9	12.5
30-60	18	24	58	1.3	2.0	0.11	5.0	8.5
60-90	6	16	78	1.4	0.7	0.05	5.1	2.5
90-120	5	19	76	1.3	0.4	0.04	5.2	2.5
Lintipe trial 2								
0-15	52	17	31	NA	1.5	0.10	5.1	9.5
15-30	38	16	46	NA	1.7	0.10	5.2	3.0
Golomoti trial 1								
0-15	52	22	26	1.4	0.9	0.06	4.5	56.5
15-30	43	20	37	1.4	0.5	0.05	4.2	20
30-60	34	19	47	1.3	0.1	0.04	4.9	12
60-90	27	22	51	1.5	0.2	0.05	4.3	16.5
90-120	29	21	50	1.7	0.2	0.02	4.2	12

Crop modeling

Model calibration and validation

Crop models in APSIM version 7.5 were parameterized using soil data collected from the agronomic trials at each of the study locations. For the first trial at each location, data on soil C, soil N, pH, bulk density and texture from depths of 0 - 15, 15 - 30, 30 – 60, 60 – 90, and 90 - 120 cm were used in model parameterization (Table 3). For Kandeu trial one, sampled soils from 60 – 90 cm were used to parameterize the 60 – 90 and 90 – 120 cm soil layers.

For the second trial at each location, data on soil C, soil N, pH and texture from depths of 0 - 15, 15 - 30 and 30 - 60 cm were used to parameterize models. At Lintipe trial two, data from 0 -15 and 15 - 30 cm only were collected. Data from trial 1 were used to parameterize the 60 – 90 and 90 – 120 soil layers at trial two. In addition, bulk density data from trial one were used to parameterize trial two

Soil water at saturation, field capacity, and the 15-bar lower limit were determined using pedo-transfer functions based on % sand, % clay, % soil organic matter, and bulk density (Saxton and Rawls, 2006) (Table 3). We determined soil organic matter as a function of total soil carbon (Sleutel *et al.*, 2007). Additional soil parameters, including soil water at air dry, crop LL, crop PAWC, crop XF, initial soil water, and initial mineral N were obtained from a library of generic soil profiles for APSIM (APSIM Initiative, 2013). For each trial, we selected a generic soil profile that was as similar as possible to the actual soil. For the first Kandeu trial, sampled soils from 60 – 90 cm were used to parameterize the 60 – 90 and 90 – 120 cm soil layers (Mabapa *et al.*, 2010).

For the second trial at each location, models were parameterized based on data from soils collected from depths of 0 - 15, 15 - 30 and 30 - 60 cm. At Lintipe data from 0 - 15 and 15 - 30 cm only were collected. Bulk densities from trial one, along with texture and organic matter from trial two, were used to compute soil water properties in these soil layers (Saxton and Rawls, 2006). Data from trial 1 were used to parameterize the 60 – 90 and 90 – 120 soil layers at trial two.

Soil parameters required by APSIM include organic carbon. We used measured values of total soil carbon as a proxy for organic carbon. As pH values were below 6 at all agronomic trials (Table 2), we judged our soils to be low in inorganic calcium carbonates. Furthermore, our measurements of total carbon fall well within the range of organic carbon values found in farmers' fields in the study region (Snapp 1998).

Daily rainfall data gathered by the extension planning area office at each study site from 2011 – 2013 were used for purposes of model calibration. Temperature and solar radiation data were obtained from the National Centers for Environmental Protection Climate Forecast System Version Two, which includes daily meteorological data at all points on the globe at a resolution of 0.25 degrees latitude and longitude (Saha *et al.*, 2014).

Calibration models were run from October 2011 through September 2013, re-setting all soil water, soil C, soil N, and surface organic matter parameters at the end of each growing season. The APSIM phosphorus module was not used, and P dynamics were not simulated. Modeled yields from the 2012-2013 season were then compared with measured yields for that season. Models were calibrated by adjusting non-soil model parameters until the modeled yields fell as close as possible to measured yields (Table 3). Measured yields from the two experimental trials at the Lintipe and Kandeu sites were used in model calibration and validation.

At the Golomoti site, models were calibrated using trial 1 only. It should be noted that planting times were adjusted in model calibration, resulting in cowpea being planted after maize in the best calibrated models at each site (Table 3). In contrast, maize and cowpea were planted simultaneously in our field trials.

At Kandeu and Lintipe, we selected an optimal calibration for each location using a cross-calibration procedure modified from Xiang et al (2008). The calibrated model for trial 1 at each site was validated against trial two by re-parameterizing it with soil data from trial two and comparing modeled yields with measured yields from trial two. The calibrated model for trial two was validated against trial one in a similar fashion. We identified the model calibration which, when validated, showed the least deviation between modeled and observed yields. This calibration was used in all further simulation exercises. As the soils in the two trials differed considerably in both texture and organic matter (Appendix A), cross-validation helped ensure that the model was capable of accurately simulating crop growth under a range of soil conditions.

Table 3: Parameters manipulated during model calibration. Values listed are the final values used in long-term simulation of cropping systems.

	Kandeu (trial 2)	Lintipe (trial 1)	Golomoti (trial 1)
Fbiom (fraction organic carbon in microbial biomass; 0-15, 15-30, 30-60, 60-90 and 90-120 cm)	0.015, 0.015, 0.015, 0.01, 0.01	0.015, 0.015, 0.015, 0.01, 0.01	0.01, 0.01, 0.01, 0.01, 0.01
Finert (fraction inert organic carbon; 0-15, 15-30, 30-60, 60-90 & 90-120 cm)	0.8, 0.8, 0.8, 0.8, 0.9	0.67, 0.67, 0.67. 0.8, 0.9	0.8, 0.8, 0.9, 0.9, 0.9
Maize variety	pan6671	r215	pan6671
Maize XF (root penetration factor; 0-15, 15-30, 30-60, 60-90, 90-120 cm)	0.7, 0.7, 0.7, 0.4, 0.3	0.5, 0.5, 0.5, 0.2, 0.2	0.4, 0.4, 0.4, 0.3, 0.3
Maize planting density (plants / m^2)	4	6	4
Maize topdress (days after planting)	60	72	52
Cowpea variety	spreading	spreading	Spreading
Cowpea XF (root penetration factor; 0-15, 15-30, 30-60, 60-90, 90-120 cm)	0.3, 0.3, 0.3, 0.2, 0.2	0.5, 0.5, 0.5, 0.5, 0.5	0.3, 0.3, 0.3, 0.2, 0.2
Cowpea planting density (plants /m^2)	5	10	5
Cowpea planting window	01 jan – 15 feb	01 jan – 15 feb	01 jan – 15 feb

Exploratory modeling

We performed exploratory modeling to contrast the performance of monocrop and intercrop systems across 26 growing seasons under varying input conditions and fertility regimes. Models were run from October 1 1979 through September 30 2005. A complete set of model parameters used in exploratory simulation is included in Appendix B. Temperature and rainfall data for long-term simulations were obtained from Malawi Meteorological Service stations that were located nearby and at similar elevation to the study sites. The best station to represent each study location was selected by comparing rainfall values measured by the extension planning area office at each study location for the years 2010 – 2013 with nearby meteorological stations (Figure 1). Solar radiation data were obtained from the National Centers for Environmental Protection Climate Forecast System reanalysis, which includes daily meteorological data at all points on the globe at a resolution of 0.3 degrees latitude and longitude (Saha *et al.*, 2010).

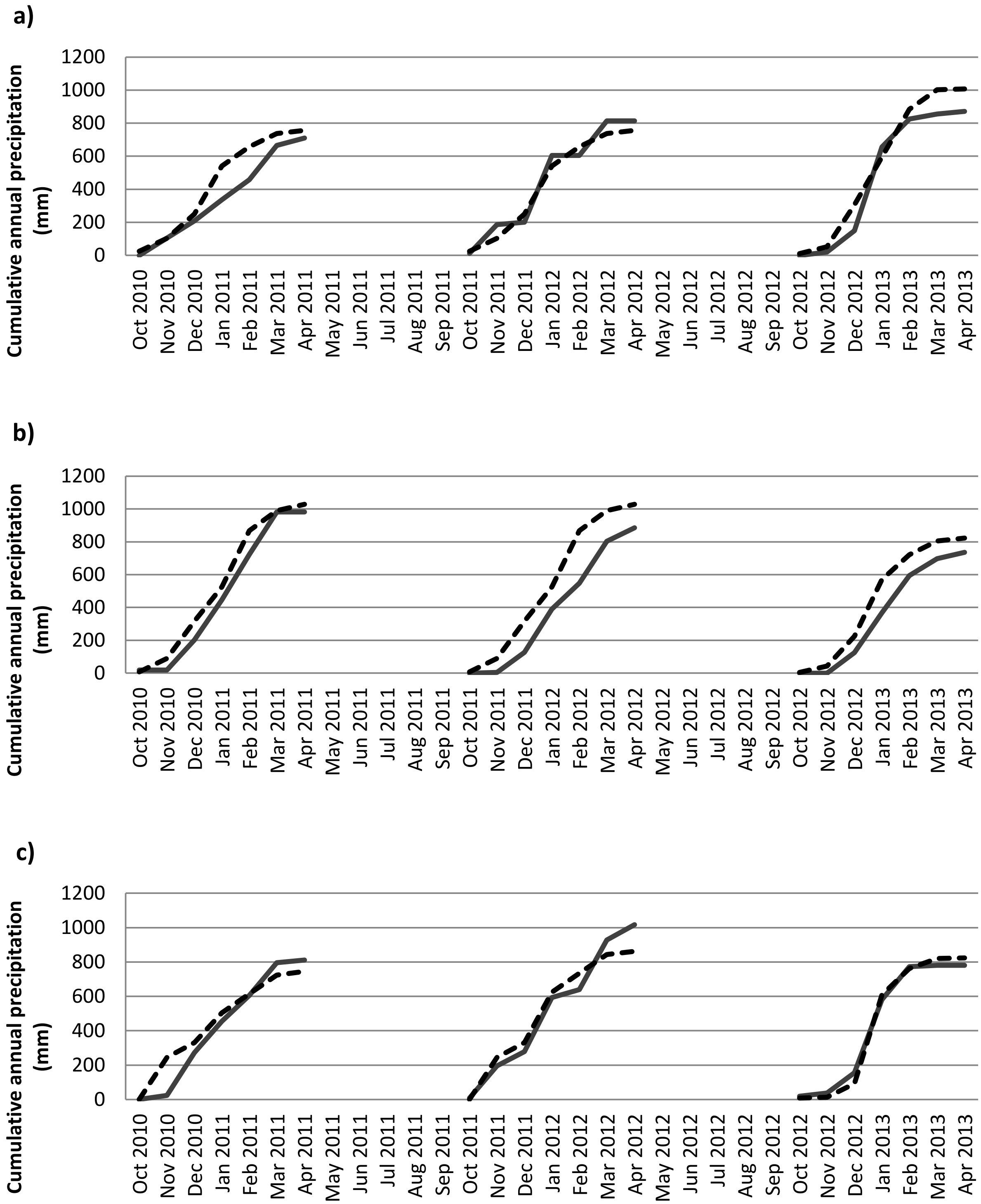


Figure 1: Comparison of cumulative precipitation at the study locations with precipitation at nearby meteorological stations. Locations are Kandeu (a), Lintipe (b) and Golomoti (c) while meteorological stations are Chileka (a), Dedza (b) and Monkey Bay (c). Data from study locations are represented by solid lines; data from meteorological stations by dashed lines.

Cowpea monocrop, maize monocrop, and maize / cowpea intercrop systems were modeled in long term simulations. Each system was modeled under two nutrient input conditions: 0kg N / ha, and 69kg N / ha split into starter (23kg N / ha) and topdress (46kg N / ha) applications. For Lintipe and Kandeu, model parameters in long-term simulations were taken from the calibrated model that displayed the least deviation from observed yields when validated. For Golomoti, calibrated parameters for trial one were used.

Long-term models were run using two levels of soil organic matter. From soil samples taken from 0 - 15 cm and 15 - 30 cm from six farmers' fields at each site, we selected the soil with the highest total C and the soil with the lowest total C (Table 4). Using total C and total N values from the high and low C soil, we re-calculated soil water properties and re-parameterize the model for organic C, C:N ratio, and soil water properties. All other model parameters remained identical between the high organic matter and the low organic matter soil.

Table 4: Soil C and N used in high organic matter and low organic matter soils in long-term simulation models. These values are based on samples taken from farmers' fields in each study location (Appendix A).

		High organic matter soil		Low organic matter soil	
		% total C	% total N	% total C	% total N
Lintipe	0-15 cm	2.241	0.132	1.291	0.079
	15-30 cm	1.894	0.089	1.028	0.071
Golomoti	0-15 cm	1.250	0.096	0.665	0.060
	15-30 cm	1.228	0.093	0.653	0.058
Kandeu	0-15 cm	0.819	0.070	0.446	0.050
	15-30 cm	0.760	0.063	0.312	0.043

Exploratory models were first run without cropping history effects. To accomplish this, we re-set all soil water, soil C, soil N, and surface organic matter parameters at the end of each growing season. This treated each simulated season as though it were the first season of establishment for the system. Models where then run a second time without re-sets, allowing effects of cropping history to accumulate. This simulated cropping systems grown for 26 consecutive years.

Statistical analysis

Analysis of agronomic trials

Analysis of variance models were used to test for treatment effects in all agronomic trials. Tukey's Honestly Significant Difference test was used to test for differences between fertilized and unfertilized maize monocrop in all trials, and between fertilized maize in monocrop and fertilized maize in intercrop with cowpea at Kandeu trials one and two.

Stability analysis

We performed stability analysis on the total calorie and protein yields from maize cowpea intercrop, and for the two crops in monocrop (as in a field planted half in maize and half in cowpea). Simulated yields in each year were plotted against an environmenal index consisting of the mean yield for all systems in each year. Sensitivity analysis provides a visual representation of how systems perform relative to one another under a range of environmental conditions. The approach can be used to assess how stable systems are in the face of inter-annual or geographic variation (Hildebrand and Russell 1996). Stability analysis has been used to explore the stability of maize / cowpea intercrop systems across a range of geographic locations (Faris et al. 1983). Stability analysis has also been used, as in our case, to depict yield stability across a range of growing seasons (Lightfoot *et al.*, 1987).

Risk analysis

We performed risk analysis on each cropping system. In risk analysis, systems are compared based on their chance meeting or exceeding a minimal acceptable value (Hildebrand

and Russell, 1996). For smallholder farming households, the chance of producing enough food to meet household food needs has been used as a minimum acceptable value in risk analysis (Kamanga *et al.*, 2010; Snapp *et al.*, 2014).

The calories and protein per-acre that must be produced to meet the nutritional needs of a typical farming household were calculated based on mean household size and landholding at each study location,. We obtained average daily calorie and protein requirements for children 0 – 14 years of age, adults 15 – 69 years engaged in moderate to heavy activity, and seniors 70 years and older, from the Food and Agriculture Organization (2004) and World Health Organization (2007). We determined the average number of children 14 and under, adults 15 – 69, and seniors 70 and over, along with average household landholding, based on our survey of households at the Africa RISING study locations (Table 5).

Table 5: Household composition and landholding based on surveys of farming households at the study locations. Calorie and protein production per hectare required to meet household needs are indicated by "Calories req." and "Protein req."

	Children under 15	Adults 15 – 69	Seniors 70 and over	Landholding (ha)	Calories req. (Mcal / ha / yr)	Protein req. (kg / ha / yr)
Lintipe	2.40	2.65	0.11	0.71	6097	114
Golomoti	2.48	2.54	0.09	0.83	5121	95
Kandeu	2.21	2.80	0.16	0.89	5005	94
Average	2.36	2.66	0.12	0.81	5365	100

Risk was calculated for each location as the probability of a cropping system meeting or exceeding the protein and calorie requirements of a typical household. We calculated calorie and protein production from each cropping system based on nutritional values obtained for crops in Malawi (N. Drost, unpublished data). The probability of each household meeting its calorie and protein needs with each cropping system was calculated as

$$P_{ht} = P(y_{cst} * a_h \geq r_{hc} \cap y_{pst} * a_h \geq r_{hp})$$

Where P_{ht} is the probability of household *h* meeting its calorie and protein needs using treatment *t*, y_{cst} and y_{pst} are the simulated calorie and protein yield per hectare in season *s* for treatment *t*, a_h is the area of arable land farmed by household *h*, in hectares, and r_{hc} and r_{hp} represent the total calorie and protein requirements for household *h* (Snapp *et al.*, 2014). Treatments *t* included maize cowpea intercrop at 0 kg N / ha, maize and cowpea monocrops at 0 kg N / ha (as in a field split half into maize and half into cowpea) maize cowpea intercrop at 69 kg N / ha, and maize and cowpea monocrops at 69 kg N / ha.

RESULTS

Farming household characteristics and practices

Use of legume crops by farmers differed by study location. At Kandeu groundnut was the most commonly grown legume, and it was not typically grown in intercrop with maize (Figure 2). Common bean, soybean, and cowpea were also relatively commonly grown at Kandeu, and most households growing these legumes intercropped them with maize. At Lintipe common bean was by far the most commonly grown legume, and most households growing common bean grew it in intercrop with maize. Groundnut was the second most commonly grown, and very few households intercropped groundnut with maize. Few households at Lintipe grew cowpea, and anecdotal reports from farmers and local extensionists suggest that it is particularly prone to attack by aphids at this site, though the causes of this susceptibility are not known. At Golomoti cowpea was the most commonly grown legume, and most households growing cowpea intercropped it with maize. Other legumes were not commonly grown at Golomoti, and anecdotal reports suggest that other legumes are unable to perform well in the dry conditions found at this site.

Farmers' use of fertility inputs differed by cropping system. Across all three study sites, 69% of households reported growing maize in intercrop with legumes, while 41% reported growing maize in monocrop (Figure 3). The majority of farmers growing maize in intercrop or monocrop applied mineral fertilizer, while a smaller but still considerable portion applied animal manure or vegetable compost to maize. Some farmers used both mineral fertilizer and manure or vegetable compost. Legumes grown in sole crop were almost never fertilized, either with mineral fertilizer or manure / compost.

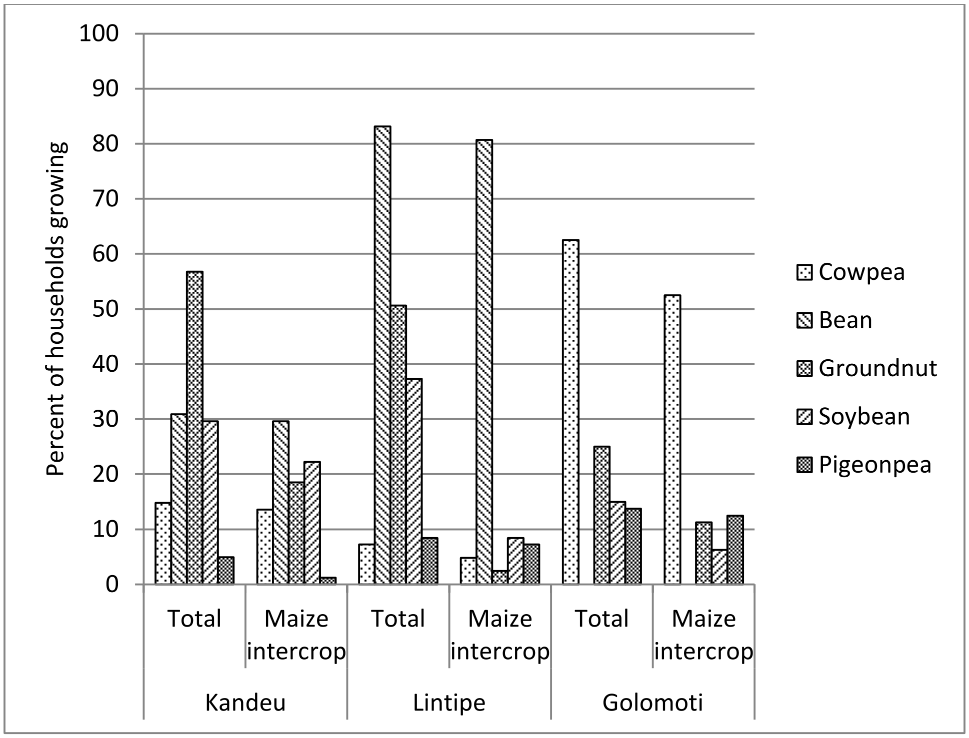


Figure 2: Percent of households growing legume crops, and percent growing legumes in intercrop with maize.

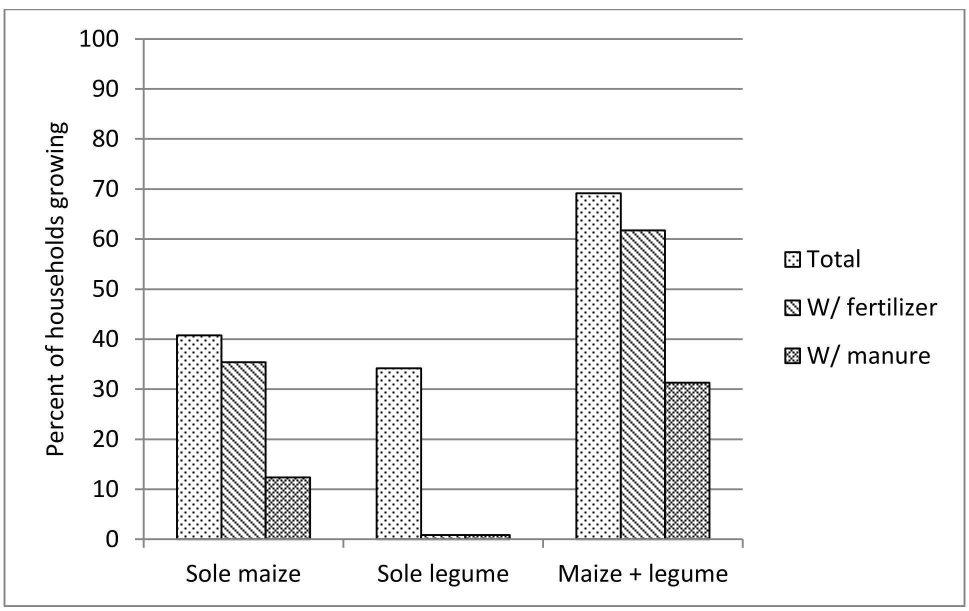


Figure 3: Percent of households growing sole maize, sole legumes, and maize legume intercrops, and percent applying mineral N fertilizer and manure to these systems. Manure includes animal waste and vegetable compost. Note that some households applied both fertilizer and manure.

Agronomic trials

There was a positive effect of fertilization with 69 kg N / ha in all agronomic trials (Table 6; Figure 4). There was no significant effect of intercropping on maize yields at either of the trials at Kandeu. Maize cowpea intercrops were not grown at the Lintipe and Golomoti locations.

Table 6: Comparison of mean yields in agronomic trials at all study locations in the 2012-2013 growing season. P-values for comparisons of trials were generated using Tukey's HSD tests. Cropping systems are abbreviated as Mz 0N = unfertilized sole maize; Mz 69N = sole maize with 69 kg N / ha and 22 kg P / ha applied; Inter 69N Mz = maize yield in intercrop with cowpea with 69 kg N / ha and 22 kg P / ha applied.

	Df treat. (residual)	Sum of squares	Mean square	F	Model p-value	Comparison	Comp. p-value
Kandeu 1	2(6)	28798195	14399098	70.56	0.0001	Mz 69N / Inter 69N Mz	0.3433
						Mz 0N / Mz 69N	0.0001
Kandeu 2	2(6)	14061350	7030675	55.84	0.0001	Mz 69N / Inter 69N Mz	0.8098
						Mz 0N / Mz 69N	0.0002
Lintipe 1	1(4)	40080576	40080576	236	0.0001	Mz 0N / Mz 69N	0.0001
Lintipe 2	1(4)	36469791	36469791	542.6	0.0001	Mz 0N / Mz 69N	0.0001
Golomoti 1	1(4)	8368305	8368305	93.13	0.0006	Mz 0N / Mz 69N	0.0006

Model calibration and validation

After model calibration, crop simulations were able to reasonably approximate observed yields in the 2012 - 2013 season. In most cases, simulated yields were brought within one standard error of the mean observed yield after calibration (Figure 4). Model calibrations for some study locations performed better in crossvalidation than others. When model parameters calibrated for Kandeu 1 were used to simulate Kandeu 2, maize at 0 kg N / ha produced nearly double the observed yields. When the Kandeu 2 calibration was used to simulate Kandeu 1, most simulated yields reasonably approximated observed yields, with maize at 69 kg N / ha noticeably under-yielding. When the Lintipe 1 calibration was used to simulate Lintipe 2, simulated yields fell very close to observed yields. However, when the Lintipe 2 calibration was used to simulate Lintipe 1, maize under-yielded considerably in monocrops at 69 kg N / ha. We used calibrated models for Kandeu 2, Lintipe 1, and Golomoti 1 in all further simulations.

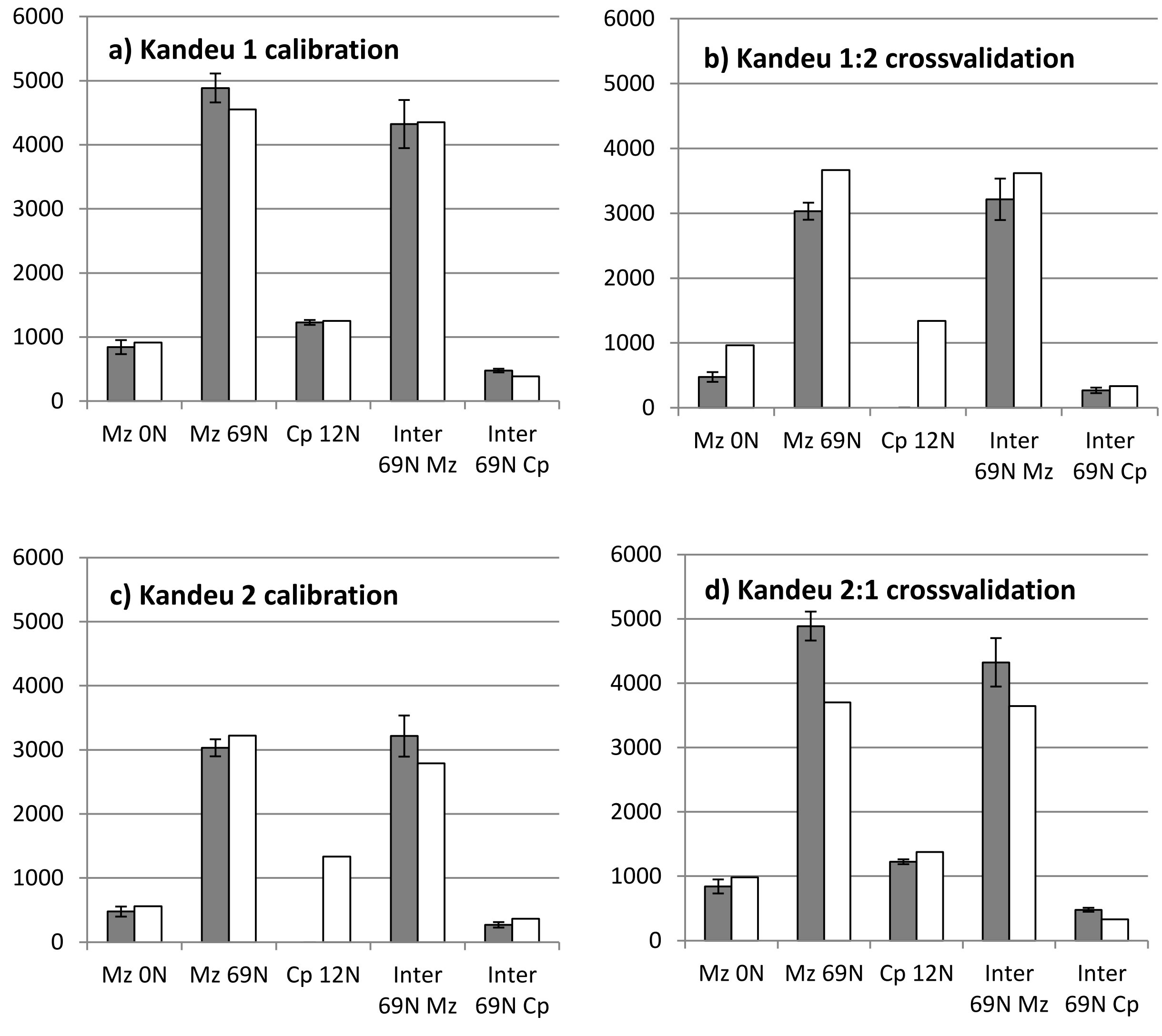
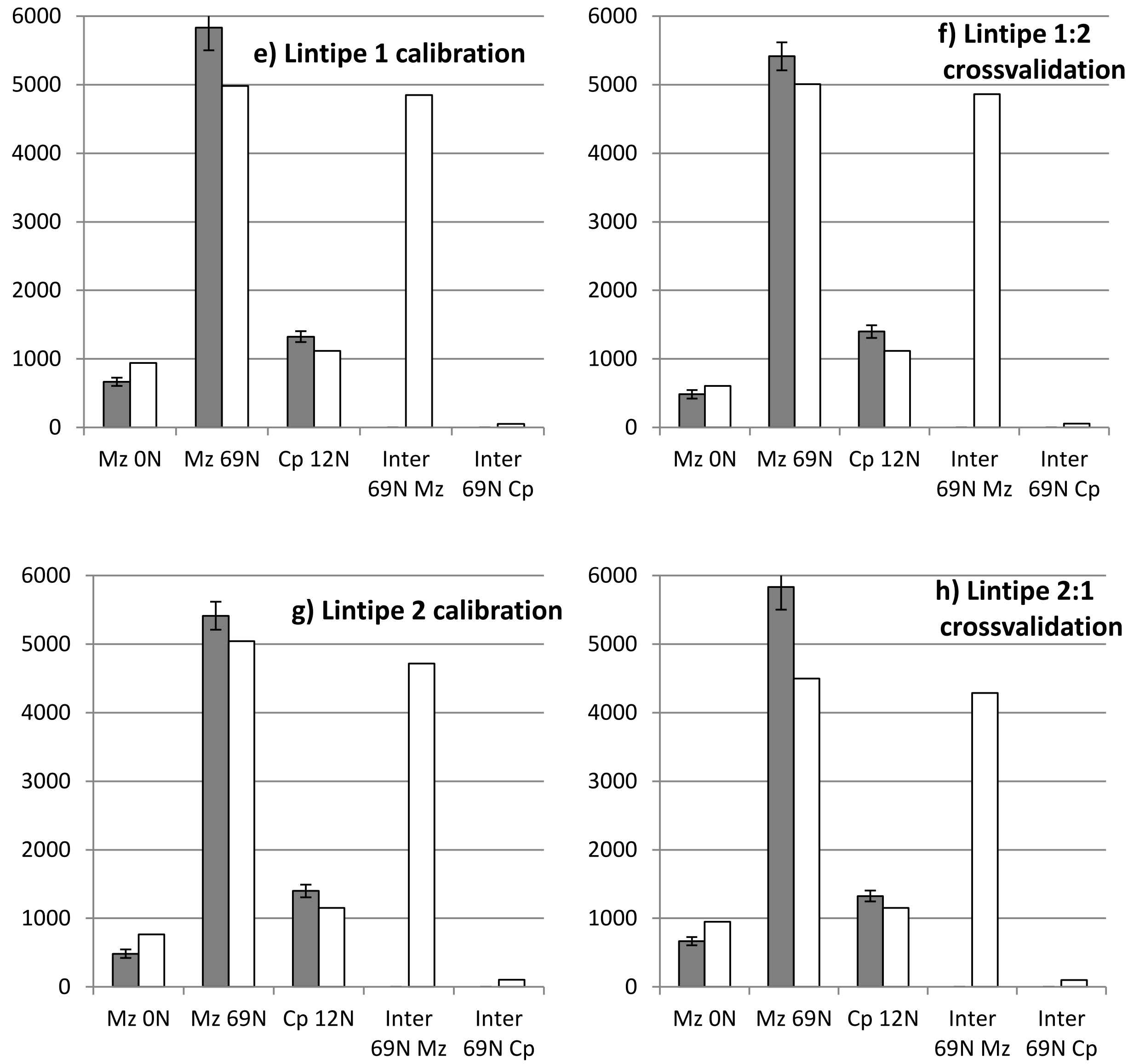


Figure 4: Calibration and crossvalidation of crop simulation models. Shaded bars are mean simulated grain yields with error bars showing one standard error of the mean. White bars are modeled yields. Cropping systems are abbreviated as Mz 0N = sole maize with 0kg N / ha applied; Mz 69N = sole maize with 69 kg N / ha applied; Cp 12N = sole cowpea with 12 kg N / ha applied; Inter 69N Mz = maize yield in intercrop with cowpea with 69 kg N / ha applied; Inter 69N Cp = cowpea yield in intercrop with maize with 69 kg N / ha applied.

Figure 4 (cont'd)



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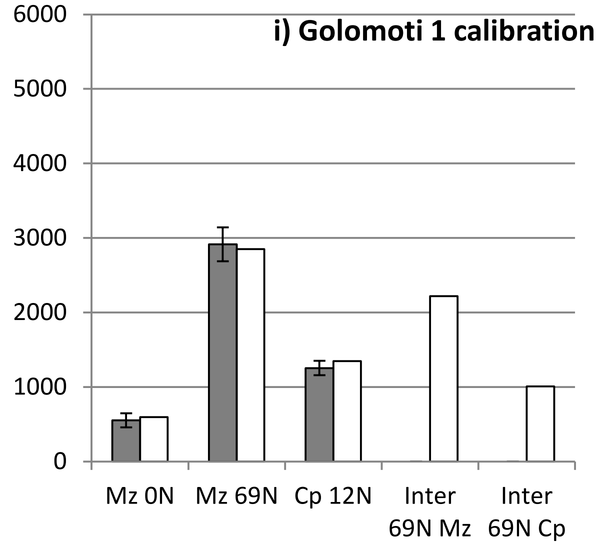

Modeled yields

In long-term simulations (1980 – 2005) in which soil parameters were re-set every year to eliminate effects of cropping history, the relationship between maize yields in intercrop and yields in monocrop varied by study location and by rates of N input (Figure 5, Figure 6). When 0 kg N / ha were applied, intercropped maize yields at the Lintipe study location under all soil conditions were approximately half of maize yields in comparable monocrops. In contrast, at the Kandeu and Golomoti study locations, maize yields in intercrop and monocrop were equivalent under all soil conditions when 0 kg N / ha were applied. When 69 kg N / ha were applied, maize yields in intercrop were roughly equivalent to yields in monocrop at all study locations and in all soils. Cowpea yields in intercrop were lower than yields in monocrop at all study locations, soils and N rates.

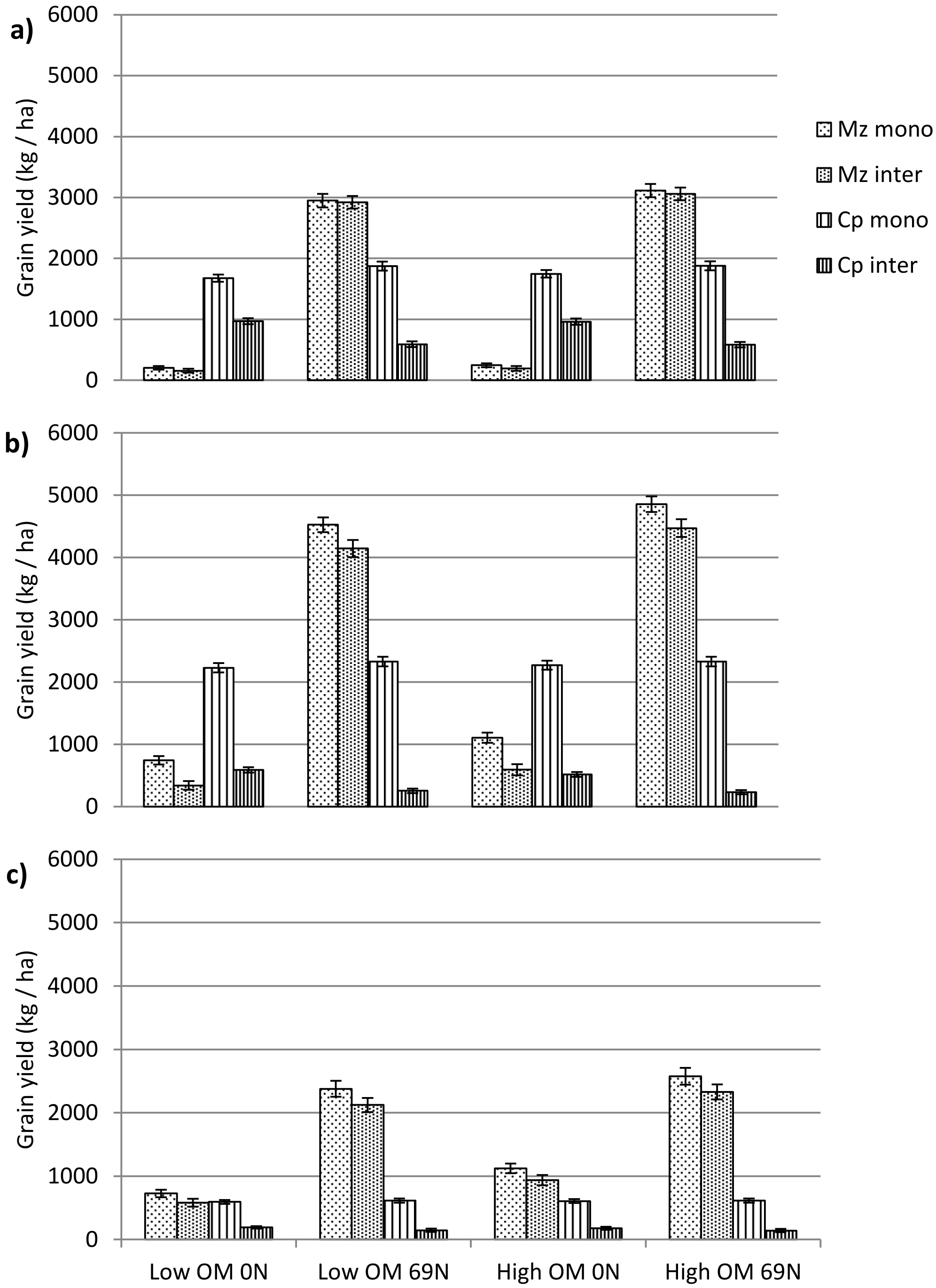

Figure 5: Modeled grain yields of cropping systems from 1980 – 2005. Soil parameters were re-set annually to remove effects of cropping history at the Kandeu (a), Lintipe (b), and Golomoti (c) study locations. Soil organic matter designated by "Low OM" and "High OM"; nitrogen inputs (kg / ha) designated by "0N" and "69N". Cropping systems abbreviated as Mz mono = maize monocrop, Mz inter = maize intercropped with cowpea, Cp mono = cowpea monocrop, Cp inter = cowpea intercropped with maize. Bars show mean yield across all years; error bars show one standard error of the mean.

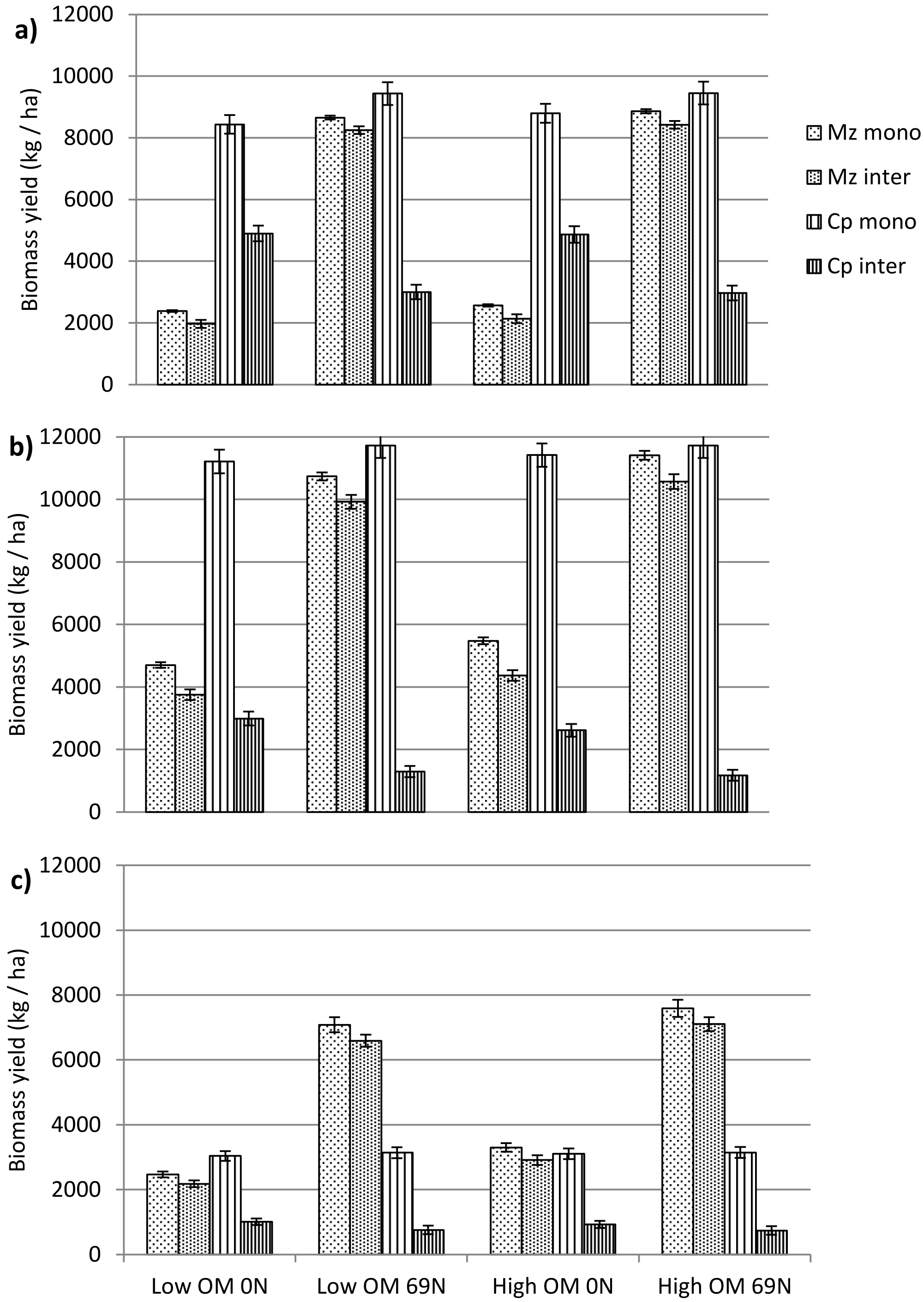

Figure 6: Modeled biomass yields of cropping systems from 1980 – 2005. Soil parameters were re-set annually to remove effects of cropping history at the Kandeu (a), Lintipe (b), and Golomoti (c) study locations. Soil organic matter designated by "Low OM" and "High OM"; nitrogen inputs (kg / ha) designated by "0N" and "69N". Cropping systems abbreviated as Mz mono = maize monocrop, Mz inter = maize intercropped with cowpea, Cp mono = cowpea monocrop, Cp inter = cowpea intercropped with maize. Bars show mean yield across all years; error bars show one standard error of the mean.

When soil parameters were not re-set every year, allowing yields to be affected by cropping history, intercropped maize tended to out-yield equivalent maize monocrops (Appendix C Figure 1). This was particularly true under unfertilized conditions, where intercropped maize drastically out-performed maize monocrop at all study locations and in all soils. When 69 kg N / ha were applied, maize in intercrop produced somewhat higher yields than maize in monocrop under all soil conditions at the Kandeu location, while monocropped and intercropped maize produced equivalent yields at Lintipe and Golomoti. Cowpea produced lower yields in intercrop than in monocrop at all study locations and under all soil conditions.

We ran models in which soil parameters were not re-set as an exploratory exercise, to see whether the relative advantages of intercrop and monocrop systems might differ due to the effects of cropping history. In APSIM, cropping history effects are primarily driven by biomass production and its contribution to soil C and N reserves (Probert *et al.*, 1998). Our confidence in these models is therefore limited, as we did not calibrate them based on measures of biomass production in the field. These results are the product of built-in assumptions in APSIM about the ratio of grain yield to biomass production for the cultivars used in our simulations, and the accuracy of these assumptions in our study locations has not been supported with data from the field. We therefore chose to perform all further analysis using models in which soil parameters were re-set every year.

Stability analysis

The relationship of calorie yields in maize cowpea intercrops to equivalent maize and cowpea monocrops varied by study location and N input (Table 7, Figure 7). In Kandeu, calorie yields in intercrop were higher than calorie yields in monocrop across the full range of environmental conditions, from the most favorable season and soil to the least favorable season and soil. This was true under both 0 kg N / ha and 69 kg N / ha. At Lintipe, on the other hand, calorie yields in intercrop were lower than those in monocrop under the full range of environmental conditions when 0 kg N / ha were applied, and higher when 69 kg N / ha were applied. At Golomoti, calorie yields were higher in intercrop at 69 kg N / ha under the full range of environmental conditions. When 0 kg N ha were applied, calorie yields were similar in monocrop and intercrop under less favorable environmental conditions, and higher in intercrop under more favorable conditions.

The relationship of protein production in maize cowpea intercrops to protein production in equivalent monocrops also varied by study location (Table 7, Figure 7). In Kandeu, intercrops consistently produced more protein / ha than monocrops when fertilized with 69 kg N / ha. With no N fertilization, intercrops produced similar amounts of protein to monocrops when environmental conditions were unfavorable, and more than monocrops when environmental conditions were favorable. In Lintipe, intercrops produced less protein than monocrops under the full range of environmental conditions, regardless of N fertilization. At Golomoti, intercrops and monocrops fertilized with 69 kg N / ha produced similar amounts of protein in unfavorable environmental conditions. Under more favorable conditions, intercrops began to produce more protein than monocrops. In unfertilized cropping systems at Golomoti, intercrops produced less protein than monocrops under unfavorable environmental conditions, and more than monocrops under favorable environmental conditions.

Calorie and protein production in maize / cowpea intercrop systems tended to be less stable across environmental conditions than in equivalent monocrops (Figure 7). This can be observed in the steeper slopes of intercrop yields when plotted against the environmental index, indicating that intercrops exhibit a sharper response to changes in environmental conditions. In many cases, this was due to intercrops producing higher calorie yields than monocrops under the most favorable environmental conditions, and equivalent or only somewhat higher yields under unfavorable conditions. Therefore, though intercrop systems were less stable than monocrops, they tended to produce more calories and protein than monocrops under the full range of environmental conditions. Exceptions to this general trend occurred in Lintipe. When 0 kg N / ha were applied at Lintipe, the intercrop system produced very low calorie yields under less favorable conditions, and only approached calorie yields in monocrop under more favorable conditions. Protein yields were consistently lower in intercrop than in monocrop at Lintipe. Protein yield stability was similar in monocrop and intercrop systems.

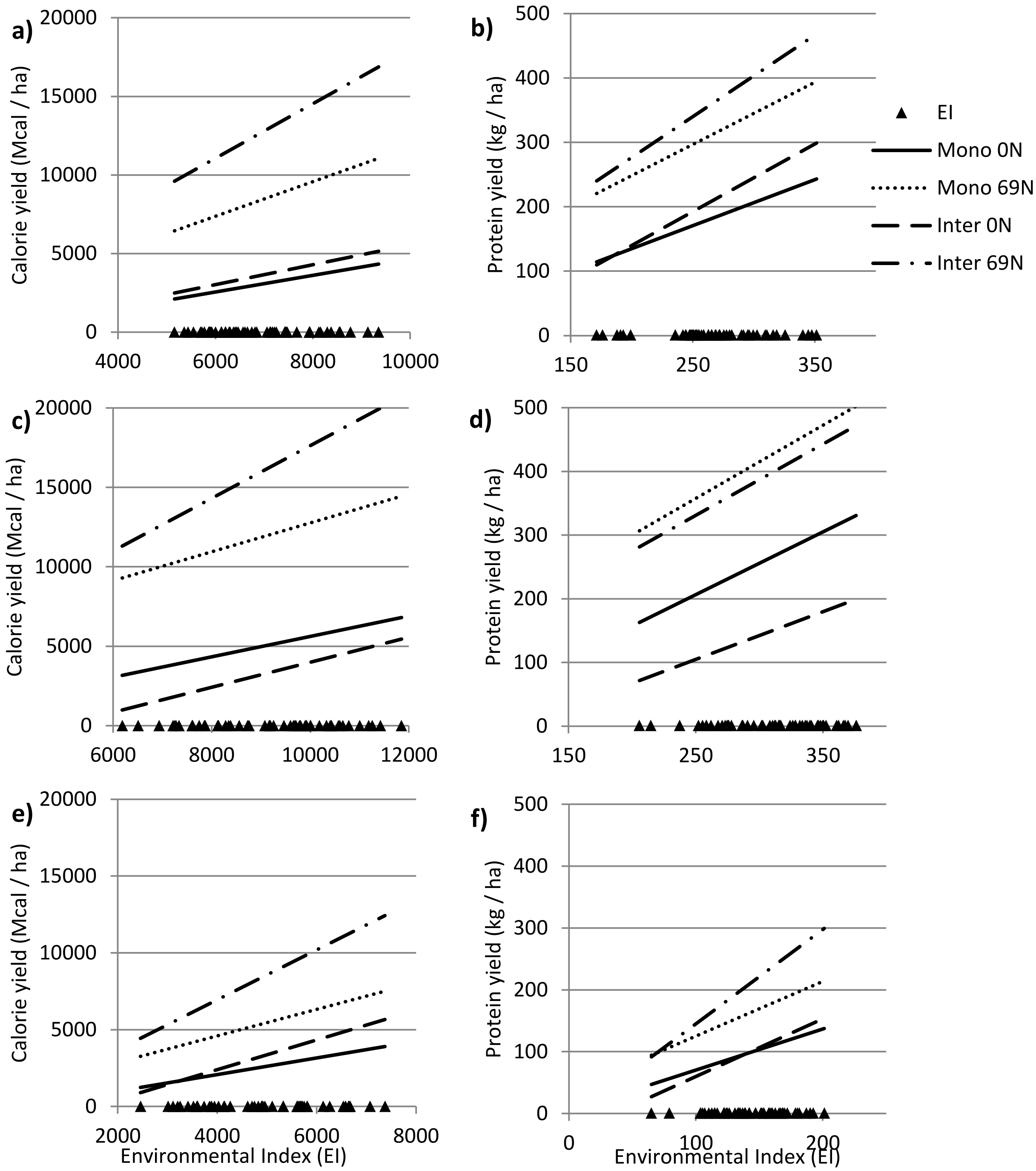

Figure 7: Stability analysis of calorie and protein yields from modeled cropping systems. Given as Kandeu calories (a), Kandeu protein (b), Lintipe calories (c), Lintipe protein (d), Golomoti calories (e), Golomoti protein (f). Calorie yields for each system in each year are plotted against an environmenal index consisting of the mean for all systems in each year. Datapoints were fit using linear regressions (Table 7). Cropping systems are abbreviated as Mono 0N = maize and cowpea monocrop at 0 kg N / ha; Mono 69N = monocrop at 69 kg N / ha; Inter 0N = maize cowpea intercrop at 0 kg N / ha; Inter 69N = intercrop at 69 kg N / ha.

Table 7: R^2 values for linear regressions used in stability analysis plots. Stability analysis plots are given in Figure 7.

		Mono 0N	Mono 69N	Inter 0N	Inter 69N
Kandeu	Calories	0.727	0.818	0.512	0.869
	Protein	0.740	0.687	0.699	0.787
Lintipe	Calories	0.682	0.801	0.655	0.806
	Protein	0.800	0.855	0.616	0.594
Golomoti	Calories	0.715	0.732	0.722	0.907
	Protein	0.673	0.651	0.711	0.832

Risk analysis

The chance of a typical household meeting their calorie and protein needs with their own production was influenced by location, N input, soil organic matter, and cropping system (Figure 8). Households at Lintipe had the highest overall chance of meeting calorie and protein needs, followed closely by Kandeu. At Golomoti, the chance of meeting calorie and protein needs was much lower. At all sites, households had a higher chance of meeting their calorie and protein needs when 69 kg N / ha were applied than under unfertilized conditions. At the Kandeu and Lintipe study locations, households met 100% of their needs under fertilized conditions in every year that the simulation was run. At all sites, high organic matter soils produced a higher chance of meeting calorie and protein needs than low organic matter soils. However, this effect was slight in comparison with the effect of soil fertility.

The typical household experienced a higher chance of meeting household calorie and protein needs with their own production using maize cowpea intercrop than using maize and cowpea monocrops at the Kandeu and Golomoti study locations. This intercrop advantage was present both in unfertilized and fertilized systems, and in low organic matter and high organic matter soils. At Lintipe, on the other hand, households experienced a higher chance of meeting calorie and protein needs using unfertilized maize and cowpea monocrops than using an unfertilized maize / cowpea intercrop. The reverse was true under fertilized conditions.

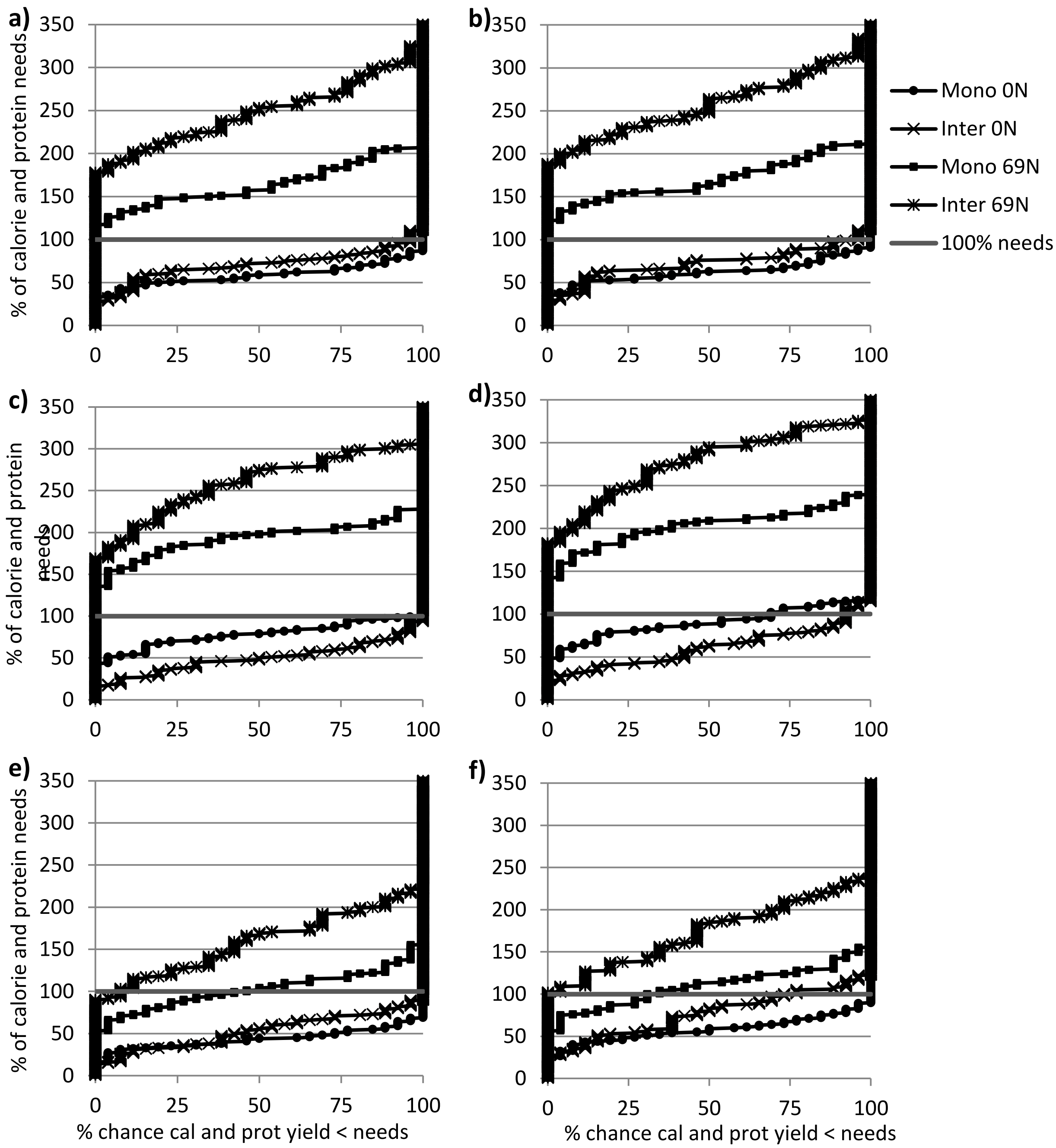

Figure 8: Probability that average households will meet calorie and protein needs with their own production. Given for low organic matter soil at Kandeu (a), high organic matter soil at Kandeu (b), low organic matter soil at Lintipe (c), high organic matter soil at Lintipe (d), low organic matter soil at Golomoti (e) and high organic matter soil at Golomoti (f). The chance that a cropping system fails to meet household calorie and protein needs is plotted against percent of household calorie and protein needs. Therefore, a point at 100% on the y axis and 40% on the x axis indicates that a system fails to meet 100% of household calorie and protein needs 40% of the time.

DISCUSSION

In all study locations and cropping systems examined, maize was severely N limited in unfertilized systems. Addition of 69 kg N / ha, the current recommended rate for maize in Malawi, increased maize yields in intercrop and monocrop dramatically. Fertilized maize produced the highest yields at Lintipe, followed by Kandeu, while producing lower yields at Golomoti (Figures 5 and 6). This trend in N response is very likely due to water limitation at Golomoti and Kandeu. While the three sites do not differ greatly in annual rainfall (Figure 1), mean temperatures are lowest at Lintipe, higher at Kandeu, and highest at Golomoti. This would increase the rate of evapotranspiration, depleting soil reserves at the latter sites. In addition, soils at Lintipe have higher clay content than Kandeu or Golomoti (Table 2), making for increased water holding capacity at Lintipe. Decreased N response under water-limited conditions has frequently been observed in both maize monocrop and maize intercrop systems (Kurtz *et al.*, 1952; Yamoah *et al.*, 2000), supporting water limitation as a cause for the differing N response between sites.

Cowpea did not appear to be N limited in any of the cropping systems examined in this study. Cowpea yields in monocrop remained relatively constant across 0 kg N / ha and 69 kg N / ha treatments (Figures 5 and 6). Cowpea typically does not exhibit a strong response to soil applications of N (Elowad and Hall, 1987), which is to be expected given its ability to supply the majority of N needs through biological N fixation (Vesterager *et al.*, 2008), though response to N fertilization has been observed in some cowpea systems (Rusinamhodzi *et al.*, 2012). The lack of N response by cowpea also accords with farmer practice. Farmers in our study locations virtually never applied fertility inputs to sole legume crops (Figure 2). This suggests that farmers are fully aware that they will achieve a greater response by applying their limited fertility resources to maize-based systems.

Relative yields of maize and cowpea in monocrop and intercrop differed between sites when each season was treated as the first season of establishment. Under unfertilized conditions, sole cropped maize produced comparable grain yields in monocrop and intercrop at both Kandeu and Golomoti, while cowpea yield was suppressed in intercrop (Figure 5). At Lintipe, on the other hand, both maize and cowpea yields were suppressed in intercrop under unfertilized conditions. This indicates that maize was competitively dominant under unfertilized conditions at Kandeu and Golomoti, while at Lintipe neither maize nor cowpea were clearly dominant, resulting in the competitive suppression of both crops. In the few studies examining competition in unfertilized, additive maize cowpea monocrops, yields of both crops have been found to be un-altered (Rusinamhodzi *et al.*, 2012), or cowpea has been suppressed by maize (Ofori and Stern, 1987). The latter case supports our results at Kandeu and Golomoti, while in the former case, use of a lower maize planting density than was used in our study may have reduced the competitive effects of maize on cowpea.

The suppression of maize by cowpea in unfertilized intercrops at Lintipe, but not at other study locations, may have been caused by the high yield potential of cowpea at Lintipe. Cowpea monocrop produced higher grain yields at Lintipe than at other sites, both in our agronomic trials (Figure 4) and in our models (Figure 5). The more vigorous growth of cowpea at Lintipe suggests that it was able to exert a greater degree of competitive pressure on its intercrop partner.

When N fertilizer was added to the system, maize became dominant at all sites. Fertilized maize yields were not suppressed in intercrop at any of our study locations. At the same time, cowpea yields were suppressed more strongly in intercrop under fertilized conditions than under unfertilized conditions, likely due to the more vigorous growth of maize. In studies of fertilized maize cowpea intercrop systems, competitive dynamics have varied. Both maize and cowpea yields can be suppressed in fertilized intercrop systems (Ofori and Stern, 1987; Watiki *et al.*, 1993), though this suppression may occur only in seasons with unfavorable rainfall and not in more favorable seasons (Hulugalle and Lal, 1986). In other systems (Rusinamhodzi *et al.*, 2012), as in our own agronomic trials (Figure 4, Table 6), maize yields have not been suppressed in fertilized intercrop systems. Our results suggest the need for further investigations to determine the environmental conditions under which cowpea will act as a strong competitor with maize.

When we included the effects of cropping history in our models, the competitive dynamics of maize cowpea intercrop systems were altered. Allowing biomass produced by previous crops to affect the growth of subsequent crops caused maize yields in unfertilized conditions to became higher in intercrop than in monocrop (Appendix C Figure 1). Under fertilized conditions, however, this improvement in maize yield due to intercropping was dampened or eliminated. Improved maize yields in intercrops under unfertilized conditions were almost certainly due to the provision of N to maize through the deposition of N-rich cowpea biomass in previous seasons (Vesterager *et al.*, 2008). Other modeling work using APSIM in Malawi in which soil parameters were not re-set has shown improved maize yield and yield stability in maize pigeonpea additive intercrop systems in successive years of establishment (Ollenberger, 2012). We cannot have complete confidence that these results reflect the behavior of actual cropping systems in Malawi, as we did not validate our models for biomass production. However, our results do suggest that further investigation of the long-term effects of maize cowpea intercropping on soil fertility and maize yields may be warranted.

Maize cowpea intercrop systems were typically less stable than monocrops of maize and cowpea at Kandeu and Golomoti. At both sites, calorie and protein yields from maize cowpea intercrop systems exhibited a stronger response to variation in environmental conditions than did the two monocrops (Figure 7). The same was true for calorie yields at Lintipe, though the stability of protein yields remained constant in monocrop and intercrop systems. The reduction in stability under intercrop systems often went hand in hand with increased yields, however. At Kandeu, calorie yields from intercrop systems across the full range of seasons and soils far exceeded yields from monocrops when 69 kg N / ha were applied. At 0 kg N / ha the intercrop advantage was less pronounced, but still apparent. Protein yields in intercrop and monocrop at Kandeu were similar under less favorable conditions, but intercrops experienced an advantage under more favorable conditions. A similar pattern was observed at Golomoti for both calorie and protein yields. At this site, intercrop yields under less favorable environmental conditions were similar to yields in monocrop, but under more favorable conditions intercrops always displayed an advantage. The lower yield stabilities observed at Kandeu and Golomoti were thus due to intercrops exhibiting a more robust response to favorable conditions than monocrops. This illustrates that yield stability alone does not provide enough information to discern whether a cropping system is likely to be advantageous to farmers.

At Lintipe, calorie production was likewise less stable in intercrops than in monocrops. While systems fertilized with 69 kg N / ha followed the same pattern observed at Kandeu, calorie yields in unfertilized intercrop systems were lower than monocrops across the full range of environmental conditions. This resulted from the competitive suppression of maize by cowpea in unfertilized intercrop systems at Lintipe. Maize contains more calories / kg than cowpea, and suppression of maize therefore led to a sharp decline in calorie yields. Protein yields were consistently higher in monocrop than in intercrop at Lintipe, with monocrops and intercrops demonstrating similar yield stability. This was likely due to the superior cowpea yields in monocrop at Lintipe. Cowpea grain is much more protein rich than maize. Therefore, since cowpea yields were sharply suppressed in intercrop, monocrops of maize and cowpea were able to produce more protein than intercrops at the site where sole cowpea performed best.

We hypothesized that maize cowpea intercrop systems would produce more calories and protein than monocrops under unfertilized conditions, but not under fertilized conditions. In fact, intercrops tended to produce higher calorie and protein yields than monocrops under both fertilized and unfertilized conditions. Our hypothesis was largely based on studies that found maize yields to be equivalent in additive monocrop and intercrop systems under unfertilized conditions, but depressed in intercrop with cowpea under fertilized conditions (Ofori and Stern, 1987; Watiki *et al.*, 1993), though in one case this effect was found only in a dry season and not in a wet season (Hulugalle and Lal, 1986). In our own agronomic trials (Table 1, Figure 4), as in at least one published case spanning multiple seasons (Rusinamhodzi *et al.*, 2012), maize yield was not suppressed in intercrop with cowpea under fertilized conditions.

We are aware of only one experimental study contrasting the total productivity of maize cowpea intercrops and maize and cowpea monocrops across varying fertility levels (Ofori and Stern, 1987). In this case, reduction in the LER with increasing N fertilization was cause by suppression of maize in intercrop with cowpea in N fertilized systems. In our own case, because maize was not suppressed in competition with cowpea, the addition of a cowpea harvest in intercrop caused fertilized intercrop systems to achieve calorie and protein yields that were consistently higher than monocrops. As we have seen in our own study and others, competitive dynamics between maize and cowpea can vary by location (Ofori and Stern, 1987;

Rusinamhodzi *et al.*, 2012). Our results therefore suggest the need for further experimentation to determine the effects of N fertilization on intercrop advantage in maize cowpea systems. Such experimentation should be carried out over multiple cropping seasons, as there is evidence to suggest that competitive dynamics between maize and cowpea can change from one season to the next (Hulugalle and Lal, 1986).

Our second hypothesis, that maize cowpea intercrop systems would be less stable than maize and cowpea monocrops, was largely conformed by this study (Figure 7). However, as previously noted, in most cases this was due to greater intercrop advantage under favorable environmental conditions. Reduced stability of this kind may actually be favorable from a farmer's perspective, as intercropping can allow them to achieve higher yields in the best seasons, and produce yields at least as high as monocrop in the worst seasons.

Intercropping decreased risk to farmers in most situations, improving the average household's chance of meeting calorie and protein needs (Figure 8). Fertilized maize cowpea intercrop systems had a higher chance of meeting household calorie and protein needs than maize and cowpea monocrops at all study locations. Under unfertilized conditions, intercrops had a higher chance of meeting household needs at Kandeu and Golomoti, but not at Lintipe. As previously mentioned, maize grain yields were suppressed in competition with cowpea in unfertilized intercrops at Lintipe (Figure 5). This caused calorie and protein yields to be lower in this system across the full range of environmental conditions (Figure 7). Consequently, unfertilized intercrops were less likely to meet household calorie and protein needs than monocrops at Lintipe.

Our general finding that intercropping decreases production risk is in agreement with other studies of risk in cereal legume intercrop systems. In Botswana, sorghum cowpea intercrops had a higher chance of meeting a minimum economic yield than sorghum and cowpea monocrops (Lightfoot *et al.*, 1987). In Malawi, unfertilized maize pigeonpea intercrops had a higher chance of meeting household maize needs than unfertilized maize monocrops (Kamanga *et al.*, 2010). In this system, intercropping maize with a legume produced a reduction in risk equivalent to adding 35 kg N / ha to sole maize. Our findings also accord partially with a modeling study that found improved economic yields in maize cowpea intercrop compared with maize and cowpea monocrops under unfertilized conditions, but not under fertilized conditions (Carberry *et al.*, 1996). As previously mentioned, the relative performance of maize cowpea intercrops and monocrops under fertilized conditions may depend on whether maize yields are suppressed by cowpea, a characteristic which can vary by location (Ofori and Stern, 1987; Rusinamhodzi *et al.*, 2012). However, as Carberry et al. (1996) do not include information about the relative performance of maize and cowpea in their models, we cannot pinpoint the cause of the differing results between their study and ours.

Our findings that maize cowpea intercropping can increase calorie and protein yields and reduce risk for smallholder farmers are supported by farmer practice. Intercropping was a common practice at all sites (Figure 2), with 69% of farmers reporting that they used some form of maize legume intercropping (Figure 3). The majority of farmers who grew cowpea reported growing it in intercrop with maize (Figure 2). This suggests that, based on their own knowledge and experience of their cropping systems, farmers in our study locations have found that growing cowpea in intercrop with maize is a worthwhile practice.

Our results do conflict with farmer practice in one regard. In our agronomic trials (Figure 4) and modeling work (Figure 5), we found that cowpea performed best at the Lintipe study location. In our survey of farmer practice, however, we found that cowpea is less commonly grown at Lintipe than at the other study locations. Anecdotal reports from farmers and extensionists suggest that cowpea experiences very high pressure from aphids at Lintipe when insecticides are not used. While we did use insecticide in our experimental trials, farmers rarely report using insecticides in the field, often citing cost as a barrier.

The absence of P dynamics in our study may also limit its applicability to some farmers' growing conditions. We did not include P dynamics in our simulation models, and all agronomic trials containing cowpea were amended with P fertilizer. While agricultural systems are not typically P limited in Malawi, there is high geographical variability in extractable soil P (Snapp, 1998), resulting in scattered patches that are P deficient. We observed this P variability at our study locations, where some farmers' fields contained very low Bray extractable P, while other fields showed much higher values (Appendix A). In P deficient soils, in the absence of P inputs, cowpea yields and biological N fixation can be limited (Vesterager *et al.*, 2008; Rusinamhodzi *et al.*, 2012). Farmers in our study location typically apply at least some mineral fertilizer to maize legume intercrop systems (Figure 2). If farmers are able to include some P in their fertilizer applications to maize cowpea intercrops, cowpea performance in intercrop is unlikely to be P limited. However, in cowpea monocrop systems which are rarely fertilized (Figure 3), some farmers' yields may be limited due to P deficiency.

In many ways, the intercrop advantage demonstrated by our study is based on conservative assumptions. By re-setting soil parameters every year, we did not include one of the chief mechanisms through which intercropping systems can achieve superior productivity to monocrops – namely the production of N rich legume biomass that can contribute N to subsequent cereal crops (Fukai and Trenbath, 1993; Chikowo *et al.*, 2004). When models were run without re-setting soil parameters, even greater intercrop advantage was observed, particularly under un-fertilized conditions. Furthermore, cowpea grown in intercrop with fertilized maize (the typical practice in our study locations) may experience an advantage over unfertilized cowpea due to freedom from P limitation – a factor which was not considered in our study. On the other hand, our use of insecticides to control aphids and other pests may have resulted in higher cowpea yields than farmers could expect without insecticides, particularly at Lintipe. Despite this drawback, we believe that our results are unlikely to over-state the advantages of maize cowpea intercrops given the conservatism of our other assumptions. We look to further experimentation with maize cowpea intercrops under farmers conditions, as part of the Africa RISING project and others, to complement our simulation results with data from the field.

Ultimately, this study will prove useful only to the extent that farmers and extensionists perceive the work to be trustworthy and relevant to their actual systems (Cash *et al.*, 2003). They are only likely to do so if they are included in the research process. We have made the first steps in this direction by including farmers and extensionists in the implementation of our study, and by basing experimental systems on local practice to the extent possible. By sharing our results with farmers and taking their suggestions into account as we design the next phases of research, we can integrate this study into a cycle of iterative co-learning that will increase its legitimacy for farmers and improve the quality of the science (McDougall and Braun, 2003).

CONCLUSIONS

Maize cowpea intercrop systems in central Malawi can produce more calories and protein than maize and cowpea monocrops under most growing conditions and in most seasons. While intercrop systems tend to be less stable than monocrops, this is due to their superior performance in seasons that are particularly favorable. Therefore, intercropping maize with cowpea rather than growing the two crops in monocrop can increase farming households' chances of meeting their food needs through their own production.

The advantages of intercropping are most pronounced and universal in systems where moderate levels of fertilizer are applied. In unfertilized systems, intercrop advantage appears to be location specific. Therefore, while our results suggest that maize cowpea intercropping can be an advantageous practice for smallholder farmers in Malawi, they also point to the need for further research into the conditions under which maize cowpea intercrops perform most favorably.

APPENDICES

APPENDIX A

Description of soils at the Africa RISING Malawi 2013 intervention sites, including the three study locations used in this work. Soils were sampled in the summer of 2013 (see Materials and Methods above). Part A describes soils sampled from Africa RISING mother trials. Part B describes soils sampled from farmers' fields situated near the Mother 1 trial at each site.

Table A.1: Description of soils from Africa RISING mother trials.

Site	Mother trial	Lat / Long	Sample type	Depth (cm)	% Sand	% Silt	% Clay	BD (g/cm^3)	% Tot C	% Tot N	pH	Bray P (ppm)
Lintipe	1: Mbidzi	34.09781 E / 14.20679 S	Pit	0–15	10	16	74	1.4	2.6	0.13	5.0	14.5
				15–30	14	21	65	1.5	2.3	0.12	4.9	4.5
				30–60	25	25	50	1.3	1.1	0.07	4.8	1.0
				60–90	6	16	78	1.4	0.7	0.05	5.1	2.5
				90–120	5	19	76	1.3	0.4	0.04	5.2	2.5
			Hoe	0–15	22	29	48	NA	2.3	0.13	4.9	13.5
				15–30	19	26	55	NA	2.2	0.12	4.9	12.5
				30–60	18	24	58	NA	2.0	0.11	5.0	8.5
Lintipe	2: Mkuwazi	34.11219 E / 14.19522 S	Hoe	0–15	52	17	31	NA	1.5	0.10	5.1	9.5
				15–30	38	16	46	NA	1.7	0.10	5.2	3.0
Golomoti	1: Msamala	34.60472 E / 14.43828 S	Pit	0–15	45	23	32	1.4	0.9	0.07	4.9	35
				15–30	44	21	36	1.4	0.6	0.05	4.9	22
				30–60	31	21	48	1.3	0.2	0.05	4.7	13.5
				60–90	27	22	51	1.5	0.2	0.05	4.3	16.5
				90–120	29	21	50	1.7	0.2	0.02	4.2	12
			Hoe	0–15	52	22	26	NA	0.9	0.06	4.5	56.5
				15–30	43	20	37	NA	0.5	0.05	4.2	20
				30–60	34	19	47	NA	0.1	0.04	4.9	12

Table A.1 (cont'd)

Site	Mother trial	Latitude / longitude	Sample type	Depth (cm)	% Sand	% Silt	% Clay	BD (g/cm^3)	% Tot C	% Tot N	pH	Bray P (ppm)
Golomoti	2: Kalumo	34.59544 E / 14.43711 S	Hoe	0–15	44	23	32	NA	1.2	0.09	5.7	26.0
				15–30	40	22	38	NA	0.6	0.05	5.5	16.5
				30–60	36	21	43	NA	0.5	0.05	5.5	11.0
Kandeu	1: Katsese	34.59762 E / 14.6297 S	Pit	0–15	70	18	13	1.5	1.1	0.09	5.0	64
				15–30	64	18	18	1.4	1.0	0.08	5.1	37.5
				30–60	67	15	18	1.3	0.6	0.05	5.2	14.5
				60–90	40	20	40	1.4	1.5	0.12	4.9	9.5
			Hoe	0–15	75	17	9	NA	1.0	0.09	Insuf*	72.5
				15–30	74	13	13	NA	0.7	0.06	5.4	42.5
				30–60	68	17	16	NA	0.8	0.06	Insuf*	27.5
Kandeu	2: Dauka	34.60672 E / 14.64078 S	Hoe	0–15	59	12	29	NA	0.7	0.06	5.0	4.0
				15–30	50	10	40	NA	0.4	0.05	4.8	2.0
				30–60	47	11	43	NA	0.2	0.04	4.9	2.0
Nsipe	1: Amosi	34.74677 E / 14.92927 S	Pit	0–15	49	22	30	1.4	1.3	0.09	4.4	40
				15–30	35	26	39	1.5	1.6	0.11	4.5	10
				30–60	20	18	62	1.5	1.3	0.10	5.1	4
				60–90	16	14	70	1.5	0.7	0.08	4.7	2.5
				90–120	25	15	60	1.5	0.4	0.13	4.9	3.5
			Hoe	0–15	54	19	28	NA	1.1	0.08	4.7	18.5
				15–30	40	17	43	NA	1.5	0.09	4.7	12.5
				30–60	24	18	59	NA	1.1	0.09	5.0	5.5
Nsipe	2: Nzililongwe	34.743611 E / 14.907222 S	Hoe	0–15	40	21	38	NA	1.6	0.11	5.0	6.0
				15–30	29	21	51	NA	1.5	0.11	5.1	5.5
				30–60	20	19	61	NA	1.5	0.13	5.2	2.0

NA indicates that a test was not run for a given sample. * "Insuf" indicates that we were unable to run a test because there was insufficient soil remaining from a given sample.

Table A.2: Description of soils from farmers' fields at the Africa RISING intervention sites.

Site (Village)	Fertility ranking	Field	Latitude / longitude	Crop	Depth (cm)	% Sand	% Silt	% Clay	% Tot C	% Tot N	pH	Bray P (ppm)
Lintipe (Mbidzi)	High	8	34.0840 E / 14.2117 S	Mz + Bn	0–15	52	22	26	1.4	0.10	5.8	20
					15–30	49	25	26	1.0	0.07	Insuf*	8
		9	34.1003 E / 14.2115 S	Mz	0–15	51	23	26	1.8	0.12	6.2	26
					15–30	56	22	22	1.0	0.07	6.3	10
		10	34.1008 E / 14.2033 S	Mz	0–15	21	28	51	2.2	0.13	Insuf*	23.5
					15–30	24	22	54	1.9	0.09	Insuf*	15.5
Lintipe (Mbidzi)	Low	2	34.0954 E / 14.2066 S	Gn	0–15	38	20	42	1.3	0.08	5.7	2
					15–30	28	20	52	1.0	0.07	5.9	1
		5	34.0925 E / 14.2057 S	Sy	0–15	34	21	45	1.6	0.10	5.6	3
					15–30	27	22	51	1.4	0.09	5.7	2.5
		7	34.0934 E / 14.2045 S	Sy + Gn	0–15	28	21	50	1.9	0.11	5.6	3
					15–30	17	19	64	1.6	0.09	5.8	2
Golomoti (Msamala)	High	3	34.5910 E / 14.4335 S	Mz + Pp	0–15	66	15	19	0.9	0.07	6.5	160
					15–30	56	17	27	0.7	0.06	Insuf*	160
		4	34.5852 E / 14.4392 S	Mz	0–15	56	24	19	1.2	0.10	Insuf*	220
					15–30	53	26	21	1.2	0.09	Insuf*	201.5
		5	34.5907 E / 14.4397 S	Mz	0–15	68	15	16	0.6	0.05	6.3	85
					15–30	55	20	25	0.7	0.05	6.2	88
Golomoti (Msamala)	Low	1	34.5868 E / 14.4307 S	Mz	0–15	63	24	13	0.9	0.08	6.6	77.5
					15–30	67	20	13	0.8	0.06	6.8	73.5
		8	34.6067 E / 14.4518 S	Cp	0–15	67	17	17	1.0	0.07	6.3	73.5
					15–30	63	18	19	0.9	0.07	6.0	71
		9	34.5992 E / 14.4412 S	Mz	0–15	62	22	16	0.7	0.06	6.0	36.5
					15–30	51	22	27	0.7	0.06	5.1	21.5

Table A.2 (cont'd)

Site (Village)	Fertility ranking	Field	Latitude / longitude	Crop	Depth (cm)	% Sand	% Silt	% Clay	% Tot C	% Tot N	pH	Bray P (ppm)
Kandeu (Katsese)	High	3	34.5929 E / 14.6281 S	Mz	0–15	75	10	15	0.4	0.05	6	55.0
					15–30	69	10	21	0.3	0.04	6	29.0
		4	34.5928 E / 14.6286 S	Mz	0–15	65	15	19	0.8	0.07	5.8	71.0
					15–30	65	12	23	0.8	0.06	5.8	68.0
		9	34.5918 E / 14.6266 S	Mz	0–15	68	14	18	0.7	0.07	5.7	43.5
					15–30	67	13	21	0.5	0.06	5.9	18.0
Kandeu (Katsese)	Low	1	34.5973 E / 14.6248 S	Mz + Sy	0–15	72	5	23	0.5	0.06	5.5	9.0
					15–30	58	10	31	0.6	0.06	6.4	4.0
		2	34.5989 E / 14.6222 S	Gn	0–15	71	11	18	0.7	0.07	5.3	4.0
					15–30	66	8	26	0.6	0.06	4.7	3.0
		6	34.5978 E / 14.6177 S	Mz + Pp	0–15	60	14	26	0.7	0.07	5.2	21.0
					15–30	65	8	27	0.6	0.07	5.5	19.0
Nsipe (Amosi)	High	4	34.7437 E / 14.9306 S	Mz	0–15	65	17	18	0.7	0.07	6.0	104
					15–30	57	13	29	0.7	0.07	6.2	93.5
		5	34.7454 E / 14.9296 S	Mz	0–15	48	17	35	1.2	0.11	5.9	15
					15–30	40	16	44	1.2	0.10	5.6	8.5
		7	34.7488 E / 14.9333 S	Mz	0–15	44	21	34	1.5	0.11	5.8	13.5
					15–30	32	23	44	1.1	0.09	Insuf*	12
Nsipe (Amosi)	Low	1	34.7454 E / 14.9269 S	Mz + Cp	0–15	35	19	47	1.4	0.11	6.0	4.0
					15–30	23	20	57	1.4	0.11	6.0	2.5
		2	34.7449 E / 14.9263 S	Mz	0–15	30	20	50	1.5	0.12	6.1	8.0
					15–30	22	21	58	1.6	0.11	6.0	4.5
		9	34.7421 E / 14.9325 S	Mz +Gn	0–15	63	15	22	0.6	0.06	5.7	8.0
					15–30	65	1	34	0.5	0.05	5.7	3.5

Crop abbreviations used: Mz = maize, Bn = bean, Gn = groundnut, Sy = soybean, Pp = pigeonpea, Cp = cowpea. * "Insuf" indicates that we were unable to run a test because there was insufficient soil remaining from a given sample.

APPENDIX B

All parameters used in exploratory crop simulation models, run in APSIM 7.5.

Table B.1: Soil parameters used in exploratory crop simulation models. Given as 0-15, 15-30, 30-60, 60-90, and 90-120cm.

	Kandeu	**Lintipe**	**Golomoti**
Starting water	60%, evenly distrib.	60%, evenly distrib.	60%, evenly distrib.
pH	4.95, 4.83, 4.86, 4.89, 4.89	4.88, 4.87, 4.83, 5.13, 5.18	4.7, 4.7, 4.71, 4.7, 4.7
BD (g / cc)	1.53, 1.42, 1.34, 1.4, 1.4	1.37, 1.5, 1.34, 1.37, 1.28	1.4, 1.4, 1.34, 1.48, 1.65
AirDry (mm / mm)	0.17, 0.18, 0.19, 0.22, 0.22	0.21, 0.23, 0.26, 0.29. 0.32	0.15, 0.18, 0.19, 0.215, 0.25
LL15 (mm / mm) (*low OM soil*)	0.18, 0.24, 0.26, 0.24, 0.24	0.29, 0.32, 0.34, 0.44, 0.43	0.16, 0.23, 0.29, 0.3, 0.3
LL15 (*high OM soil*)	0.19, 0.24, 0.26, 0.24, 0.24	0.29, 0.32, 0.34, 0.44, 0.43	0.16, 0.23, 0.29, 0.3, 0.3
DUL (mm / mm) (*low OM soil*)	0.28, 0.36, 0.38, 0.37, 0.37	0.41, 0.42, 0.45, 0.48, 0.52	0.28, 0.35, 0.42, 0.42, 0.37
DUL (mm / mm) (*high OM soil*)	0.29, 0.36, 0.38, 0.37, 0.37	0.41, 0.43, 0.45, 0.48, 0.5	0.28, 0.35, 0.42, 0.42, 0.37
SAT (mm / mm) (*low OM soil*)	0.42, 0.46, 0.49, 0.47, 0.47	0.48, 0.43, 0.49, 0.48, 0.52	0.47, 0.47, 0.49, 0.44, 0.38
SAT (mm / mm) (*high OM soil*)	0.42, 0.46, 0.49, 0.47, 0.47	0.48, 0.43, 0.49, 0.48, 0.52	0.47, 0.47, 0.49, 0.44, 0.38
maize LL (mm / mm)	0.21, 0.23, 0.26, 0.29, 0.32	0.21, 0.23, 0.26, 0.29, 0.32	0.21, 0.23, 0.26, 0.29, 0.32
maize KL	0.08, 0.08, 0.08, 0.08, 0.06	0.08, 0.08, 0.08, 0.08, 0.06	0.08, 0.08, 0.08, 0.08, 0.06
maize XF	0.7, 0.7, 0.7, 0.4, 0.3	0.5, 0.5, 0.5, 0.2, 0.2	0.4, 0.4, 0.4, 0.3, 0.3
cowpea LL (mm / mm)	0.21, 0.23, 0.26, 0.29, 0.32	0.21, 0.23, 0.26, 0.29, 0.32	0.21, 0.23, 0.26, 0.29, 0.32
cowpea KL	0.08, 0.08, 0.08, 0.08, 0.06	0.08, 0.08, 0.08, 0.08, 0.06	0.08, 0.08, 0.08, 0.08, 0.06
cowpea XF	0.5, 0.5, 0.5, 0.5, 0.5	0.5, 0.5, 0.5, 0.5, 0.5	0.5, 0.5, 0.5, 0.5, 0.5
Summer Cona:	6.6	6.6	6.6
Summer U:	1.5	1.5	1.5
Summer Date:	1-Nov	1-Nov	1-Nov
Winter Cona:	6.6	6.6	6.6
Winter U:	1.5	1.5	1.5
Winter Date:	1-Apr	1-Apr	1-Apr
Diffusivity Constant:	88	88	88
Diffusivity Slope:	35.4	35.4	35.4

Table B.1 (cont'd)

	Kandeu	**Lintipe**	**Golomoti**
Soil albedo:	0.2	0.2	0.2
Bare soil runoff curve number:	85	85	85
Max. reduction in curve number due to cover:	20	20	20
Cover for max curve number reduction:	0.8	0.8	0.8
SWCON	0.2, 0.2, 0.2, 0.2, 0.2	0.2, 0.2, 0.2, 0.2, 0.2	0.2, 0.2, 0.2, 0.2, 0.2
Root C:N ratio	45	45	45
Root weight (kg / ha)	100	100	100
Soil C:N ratio	6.81	14.1	8.06
OC (%) (*low OM soil*)	0.446, 0.312, 0.211, 0.211, 0.211	1.291, 1.028, 1.076, 0.652, 0.395	0.665, 0.653, 0.246, 0.154, 0.208
OC (%) (*high OM soil*)	0.819, 0.76, 0.211, 0.211, 0.211	2.241, 1.894, 1.076, 0.652, 0.395	1.25, 1.228, 0.246, 0.154, 0.208
FBiom	0.015, 0.015, 0.015, 0.01, 0.01	0.015, 0.015, 0.015, 0.01, 0.01	0.01, 0.01, 0.01, 0.01, 0.01
FInert	0.8, 0.8, 0.8, 0.8, 0.9	0.67, 0.67, 0.67, 0.8, 0.9	0.8, 0.8, 0.9, 0.9, 0.9
Initial NO3 (kg / ha)	1, 1, 1.5, 1.5, 0.25	1, 1, 1.5, 1.5, 0.25	1, 1, 1.5, 1.5, 0.25
Initial NH4 (kg / ha)	0.1, 0, 0, 0, 0	0.1, 0, 0, 0, 0	0.1, 0, 0, 0, 0

Table B.2: Management parameters used in exploratory crop simulation models.

	Kandeu	**Lintipe**	**Golomoti**
Sow maize using a variable rule with intercropping			
Name of this crop	maize	maize	maize
Cultivar :	pan6671	r215	pan6671
Method of cropping	intercrop	intercrop	intercrop
Exclude from rotation sequence	no	no	no
Sowing window START date (dd-mmm)	01-nov	01-nov	01-nov
Sowing window END date (dd-mmm)	30-dec	30-dec	30-dec
Must Sow	yes	yes	yes
Amount of cumulative rainfall (mm)	15	15	15
Number of days to accumulate rainfall (days)	3	3	3
Amount of soil water (mm)	15	15	15
Sowing opportunity number to sow on (1..n)	1	1	1
Upper limit of sw in top layer (0-2) (mm esw/mm soil)	2	2	2
Lower limit of sw in top layer (0-1) (mm esw/mm soil)	0	0	0
Sowing density (plants/m2)	4	6	4
Sowing depth (mm)	30	30	30
Row spacing (m)		0.75	
Amount of starter fertiliser at sowing (kg/ha) (*69 kg N / ha inter and monocrop*)	23	23	23
Amount of starter fertiliser at sowing (kg/ha) (*0 kg N / ha inter and monocrop*)	0	0	0
Type	urea_N	urea_N	urea_N
Number of days after sowing to apply top-dress fertiliser (days)	60	72	52
Amount of topdress fertiliser (kg/ha) (*69 kg N / ha inter and monocrop*)	46	46	46
Amount of topdress fertiliser (kg/ha) (*0 kg N / ha inter and monocrop*)	0	0	0
Type	urea_N	urea_N	urea_N
Planter type	user_defined	user_defined	user_defined
User_defined depth of seedbed preparation (mm)	150	150	150
Fraction of weed population killed (0-1)	1	1	1
User_defined fraction of surface residues to incorporate (0-1)	1	1	1
CN reduction after tillage () :	0	0	0
Amount of cumulative rain to dissipate tillage effects on cn () :	0	0	0

Table B.2 (cont'd)

	Kandeu	**Lintipe**	**Golomoti**
Sow maize using a variable rule with intercropping			
Number of days before window to prepare seed-bed (days)	0	0	0
Must Till (yes/no)	no	no	no
Tillage type (user_defined, chisel, disc, planter)	disc	disc	disc
User_defined depth of seedbed preparation (mm)	100	100	100
User_defined fraction of surface residues to incorporate (0-1)	1	1	1
Biomass removal fraction of growing weeds from field (0-1)	0	0	0
CN reduction after tillage () :	0	0	0
Amount of cummulative rain to dissipate tillage effects on CN () :	0	0	0
Sow cowpea using a variable rule with intercropping (only values that differ from the sow maize rule are listed)			
Cultivar :	spreading	spreading	spreading
Sowing window START date (dd-mmm)	1-jan	1-jan	1-jan
Sowing window END date (dd-mmm)	15-feb	15-feb	15-feb
Must Sow	yes	yes	yes
Amount of cumulative rainfall (mm)	30	30	30
Number of days to accumulate rainfall (days)	2	2	2
Amount of soil water (mm)	0	0	0
Sowing density (plants/m2)	5	10	5
Amount of starter fertiliser at sowing (kg/ha) (*69 kg N / ha monocrop*)	23	23	23
Amount of starter fertiliser at sowing (kg/ha) (*0 kg N / ha monocrop and all intercrops*)	0	0	0
Amount of TopDress fertiliser (kg/ha) (*69 kg N / ha monocrop*)	46	46	46
Amount of TopDress fertiliser (kg/ha) (*0 kg N / ha monocrop and all intercrops*)	0	0	0

Table B.2 (cont'd)

	Kandeu	**Lintipe**	**Golomoti**
Harvesting rule for maize			
Fraction of stover to remove (not for maize):	1	1	1
Harvesting rule for cowpea			
Fraction of stover to remove (not for maize):	1	1	1
Tillage with C:N reduction on fixed date			
Tillage date (dd-mmm) :	1-nov	1-nov	1-nov
Tillage type :	user_defined	user_defined	user_defined
User_defined depth of seedbed preparation (mm) :	15	15	15
User_defined fraction of surface residues to incorporate (0-1):	.8	.8	.8
CN reduction after tillage () :	10	10	10
Amount of cumulative rain to dissipate tillage effects on CN ()	300	300	300
Remove residues at harvest			
Name of crop harvest to trigger residue removal	maize	maize	maize
Biomass removal fraction from field (0-1)	1	1	1
Name of crop harvest to trigger residue removal	cowpea	cowpea	cowpea
Biomass removal fraction from field (0-1)	1	1	1
Reset water, nitrogen and surface OM on fixed date (*only models with soil parameters reset*)			
Date of reset (dd-mmm) :	15-jul	15-jul	15-jul
Reset soil water?	yes	yes	yes
Reset soil nitrogen?	yes	yes	yes
Reset surface organic matter?	yes	yes	yes

Table B.3: Other parameters used in exploratory crop simulation models.

	Kandeu	**Lintipe**	**Golomoti**
Organic matter type	maize	maize	maize
Initial surface residue	0	0	0
C:N ratio of initial residue	75	75	75
Fraction of residue standing	0	0	0

APPENDIX C

Outputs from cropping system models run from 1980 – 2005 in which soil parameters were not re-set annually, allowing for cumulative effects.

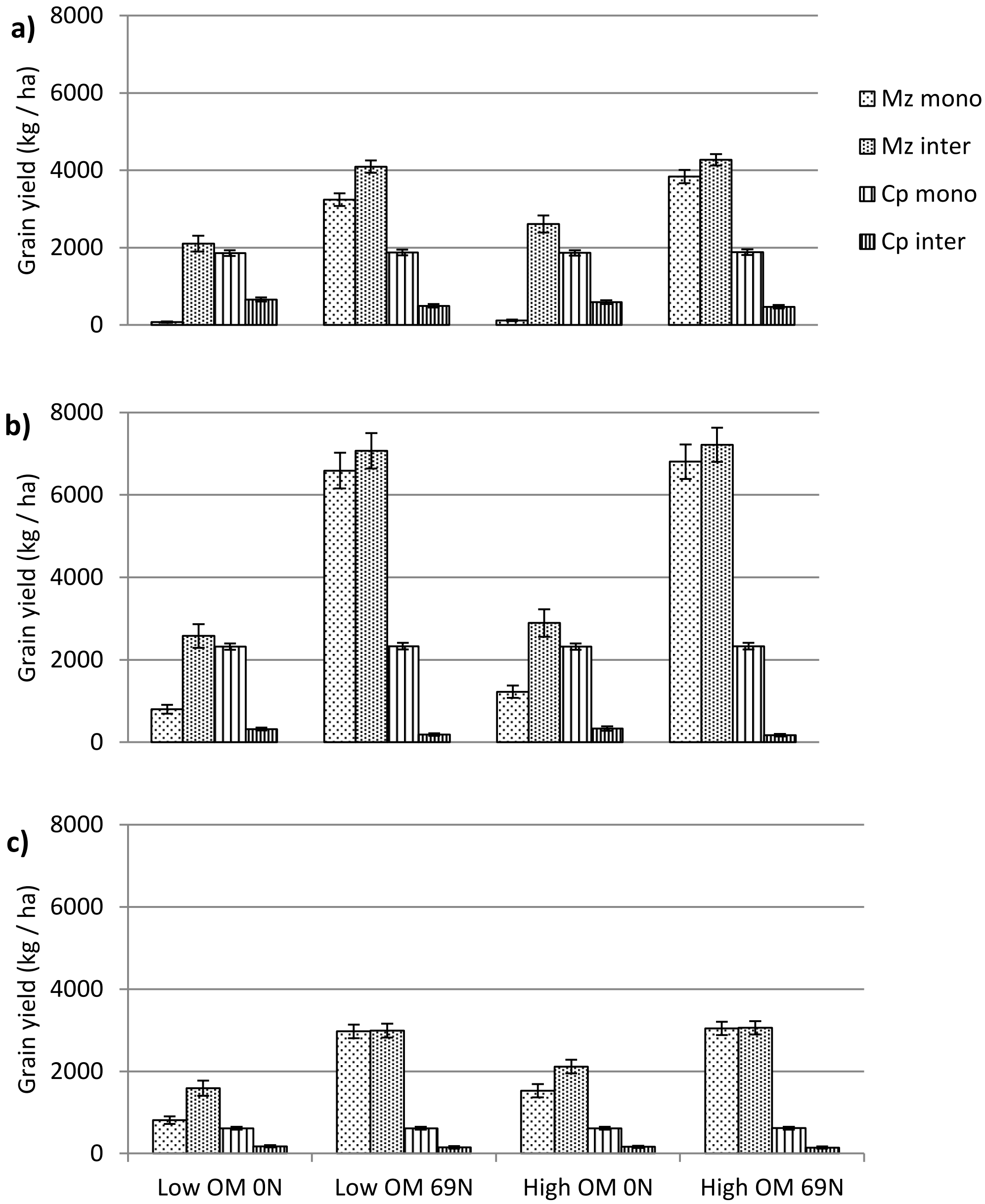

Figure C.1: Modeled grain yields of cropping systems from 1980 – 2005 in which soil parameters were not re-set annually, allowing for cumulative effects. Given for the Kandeu (a), Lintipe (b), and Golomoti (c) study locations. Soil organic matter designated by “Low OM” and “High OM”; nitrogen inputs (kg / ha) designated by “0N” and “69N”. Cropping systems abbreviated as Mz mono = maize monocrop, Mz inter = maize intercropped with cowpea, Cp mono = cowpea monocrop, Cp inter = cowpea intercropped with maize. Bars show mean yield across all years; error bars show one standard error of the mean.

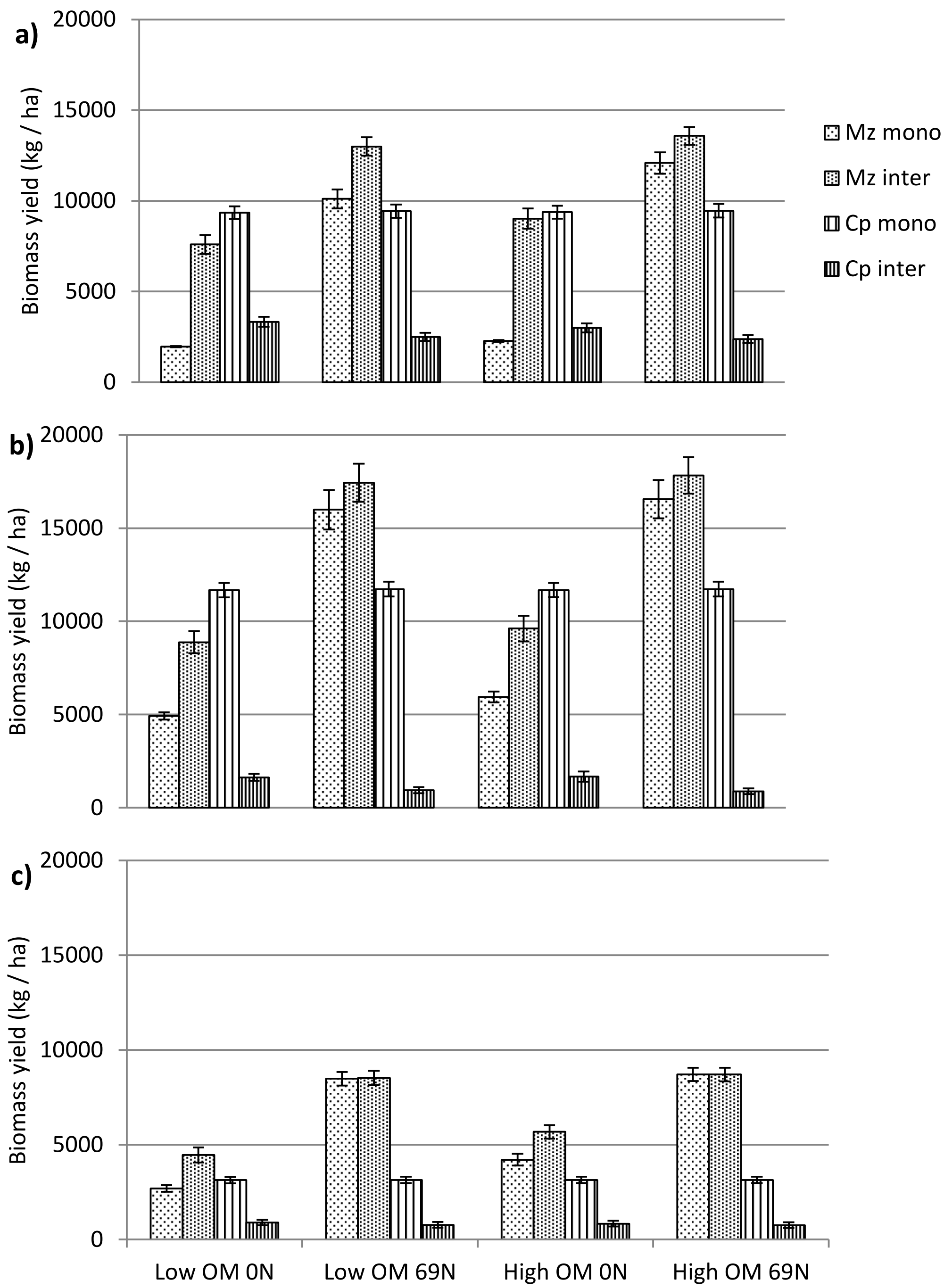

Figure C.2: Modeled biomass yields of cropping systems from 1980 – 2005 in which soil parameters were not re-set annually. Given for the Kandeu (a), Lintipe (b), and Golomoti (c) study locations. Soil organic matter designated by "Low OM" and "High OM"; nitrogen inputs (kg / ha) designated by "0N" and "69N". Cropping systems abbreviated as Mz mono = maize monocrop, Mz inter = maize intercropped with cowpea, Cp mono = cowpea monocrop, Cp inter = cowpea intercropped with maize. Bars show mean yield across all years; error bars show one standard error of the mean.

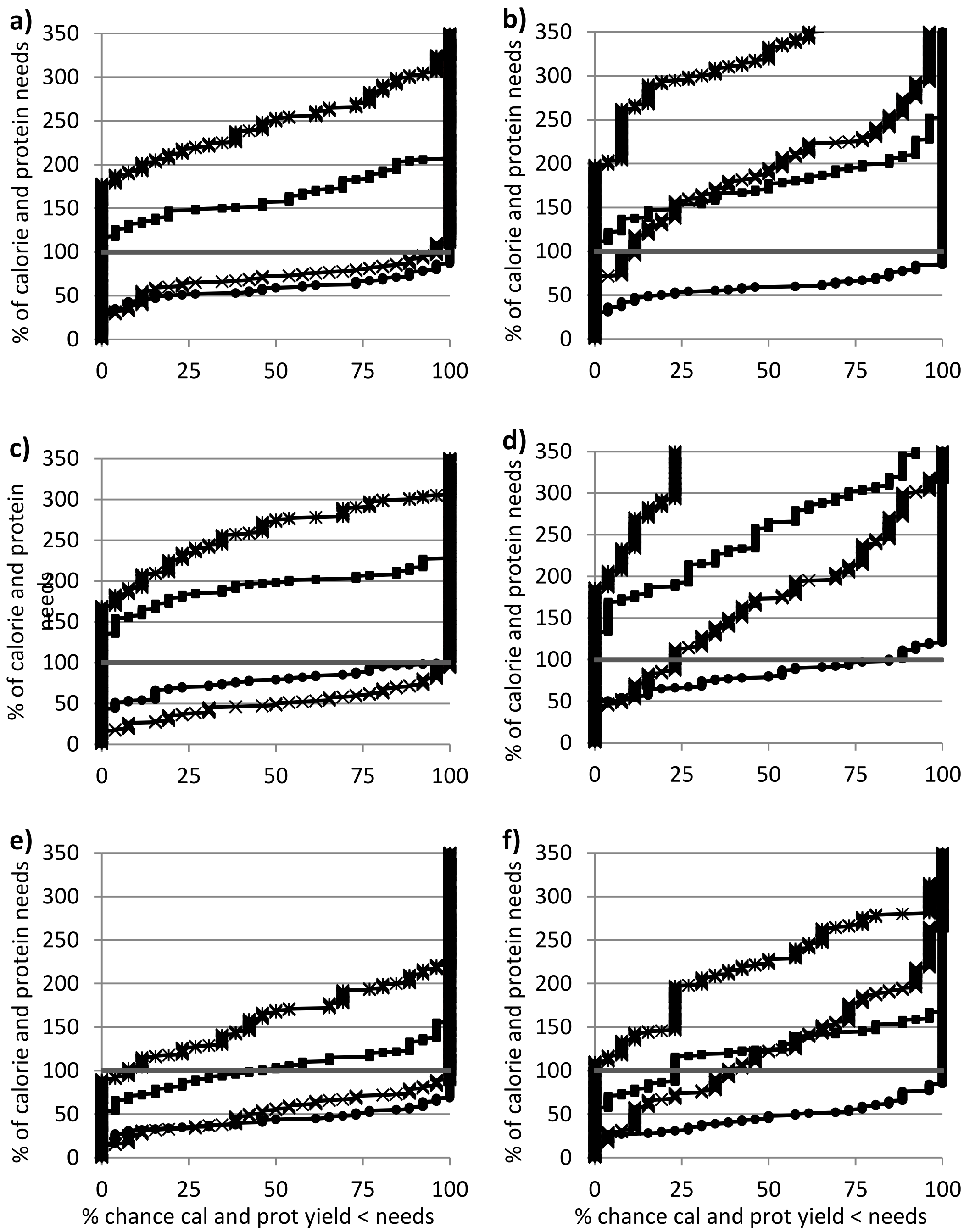

Figure C.3: Probability that average households will meet calorie and protein needs with their own production; contrast of simulations in which soil parameters were reset annually and simulations in which parameters were not reset annually. Shown for low organic matter soil at Kandeu with resets (a) and without resets (b), low organic matter soil at Lintipe with resets (c) and without resets (d), and low organic matter soil at Golomoti with resets (e) and without resets (f). The chance that a cropping system fails to meet household calorie and protein needs is plotted against percent of household calorie and protein needs. Therefore, a point at 100% on the y axis and 40% on the x axis indicates that a system fails to meet 100% of household calorie and protein needs 40% of the time

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