1

To Meet Future Food Demands We Need to Change from Annual Grain Legumes to Multipurpose Semi-Perennial Legumes

Henning Høgh-Jensen
Department of Environmental Science,
Aarhus University,
Denmark

1. Introduction

The last meal of an Iron Age man buried in a Danish bog included at least 60 plant species, including barley, linseed and species we now consider weeds. A modern man relies in contrast on a remarkable small number of crop plants, mostly cereal stables like wheat, rice and maize (Evans, 1998). Both land and people in Sub-Saharan Africa are suffering. Natural resource management is in distress and most rural Africans remain poor and food insecure despite widespread macroeconomic, political and sectorial reforms. Most predictions are that these Africans will remain food insecure in the foreseeable future (Pinstrup-Andersen & Pandya-Lorch, 2001). Innovations are, however, changing this landscape much faster than we could expect.

A market-oriented agriculture has been promoted by many agents of change. And change is happening. The last 10 years a renewed optimism has taking root in the fact that a number of African countries are demonstrating high economic growth rates (Radelet, 2010). We do not know the winners and the losers yet – just that they are there. Not all farmers will have the capacity to join the market orientations by high-value commodities. They are simply not able to innovate.

Nitrogen is a major limiting nutrient for food production but the growing demand for food is met in two ways. One through fossil fuel driven fixation of nitrogen, Haber-Bosch nitrogen (Erisman et al., 2008), is one way and symbiotic fixation of nitrogen, leguminous nitrogen (Giller, 2001), is the other. Feeding approximately half of humanity is made possible by Haber-Bosch nitrogen, the other half by leguminous nitrogen. With the current focus on reducing emissions of greenhouse gasses while simultaneously increasing the biomass production for food, fibre, feed and fuel, the use efficiency of the leguminous nitrogen must be improved.

Annual grain legumes basically satisfy their own need for nitrogen via their capability for fixing atmospheric nitrogen (see e.g. Unkovich et al., 2010). However, they seldom contribute much to soil fertility or to subsequent crops. Further, due to their annual structure they must be reseeded every season with consequences for investing resources and potential susceptibility for unfavourable growth conditions during the renewed crop establishment phase.

Legume seeds hold a carbon-nitrogen ratio of approximately 10 compared to values up to 30 for cereals. Thus from a diet point of view, grain legumes are very valuable protein sources. This importance has been recognized since ancient history (Cohen, 1977). In addition to the nitrogen located in the grain, some nitrogen pools are located in the residues, which can be utilized for fodder or returned to the soil. Another important leguminous nitrogen pool is in the roots and rhizodeposits (Wichern et al., 2008).

2. Innovation

Innovation is a buzz-word and there are a multitude of definitions. Within the business management literature, innovation is mostly seen as a tool used by entrepreneurs to create a resource that will give them an advantage over their competitors (Drucker, 1985, p. 27). Or more broadly, some see an innovation in an idea, practice or object that is new to the individual; a newness that gives a value to the individual when implemented (Rogers & Shoemakers, 1971, p. 19; Urabe, 1988, p. 3). So we can say that innovation is linked to entrepreneurs and it represents *newness*, it has a relation to *invention* or to its process of *adoption* and is as such both a *process* and an *outcome*, where the final feature of involving change or a *discontinuity* with the prevailing product/service or market paradigm may be the most important.

Innovation can be triggered by many factors. It may be a farmer that explores new possibilities to solve an irritating problem. Or it may be a social way of responding and adapting to changes in access to natural resources, assets or markets. The photo in Figure 1 illustrates an innovation developed by the entrepreneur AMFRI Farm, a private company in Uganda exporting organic fruits, species and pulps overseas. The plastic bag contains just two different chillies, a ginger tuber and lemongrass. Based on this simple combination, the net profit per unit of specie is larger than if each species is sold in bulk amounts.

The innovation is that one bag fits into a busy dinner-shopping westerner who like fresh spices but do not want to buy a whole lot of chillies. The innovation is that it gives an important value to the customer; a value which makes the customer very little sensitive to how many cents that she is paying per individual chilli. And it is all packed in one little bag – ready to be shopped and go! Other examples of such market-oriented value chain innovations are testing of consumers preferences. Jones et al. (2002) describes how green pods of pigeonpea were presented to a UK market segment and how they responded to colour differences in the pods.

A cropping-oriented form of innovations is a more local oriented innovation than market-oriented innovation often are, simply because it has to take into account the spatial variability in soil fertility, precipitation, crop growth preferences, etc. The innovations are often found in the management of the crops. Examples of such documented and published innovation include the development of MBILI systems (Woomer et al., 2004) in Kenya where double rows of legumes and cereals are planted to decrease the competitive pressure on the legumes. Another is the push-pull plant protection technologies developed by the international research institute ICIPE (Khan et al., 2011), which by planting designs try to manipulate the pests.

Fig. 1. Illustration of innovations at AMFRI FARMS LTD.'s packing site in Kampala, Uganda. Photo by Henning Høgh-Jensen.

Other forms of innovations take place in research. This includes the researcher developed but farmer-centred models of plant breeding (Bänzinger et al., 2006) or the introduction of modern varieties of pigeonpea in eastern and southern Africa (Myaka et al., 2006); the latter we will return to later. Innovations also include the attempts to let nutrient additions solve the lack of yields by a micro-dosing approach (Twomlow et al., 2010) that basically reflects the denial of scientists to accept that inorganic fertilizers are not used by farmers for stable cereals, thereby also the failure of the Green Revolution technology package in Africa.

Such approaches generally assume that response curves are favourable, e.g. generating approximately 5 kg of additional grain for each kg of applied inorganic nitrogen. The example of Twomlow et al. (2010), however, demonstrates that the scientists apparently never checked the socioeconomic conditions for the farmers but only tested the geophysicalecological conditions by trials across multiple farms. They did not ask the simple question to the farmer: "are you able to pay for this investment?"

Three long-term experiments in Africa, one each from Kenya, Nigeria and Burkina Faso, outline the basic concept that we operate under this sub-continent. The extracted outcome from Kapkiyai et al. (1999) presented in Figure 2 illustrates the benefits on crop yields of feeding the soil various carbon sources. Franke et al. (2008) and Bostick et al. (2007) largely support the learnings from these empirical effects of various technologies on yield and soil quality. Table 1 illustrates a practical finding from such trials, namely that the total soil carbon content only change little and slowly but it is in the intermediate carbon pools that the management differences are detectable. Similar findings under Asian conditions have been presented by Wen (1984), by Khan et al. (2007 for North American conditions, and under North Scandinavian conditions by Ågren & Bosatta (1996).

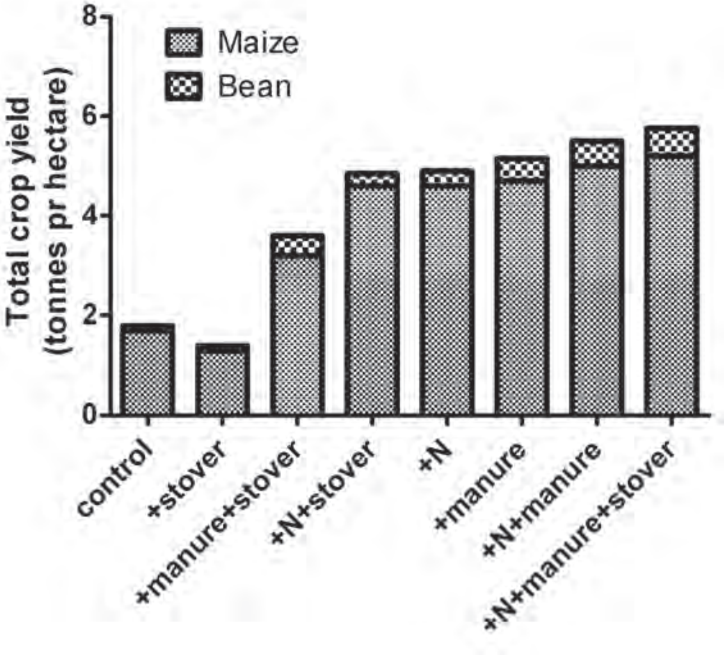

Fig. 2. Long-term effect of residue/manure management in Kabete, Kenya, after 18 yr on a Humic Nitisol. Manure signifies 10 tonnes farm yard manure per hectare and N signifies 120 kg nitrogen and 52 kg phosphorus per hectare in inorganic fertilizers (modified from Kapkiyai et al., 1999).

Soil feeding strategy	Particulate organic carbon (mg C kg^{-1} soil)	Total soil organic carbon (tonnes C ha^{-1})
No addition (control)	713	24.5
Maize stover retention	748	25.5
FYM	1459	26.0
No organic material + inorganic fertilizers	695	24.0
Maize stover retention + inorganic fertilizers	942	25.0
FYM + inorganic fertilizers	1514	26.0
Maize stover retention + FYM + inorganic fertilizers	1613	28.0

Table 1. Long-term effects on soil organic carbon pools of different soil feeding strategies (after Kapkiyai et al., 1999).

3. Crop nutrient limitations for feeding mankind

The use of agrochemicals by many small-scale farmers is reaching a low of 9 kg in Sub-Saharan Africa (FAO, 2003). The reason for this is often sought in the variability of returns to their use in drought-prone climates (e.g. Benson, 1998). However, this simplistic cause-effect relation is inadequate. An important aspect is that blanket recommendations disseminated through the extension systems have been based on the aim of maximizing crop yields (see e.g. Khan et al., 2007). The farmer and the farming families may, however, have many other issues on their agenda that cause such recommendations to fail (Barrett et al., 2002a). Furthermore, the extension systems often target males despite the fact that many of the farmers are female (Gilbert et al., 2002). In the most dramatic manifestations, the non-use of fertilizers can be observed in for example Southern Malawi among smallholders, who nevertheless still attempt to crop soils that are depleted beyond the situations where they can sustain a maize crop without additional nitrogen inputs. A major reason why these small-holders use very little, or no, fertilizer is that they cannot afford to buy it. However, simple cost-benefit analyses have also shown that it is not profitable to apply fertilizer on maize in southern Malawi under present prize conditions (Whiteside, 1998) and that, as a rule of thumb, farmers need an additional 5 kg of grain for every kg of N applied (Twomlow et al., 2010).

Under temperate conditions, leguminous nitrogen can be controlled and transferred to subsequent crops, even when the nitrogen providing crops are incorporated (Eriksen et al., 2004; Høgh-Jensen and Schjoerring, 1997). That makes the use of annual leguminous crops a sustainable approach. Under tropical conditions, however, leguminous nitrogen cannot be conserved and controlled in the same manner and thus transfer to subsequent crops when using annual crops are small (Laberge et al., 2011). That may not make the use of annual leguminous crops an unsustainable approach but clearly the nitrogen pools left by the crops are lost and not available to the subsequent crop. This may be due to leaching following heavy rain showers before the subsequent crops' roots can assess the nitrogen and/or there may be gaseous losses involved following denitrification.

Approaches to quantify the amounts of atmospheric nitrogen fixed by grain legumes erroneously base their estimates on the nitrogen located in harvested biomass above-ground (Herridge et al., 2008; Unkovich et al., 2010). This approach ignores the depositions below-ground associated with crop roots (Gregory, 2006); deposits can benefit subsequent crops (Laberge et al., 2011).

The initial transfers of nitrogen from annual grain legumes to subsequent crops are relatively small (Høgh-Jensen et al., 2005; Laberge et al., 2011). However, Høgh-Jensen et al. (2006) concluded that N-rich leaf litter together with root residues from pigeonpea grown as annual crops well into the dry season is able to enhance a sustainable maize yield that is approximately twice the yield of maize grown in sole stand. The potential of the crops when cultivated as semi-perennials are yet not well-understood but has be partly tested in agroforestry systems (Daniel & Ong, 1990; Odeny, 2007).

4. Semi-perennial legumes in Africa

The current section will investigate the use of semi-perennial legumes in Africa in particular as this continent to a very limited degree has taken up the use of Haber-Bosch nitrogen. Traditional African agriculture is often pictured as inefficient and unproductive. The prejudice in the statement of a Rhodesian administrator in 1926 that intercropping is nothing more than "hit and miss planting in mixtures" (Juggens, 1989, as cited in Barrett et al., 2002a) derogates a view that persists until today. The challenges remain of inducing a sustainable intensification by improving productivity and natural resource management. But much progress thas been made – both in understanding the socio-biophysical complexity and decision making rationality of the farmer as well as in feasible and attractive options.

Scholars are often quite pessimistic when viewing the potential of legumes to contribute further to feeding other crops (Breman & van Reuler, 2002; Palm et al., 1997). But their point of departure is often annual legumes like beans, soybean, cowpea, and groundnuts. Legumes have a C_3 photosynthesis that is characterized by relatively low optimum growth temperatures and water use efficiencies and further, often they do not have an erect growth. Thus, these annual grain legumes are all sensitive to competition for phosphorus, water and light. Further - and maybe even more important - is that evaluations may be based on the false premise that semi-subsistence agriculture cannot support widespread improved natural resource management in contemporary Africa (Barrett et al., 2002b). In other words, improved natural resource management must re-pay the investment on a rather short term basis and thus it is linked to high-value cash crops!

Intercropping of maize and grain legumes is a common practice in many areas in Africa although the rationale behind is not always clear. Pigeonpea is a multipurpose leguminous shrub, which thrives on relatively poor soils (Daniel & Ong, 1990; Odeny, 2007). It is grown with the aim of increasing household cash income and for food, fodder, firewood, and soil fertility improvement. There is an increasing international market for pigeonpea grain. Thus, maize intercropped with long-duration pigeonpea has emerged as a highly productive system with multiple beneficial effects on the farming systems (Kumar Rao et al., 1983; Nene & Sheila, 1990). Consequently, these cropping systems are widespread in some areas of eastern and southern Africa. Intriguingly, however, few kilometres away pigeonpea may not be found and this without apparent socio-economic, cultural or biophysical causes to explain the change. Previous research has shown that integration of pigeonpea into the maize-dominated cropping systems may be a significant low-cost, low-technological step towards increased food production, improved household diet and alleviation of soil degradation and poverty among small holders in semi-arid Africa (Jones et al., 2002; Mergeai et al., 2001; Versteeg and Koudokpon, 1993).

5. Socio-economic aspects of pigeonpea

Africa's declining per capita food production is paradoxical as most African economies are agriculturally based and approx. 75 % of the population lives in rural areas. As a multiple purpose (Table 2), the drought-resistant crop pigeonpea (Figure 3) provides many benefits to the resource-poor farming families. The integration of pigeonpea into the maize-dominated cropping systems of southern and eastern semi-arid Africa has been shown to lead to multiple benefits.

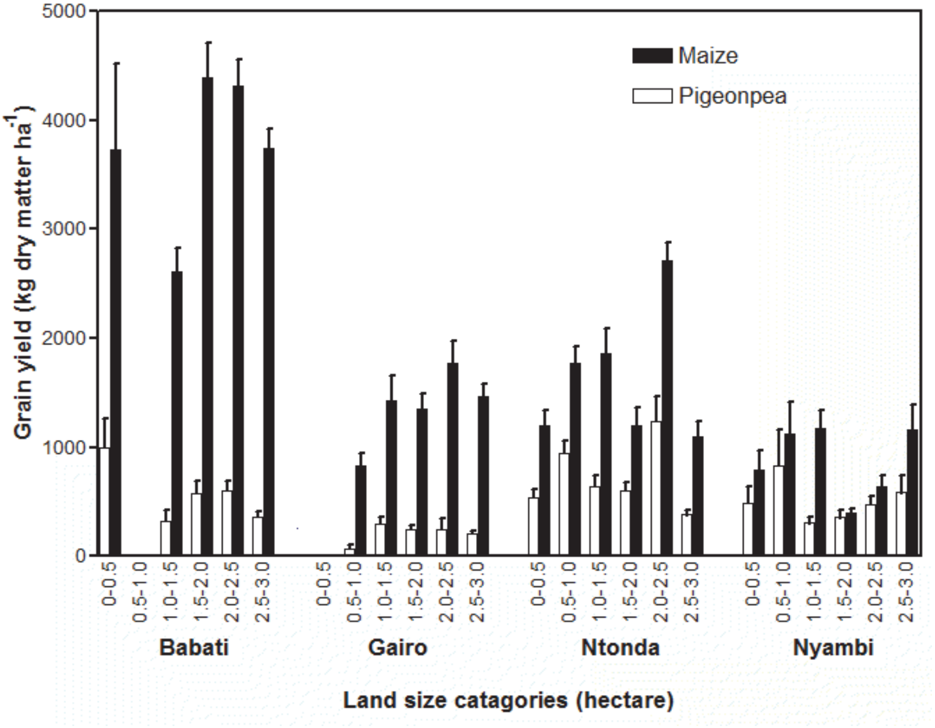

Fig. 3. Relation between land size and mean grain yields from four sites of maize and pigeonpea over two consecutive cropping seasons. Bars represent means±standard error; n varies depending on category (Høgh-Jensen & Odgaard, unpublished data).

Consequently, leguminous nitrogen may be added to the system in substantial quantities if the right uses of the crop are possible. The crop traits to look for may be similar to pigeonpea, i.e. semi-perennial and with use for food, fuel, fodder and of course cash. This example indicates that even under tropical conditions, leguminous nitrogen can efficiently be used to boost production.

As the global economies try to reduce their fossil fuel dependencies, the request of bio-based resources will increase as, in principle, all organic chemicals can be obtained from biomass. Physical and economic constraints must be expected for satisfying this demand in a similar manner as for food. In this light, the potential higher nitrogen use efficiency that semi-perennial legumes offer together with the multipurpose use that is exemplified by pigeonpea will be required to obtain a sustainable development. Furthermore, pigeonpea is drought tolerant and well-adapted to diverse environments. However, one thing is the potential benefits in terms of increased productivity and improved soil fertility, which we have documented above. A different question is how farmers perceive the benefits of integration of pigeonpea.

The main reason for women being less productive than men in relation to maize yields appears to be that women have less access to chemical inputs and technical know-how than men and it is stressed that when women have equal access to such inputs their productivity matches that of men (Gilbert et al., 2002; Gladwin, 2002). Further, the households with most land obtained the highest maize yields. However, pigeonpea showed exactly the opposite effect; favoured by the households with small land access (Odgaard R & Høgh-Jensen H, unpublished). Pigeonpea grain yields were further unaffected (P=0.69; data not shown) by gender of household head.

Due to its multipurpose nature, grain yield of pigeonpea may not meaningfully be taken as a reliable productivity indicator alone. In addition to the grain yield, the importance of green pods in the diet and food security, firewood, soil fertility boasting and livestock benefit (Table 2) must be taken into consideration. Finally cash diversification is a very important issue as possible surpluses of maize often are sold at harvest. As pigeonpea can be sold both as green pods, as dry grain and as seed it is a potential source of income (and food) during a large part of the year.

The high rating of green pods that Tanzania farmers attribute to pigeonpea crops (Table 2) and the very low mature grain yield that was harvested in Malawi (partly shown in Figure 2) indicate that pigeonpea plays an important role in the diet of farmers. As one out of five malnourished children reside in Sub-Saharan Africa (Rosegrant et al., 2001), pigeonpea may play an undervalued role in health and food security through its contribution to a balanced diet. Furthermore, as surplus maize is sold in May-June to cover school fees and debts, among others, the crops of pigeonpea that can be harvested in August-November gives the farmer a small income for which new farming inputs can be acquired. This diversification is obtained with very minor additional labour demands, which is an important issue for female farmers as the stressed by the female participants (Høgh-Jensen & Odgaard, unpublished data), which agrees with Snapp & Silim (2002).

In Malawi, the two sites do not differ in relation to the question of cash and food as being major purposes of growing pigeonpea: 68 % of the farmers at both sites attribute pigeonpea to cash, 95 % to food. However, at Nyambi (a very poor soil site) 100 % attribute pigeonpea to firewood whereas only 68 % do so at Ntonda (a better soil site). The main explanation for the difference in relation to firewood is the question of distance to other sources of firewood. In Tanzania, all farmers at both sites see pigeonpea as a food as well as a cash crop, but also firewood is seen as an important product of the crop. However, as indicated by Table 2, pigeonpea is attributed a number of other functions by the respondents.

	Gairo (% of respondent)	Babati (% of respondent)
Cash	100	100
Food	96	94
Eat dry	32	50
Eat green	60	88
Firewood	89	94
Soil fertility	58	75
Medicinal uses for mainly human	31	13
Feed for livestock	15	94

Table 2. The purpose of growing pigeonpea by Tanzanian farmers at two sites (Høgh-Jensen, 2011).

Although all respondents at the two sites in Tanzania state that pigeonpea is grown both for food and cash purposes, the cash amounts obtained from pigeonpea sales differs in the two areas. While there is a fairly well established market for pigeonpea in Babati and a reasonably well-organized trade in the crop out of the district, the pigeonpea trade in Gairo is different. Here pigeonpea is mainly sold at local markets or to local traders, who ferry the crop mainly to the market in Dar es Salaam, a 4 hours drive at tarmac roads. It appears that it is mainly the men who are involved in pigeonpea trade in Babati, whereas both men and women are involved in the various forms of trade taking place in Gairo.

In Babati, the crop has mainly been introduced as a cash crop and consequently the male sex seems to be the main manager of the income from the crop, and also the main decision maker in relation to use of the crop and the land on which it is grown. Considering the heavy labour input provided by women in farming activities of all kinds, a voice of caution as to the potential role of pigeonpea in improving gender relations needs to be raised. The strong emphasis on the commercial aspects of growing pigeonpea in Babati, combined with the male control of cash income and other resources, may, as discussed, lead to increasing gender inequality instead of reducing it. For similar effects of rapid commercialization see for example Mbilinyi (1991). Moreover, the commercialization of land and other resources in Babati has contributed to constraints for the young generation in relation to getting access to arable land. The growing of pigeonpea has enhanced these constraints.

In Gairo, on the other hand, very few men claim to be main managers of the income. The majority of the respondents irrespective of sex claimed that both husband and wife are involved in selling the crop, controlling the income and making decisions.

The situation in Malawi, especially in Ntonda where more than 50 % of the respondents are women, seems to be similar to the one in Gairo, apart from the fact that women seem to be more involved in the local pigeonpea trade than men.

In many African societies, men and women do have separate income streams and different rights to cash crops grown on the families land. In some cases, it is the females who cultivate the majority of the food crops. Pigeonpea appeared as one of the few examples where the products cut across these patterns as both men and women in various ways and to varying degrees enjoy the multiple benefits, which can be derived from it. Some research has shown, though, that different services associated with the pigeonpea crop, are valued differently by men and women. It has been found for example that women do not value soil fertility services but value food consumption (Snapp & Silim, 2002). Compared to our findings this is much too general a statement. While men seem to be more concerned about soil fertility than women in for example Babati, where the majority of the respondents are male, all the female respondents in the traditionally pigeonpea-growing area of Ntonda maintained that pigeonpea improves soil fertility.

There is effective market demand for both whole grain pigeonpea as well as processed pigeonpea products from eastern and southern Africa in several global markets (Jones et al., 2002). In Malawi, pigeonpea is sold and bought on local markets and the local markets are functioning as outlets to the larger absorbing world market. The Indian market has a huge absorbing capacity in August-September where the home supply is not able to meet the demand. Mostly the harvest in Malawi will be too late for that market, using medium-to-long duration varieties, and thus the crops can not fetch premium prices. No farmers have apparently showed sufficient entrepreneurship to venture into production of short-duration varieties to obtain a high-value cash and export crop. And it is anticipated that a significant backup must be created to make this a realistic strategy for resource-poor farmers.

6. Nutrient limitations to the technology

In the case of cereals, like maize, the relation between harvest grain and total biomass (so-called harvest index) is relatively linear. Figure 4 illustrates this point quite nicely with grain yields ranging from below 1 to as high as 9 tonnes maize grain per hectare. It is also seen that the grain yield was about 54 % of total biomass at all yield levels at Babati and Gairo, the two Tanzanian sites. Hence the conditions for grain development were optimal in Tanzania. Drought conditions can, however, lower the harvest index significantly as grain development may be hindered as demonstrated in the two Malavian sites of Ntonda and Nyambi (Figure 5).

The same data can due to the range in yields be used for investigating the effect of soil fertility on grain yields. Using an upper boundary line analytical approach (Anderson & Nelson, 1974; Walworth & Summer 1988) the following figure can be generated (Figure 6), demonstrating that soil nitrogen availability was determining biomass yields. The variability in soil-N fertility and maize yield from farm to farm were associated with the year span and of intercropping maize and pigeonpea in the past. Hence, it appears that the accumulation during the years of the added effect of pigeonpea in the cropping system can increase soil-N fertility from 1 tonne maize per ha to 9 tonnes maize per ha. A threshold of around 0.10 % soil nitrogen was identified (Figure 6). Consequently farming practice is very important and variability in soil nitrogen availability can be created by the year span of maize and pigeonpea intercropping.

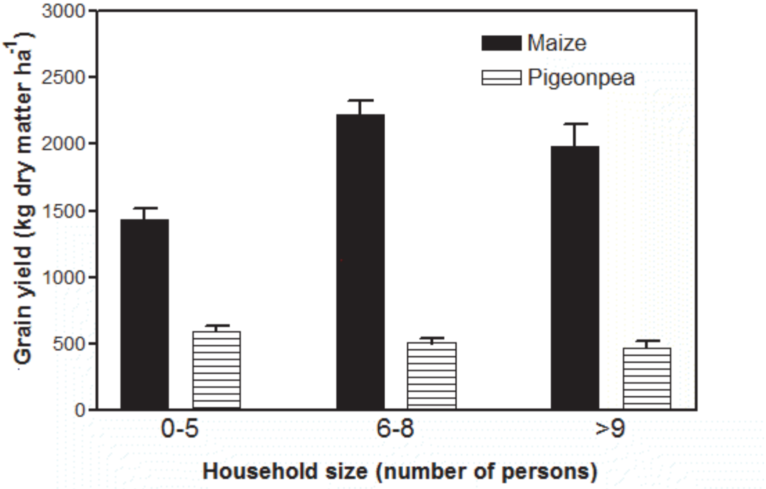

Fig. 4. Relation between household size and mean grain yields of maize and pigeonpea over two consecutive cropping seasons. Bars represent means±standard error; n=480 for pigeonpea and 640 for maize (Høgh-Jensen & Odgaard, unpublished data).

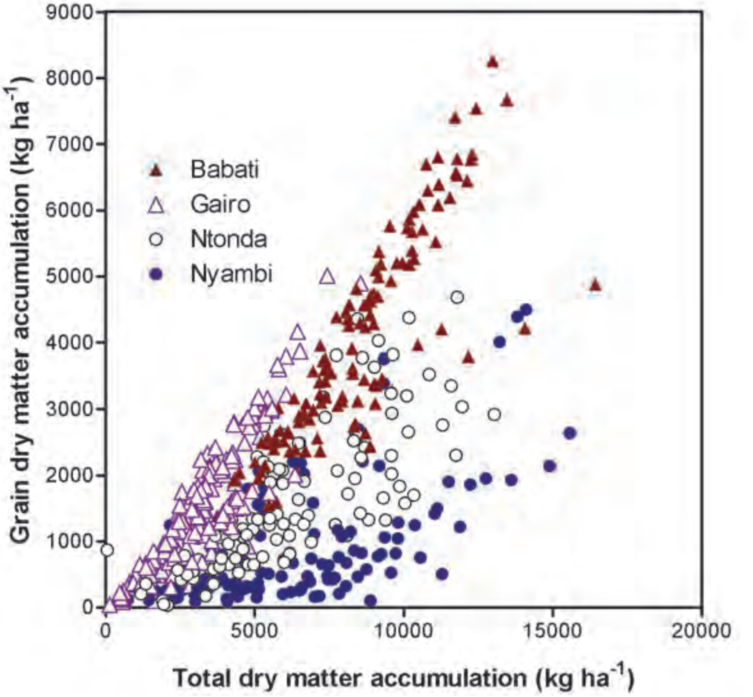

Fig. 5. Maize yields from farmers fields in Tanzania in the season of 2002 and 2002 from four different sites.

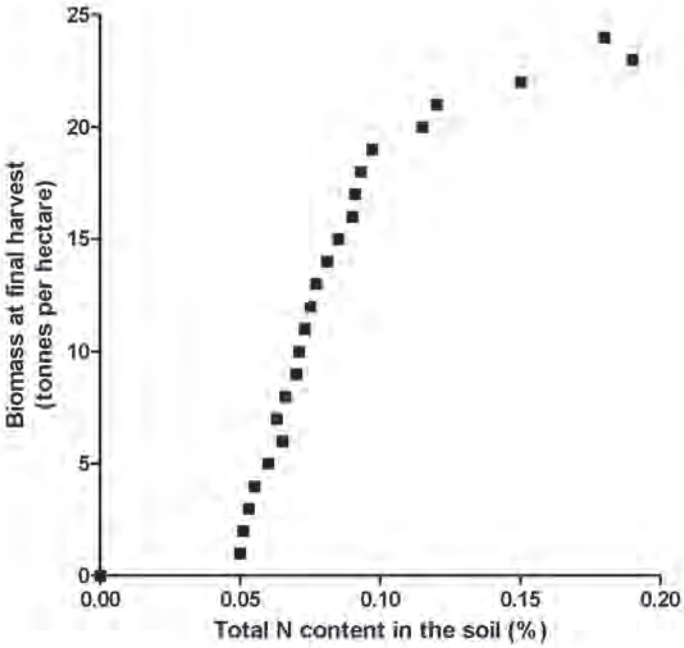

Fig. 6. Maize biomass accumulation in farmers fields in Tanzania in the season of 2002 in relation to soil nitrogen (Nielsen & Høgh-Jensen, 2006).

No relation were seen between the concentration of nitrogen in the ear leaf tissue sampled at the tasseling stage and the final harvest or the level of soil-N because the N uptake at that time still was limited by the capability of the plants to absorb N into new tissue. The main reason is the accumulation of nitrate due to the N-flush from the onset of the rainy season (Høgh-Jensen et al., 2009).

7. Modelling

The flux of nitrogen through the grain legume in mixtures with non-legumes may be a major driving force for sustaining productivity in smallholder systems. This flux is enhanced through biological N_2 fixation and comprises three major flows of nitrogen. First, legume nitrogen is present in the living plant material, that can be harvested and the residues are incorporated in the soil and utilised by subsequent crops. Secondly, the turnover of legume tissue can lead to nitrogen transfer to associated species. Thirdly, the turnover of maize tissue can lead to deposits under conditions where nitrogen is not rapidly mineralised and made available to the plant.

Dynamic simulations models have been developed that are capable of simulating different aspects of the nitrogen cycle and dynamics, as well as biomass production in wheat and other cereals. Furthermore, models have been developed for leguminous grain crops like soyabean (Lim et al., 1990; Thies et al., 1995), faba bean (Stützel, 1995) and groundnut

(Hammer et al. 1995). Nevertheless, none of these approaches take N_2-fixation into account in a mechanistic manner in spite of its importance for nitrogen dynamics of legume-based cropping systems in the short as well as in the longer term. Simulation models can compliment traditional field experiments in researching alternative management options (Carberry et al., 2002).

7.1 The model in brief

DAISY (a soil-plant atmosphere system model) is a one-dimensional open-source (http://www.dina.kvl.dk/~daisy/) agroecosystems model that, in brief, simulates crop growth, water and heat balances, organic matter balance, and the dynamics of N in agricultural soils. This simulation is based on information on management practices and weather data. The simulation of the organic matter balance and the N dynamics is strongly interconnected; hence the organic matter model is considered an integral part of the overall N balance model. Weather data are used as driving variables (input to DAISY). These variables can be viewed as connections to the surrounding environment. The minimum data requirement are daily values of global radiation, air temperature and precipitation (Hansen et al., 1991).

The model allows simultaneous growth of multiple species, which is utilised in the present study. In the crop model, the crop is divided into shoots and roots. The shoot is characterised by dry matter content and leaf area index, while the root system is characterised by dry matter content, rooting depth and root density. Gross canopy photosynthesis may be limited by water and/or N deficiency. The information of water supplied in the driving variables and N status is calculated using information on the actual soil profile.

Nitrogen fixation is simulated as described by Høgh-Jensen (Høgh-Jensen, 1996) and can be understood as a negative feedback regulation of N_2-fixation when external inorganic N is available (Soussana et al., 2002). N_2-fixation is governed by two factors. First, pigeonpea compete with associated crops for inorganic N. This competition is determined by growth and associated N uptake kinetics as described by Michaels Mentons' V_{max}. Secondly, an arbitrary fixation rate, set at 0.95, describes the nitrogen uptake by N_2 fixation relative to the crops optimal N demand at the present development stage according to Ryle et al. (1979).

7.2 Scenario management

The greater complexity of intercropping systems compared to mono crops poses an enormous difficulty for modelling them. However, one way to tackle this problem of complexity is to start by modelling crops in pure stands and to identify key processes that are of importance for the research question.

In the present study, the return of residues and senescence rate of plant tissue was identified as determining the long-term impact of incorporating pigeonpea into the maize cropping system. Following this approach, two crop modules were developed for maize and pigeonpea that fitted to the development and yields obtained in field trials in southern Malawi under farmers conditions. This includes concentrations of N in different organs of the crops as well as pigeonpea leaf litter.

All simulations were conducted by DAISY version 2.47. The temperature function that influence soil organic matter turnover was modified to decrease mineralization in dry soil. The driving weather data were obtained from Chileka airport, 5 km north of Blantyre, Malawi, and supplemented, in particular on global radiation, with the use of the weather generator MarkSim® (www.ciat.cgiar.org).

All scenarios assumed a 100 % return of all residues from the maize to the system. Similarly, pigeonpea residues were assumed incorporated or recycled. However, as stems normally are utilised for firewood only 20 % of stems were recycled. No fertiliser was added in the simulations. These management options agree with real life situations of southern Malawi as the stocking density of ruminants is very low and maize residues are being incorporated into the soils. This often takes place right after harvesting the maize grain. As the crops are grown on ridges, incorporation is easy.

However, maize residues are not incorporated in the simulations before preparing for seeding a new crop. Further, pigeonpea shed their leaves during the dry season. Thus, the amount of green leaves is low at the time of the last harvest of the pods. Due to severe resource constraints, most resource-poor smallholders only apply minimal or no mineral fertilisers to their maize crops. Data on soil profiles were obtained from soil samples and supplemented with literature values (see Mwanga 2004).

7.3 Simulations outcomes

Technologies to improve productivity of nutrient-poor soils have historically depended on high levels of inputs. However, smallholder farmers rarely have sufficient cash to invest in fertilisers. Nor do they have labour or land to invest in the production of green manures or compost. Therefore, biologically based interventions to improve soils and farmers food security must necessarily have their starting point in the cropping already taking place; that is in the cropping of maize. In contrast to the use of agrochemicals like fertilisers, it is possible for even the poorest farmers to intercrop the maize with pigeonpea varieties. This may be why this technology dominates the whole of southern Malawi and parts of southern Tanzania.

The development of crop modules is based on a combination of literature values and experimental data on crop yields and crop quality. Even so, there is a need for further refinement and test of these modules. However, a realistic development - relative and in time - of crop organs was obtained (Figure 7) when simulated in pure stands and intercropped.

In the field situation, dead material does not accumulate to any significant extent on the soil surface as long as the soil is moist. Nevertheless, as pigeonpea shed most of its leaves during the dry season, these leaves accumulate on the dry soil surface although soil fauna still incorporate it into organic matter. Furthermore, the importance of root senescence of a short duration crop, like maize, may not be significant whereas the long duration pigeonpea may have substantial impact.

In an intercropping situation, the input from the pigeonpea to the systems in one cropping season exceeded the input from maize 3-fold of dead organic carbon and 50-fold of dead organic nitrogen. This contrasts to the common view that residues are normally of a low

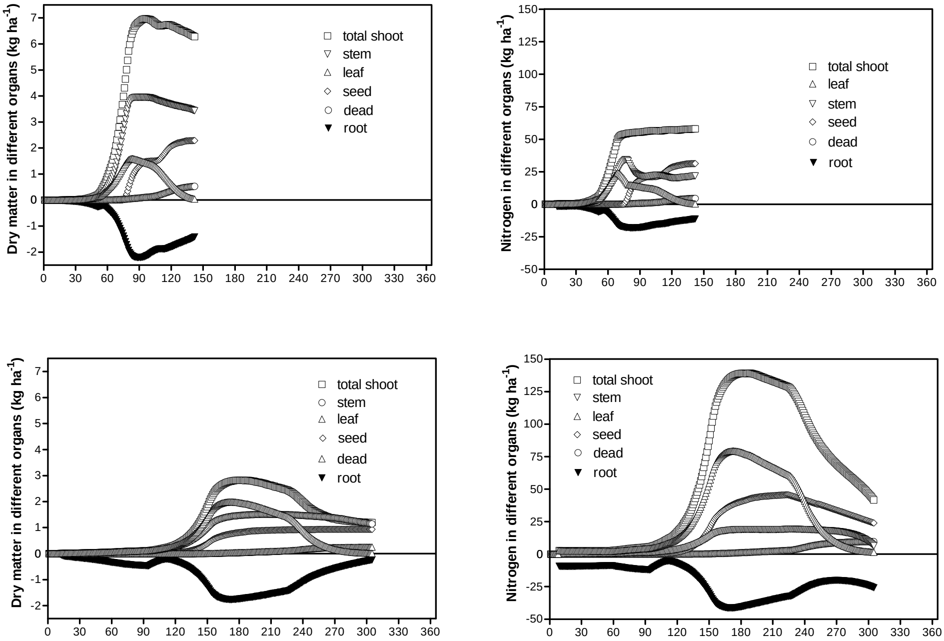

Fig. 7. Simulated dry matter (right) and nitrogen (left) simulations in different pools over one cropping season (days) of maize (top) and pigeonpea grown in mixture (bottom).

quality that is not able to sustain the nutrient requirement of subsequent crops (Palm et al., 1998). However, a high quality of approx. 20 g kg^{-1} nitrogen of pigeonpea leaves is well documented (see references in Sakala et al., 2003). In a simulation study of maize using the model CERES-Maize, Harrington and Grace (1998) set residue addition to 500 kg dry matter pr hectare without considering a death rate on the roots.

Simulation of pure stand maize demonstrates how small the productivity in these systems is without fertiliser applications (Figure 8). The accumulation of N is very small as the flux of N in the systems are small due to the fact that these fluxed deviates from humus and the small amounts of nitrogen located in previous crop residues. This results in the grain yields of less than 1 tonnes per hectare that are so common for low-input Sub-Saharan Africa (Figure 8).

Adding 70 kg N ha^{-1} yr^{-1} improve the grain yields to approx. 2 tonnes per hectare (Table 3). However, similar maize yields can be obtained by intercropping maize with pigeonpea without fertiliser applications (Figure 8; Table 3). In addition, the intercropped systems have the additional beneficial grain yields of pigeonpea (Table 3). Furthermore, firewood, (see stem in Figure 7), which is a scarce resource in many of these areas, is also a pigeonpea by-product that is highly valued. Thus, in terms of productivity of the systems, the intercropped systems come out very convincingly.

The balance between maize and pigeonpea yields fluctuates but at the end of the second season the effect of pigeonpea was very clear (Figure 8; Table 3). However, these balances are strongly affected by the simulation of organic matter turnover in the soil and although DAISY is successful under temperate and subtropical conditions (Jensen et al., 1997), there is

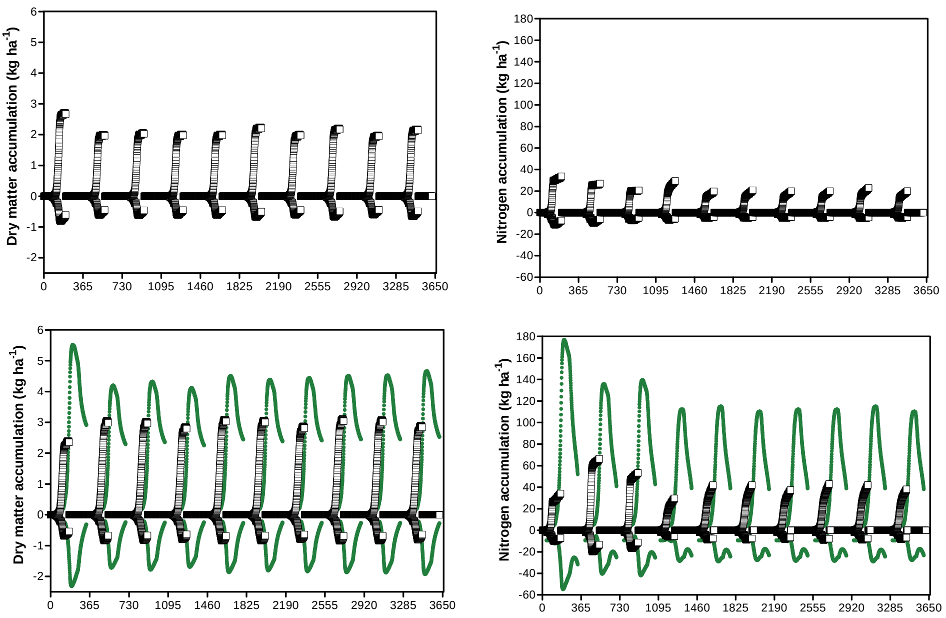

Fig. 8. Simulated dry matter (left) and nitrogen (right) over 10 years of maize (square) in pure stand (top) and maize-pigeonpea (line) intercropped (bottom).

Cropping system	Grain yield (kg DM ha^{-1})									
	Yr 1	Yr 2	Yr 3	Yr 4	Yr 5	Yr 6	Yr 7	Yr 8	Yr 9	Yr 10
Pure stand maize without fertilizer	1382	816	880	838	835	993	843	969	816	947
Pure stand maize with 70 kg N ha^{-1} yr^{-1}	2469	2013	1743	2010	2037	1842	1935	2087	1807	1906
Maize in mixture without fertilizer	1459	2094	2091	1904	2138	2104	1943	2147	2121	1943
Pigeonpea in mixture without fertilizer	945	963	931	943	943	963	931	943	943	943

Table 3. Simulated dry matter (DM) grain yields of maize in pure stand when receiving nil or 70 kg nitrogen ha^{-1} annually or unfertilised maize-pigeonpea over a 10-years period.

a need for testing the model on well-defined long-term trials under tropical conditions. The current dataset contains yield data from maize in Malawi, which means that these maize trials contain two seasons residue effect. When comparing all maize in mixture with all maize in pure stand from this third cropping season the mixture yielded 1910 kg grain dry matter pr hectare compared to 1560 kg grain dry matter pr hectare from the pure stands.

When comparing the nitrate losses from the two different systems, i.e. maize in pure stand and maize-pigeonpea intercropped, the intercropped system is associated with a substantial larger loss of nitrate (data not shown); from less than 20 kg N ha^{-1} yr^{-1} in the pure maize stand to more than 70 kg N in the intercropped stand. The size of this loss is detectable during the second season that the crops are intercropped. This simulated loss is in agreement with the nitrate concentrations found at the end of the dry season (Borgen, 2004).

Total seasonal rainfall and crop yield is not well correlated under precipitation patterns like Malawi. Maize is especially susceptible to periods of droughts during the flowering phase of crop development (see Figure 5). Compared to the cropping season of 2001-2002, February 2002 had nearly half the rainfall of the thirty-year's mean in Malawi, which is critical as February is the normal month for flowering and crop grain yields may be affected.

8. Conclusions

Maize is a major stable food in Sub-Saharan Africa but low soil fertility, limited resources and terminal drought are the main determining factors affecting the productivity of maize in the developing world. Consequently, new technologies and approaches must be innovated as those currently on the shelves do not seem to solve this major challenge (Schlecht et al., 2006).

An obvious approach is to seek among the legume-based technologies for answers to some of the problems. This is not necessarily a new approach (Giller, 2001; Graham & Vance, 2003; Lupwayi et al., 2011; Vesterager et al., 2007) but the scientific world divides in two camps when promoting solutions. One focuses on a reversal of the apparent decline in soil fertility (see e.g. discussions in Kumwenda, 1998; Snapp, 1998; and Schlecht et al., 2006) and another focuses on strategies that utilize crops and crop management to get the best out of the existing biophysical environment. The current chapter acknowledge that legume N in crop residues easily exceed the 50 kg fertilizer-nutrient per hectare recommended by African heads of states at the Fertilizer Summit held in 2006 in Abuja, Nigeria. The chapter, however, also acknowledge that this legume nitrogen is difficult to manage. But most importantly it acknowledge that many of the regions most starving communities are in locations that cannot sustain crops that produce the above-mentioned equivalents of 50 kg fertilizer-nitrogen (Sumberg, 2002). Under such conditions, perennial legumes are one possible important answer to an erratic and harsh environment.

Pigeonpea is one of the few leguminous crops with a high potential to enhance soil fertility due to its complementarity with maize (McCown et al., 1992). Furthermore, associated labour inputs are minimal and seed costs are low compared to other green manure or agroforestry species (Sakala et al., 2003). In risky environments farmers are reluctant to invest in fertilisers (Mwanga, 2004) because they have limited access to cash and they are not sure of the returns.

Simulations confirm empirical data that N-rich leaf litter together with root residues from pigeonpea are able to enhance a sustainable maize grain yield that is approximately twice the yield of maize grown in pure stand. Simultaneously, nitrate leaching is predicted to increase substantially following the inclusion of the pigeonpea in the maize-based cropping systems. The simulated data (Figure 8) agrees partly with the measured data in the sense that the residue effect is measurable after two cropping season.

Maize is frequently intercropped with pigeonpea in eastern and southern Africa (Odeny, 2007; Myaka et al., 2006; Snapp & Silim, 2002). However, the poor seed quality and low plant stand of the pigeonpea crop often result in low residual effects of nutrients -

particularly nitrogen and phosphorus - to the subsequent maize crop. Consequently, such systems must enhance the legume population to make a significant impact. This requires availability of modern seed varieties.

Further, alternatives to intercropping must be developed. In some areas, the rainfall is not sufficient to sustain two intercropped crops (Postel, 2000). Under such conditions, rationing of the pigeonpea should be considered, which would maintain the seeding capacity of the trees but eliminate the hassle and risks by re-establishing the crop.

The market orientation is the predominate paradigm in Agricultural Research for Development (see Høgh-Jensen et al., 2010, for further discussion) but approaches like suggested above with semi-perennial legumes is not in conflict with this paradigm. In contrast it holds the potential for being included in both a market-driven development (Jones et al., 2002) and in poverty alleviation or food security oriented development efforts due to its adaptation to harsh environments.

9. References

Ågren, G.I. & Bosatta, E. (1996). *Theoretical Ecosystem Ecology. Understanding Elements Cycles*. Cambridge University Press, Cambridge.

Anderson, R.L. & Nelson L.A. (1974). A family of models involving straight lines and concomitant experiential designs useful in evaluating response to fertilizer nutrients. *Biometrics,* 31, pp. 308-318.

Barrett, C.B., Place, F., Aboud, A. & Brown, D.R. (2002a). The challenge of stimulating adoption of improved natural resource management practices in African Agriculture. In: *Natural Resource Management in African Agriculture* (eds.: C.B. Barrrett, F. Place & A.A. Aboud), pp. 1-22, CABI Publishing, Wallingford.

Barrett, C.B., Place, F., Aboud, A. & Brown, D.R. (2002b). Towards improved natural resource management in African agriculture. In: *Natural Resource Management in African Agriculture* (eds.: C.B. Barrrett, F. Place & A.A. ABoud), pp. 287-296, CABI Publishing, Wallingford.

Bänziger, M., Setimela, P. S., Hodson, D. & Vivek, B. (2006). Breeding for improved abiotic stress tolerance in maize adapted to southern Africa. *Agriculture and Water Management*, 80, pp. 212-224.

Benson, T.S. (1998). Developing flexible fertiliser recommendations for smallholder maize production in Malawi. In: *Soil Fertility Research for Maize-Based Farming Systems in Malawi and Zimbabwe* (eds.: S.R. Waddington, H.K. Murwira, J.D.T. Kumwenda, D. Hikwa and F. Tagwira), pp. 275-285. Harara, Zimbabwe: Soil Fert Net and CIMMIT-Zimbabwe.

Borgen, S. (2004). *Mineralization potential of tropical soils after cultivation with pure stand maize or maize/pigeonpea intercrop mixture*. BSc thesis. Copenhagen, Department of Agricultural Sciences, KVL. 39 p.

Bostick, W.M., Bado, V.B., Bationo, A., Soler, C.T., Hoogenboom, G. & Jones, J.W. (2007). Soil carbon dynamics and crop residue yields of cropping systems in Northern Guinea Savanna of Burkina Faso. *Soil & Tillage Research*, 93, pp. 138-151.

Breman, H. & van Reuler, H. (2002). Legumes: When and where an option? (No panacea for poor tropical West African soils and expensive fertilizers). In: *Natural Resource Management in African Agriculture* (eds.: C.B. Barrrett, F. Place & A.A. ABoud), pp. 285-298, CABI Publishing, Wallingford.

Carberry, P.S., Probert, M.E., Dimes, J.P., Keating, B.A. & McCown, R.L. (2002). Role of modelling in improving nutrient efficiency in cropping systems. *Plant and Soil*, 245, pp. 193-203.

Cohen, M.N. (1977). *The Food Crisis in Prehistory: Overpopulation and the Origins of Agriculture*. Yale University Press, New Haven, CT.

Daniel, J.N. & Ong, C.K. (1990). Perennial pigeonpea: a multi-purpose species for agroforestry systems. *Agroforestry Systems*, 10, pp. 113-129.

Drucker, P. (1985). *Innovation and Entrepreneurship*. Heinemann, London.

Eriksen, J., Askegaard, M. & Kristensen, K. (2004). Nitrate leaching from an organic dairy crop rotation: the effects of manure type, nitrogen input and improved crop rotation. *Soil Use and Management*, 20, pp. 48-54.

Erisman, J.W., Sutton, M.A., Galloway, J., Klimont, Z. & Winiwarter, W. (2008). How a century of ammonia synthesis changed the world. *Nature Geoscience*, 1, pp. 636-639.

Evans, L.T. (1998). *Feeding the Ten Billion. Plants and Population Growth*. Cambridge University Press, Cambridge.

FAO (2003). *FAOSTAT*. FAO, Rome.

Franke, A.C., Laberge, G., Oyewole, B.D. & Schulz, S. (2008). A comparison between legume technologies and fallow, and their effects on maize and soil traits, in two distinct environments of the West African savannah. *Nutrient Cycling in Agroecosystems*, 82, pp. 117-135.

Gilbert, R.A., Sakala, W.D. & Benson T.D. (2002). Gender analysis of a nationwide cropping system trial survey in Malawi. *African Studies Quarterly*, 6(1), retrieved on http://web.africa.ufl.edu/asq/v6/v6i1a9.htm.

Giller, K.E. (2001). *Nitrogen fixation in tropical cropping systems.* CABI Publishing, Wallingford.

Gladwin, C.H. (2002). Gender and Soil Fertility in Africa: Introduction. *African Studies Quarterly*, 6(1), retrieved on http://web.africa.ufl.edu/asq/v6/v6i1a9.htm.

Graham, P.H. & Vance, C.P. (2003) Legumes: Importance and constraints to greater use. *Plant Physiology*, 131, pp. 872-877.

Gregory, P.J. (2006). Roots, rhizosphere and soil: the route to a better understanding of soil science. *European Journal of Soil Science*, 57, pp. 2-12.

Hammer, G.L., Sinclair, T.R., Boote, K.J., Wright, G.C., Meinke, H. & Bell, M.J. (1995). A peanut simulation model: I. Model development and testing. *Agronomy Journal*, 87, pp. 1085-1093.

Hansen, S., Jensen, H.E, Nielsen, N.E. & Svendsen, H. (1991). Simulation of nitrogen dynamics and biomass production in winter wheat using the Danish simulation model DAISY. *Fertilizer Research*, 27, pp. 245-259.

Harrington, L. & Grace, P. (1998). Research on soil fertility in southern Africa: Ten awkward questions. In: *Soil Fertility Research for Maize-based Farming Systems in Malawi and Zimbabwe* (eds.: S.R. Waddington, H.K. Murwira, J.D.T. Kumwenda, D. Hikwa & F. Tagwira), pp. 3-11, CIMMIT.

Herridge, D.F., Peoples, M. & Boddey, R.M. (2008). Global inputs of biological nitrogen fixation in agricultural systems. *Plant and Soil*, 31, pp. 1-18.

Høgh-Jensen, H. (1996). Simulation of nitrogen dynamics and biomass production in a low-nitrogen input, water limited clover/grass mixture. In: *Dynamics of Roots and Nitrogen in Cropping Systems of the Semi-Arid Tropics* (eds.: O. Ito, C. Johansen, J.J. Adu-Gyamfi, K. Katayama, J.V.D.K. Kumar Rao & T.J. Rego), pp 585-601, Japan International Research Center for Agriculture, Ibaraki.

Høgh-Jensen, H. (2011). Legumes' rhizodeposition feeds a quarter of the world. In: *Clovers: Properties, Medicinal Uses and Health Benefits* (eds.....), pp. xx-xx, Nova Publishers. *Forthcoming*

Høgh-Jensen, H. & Schjoerring, J.K. (1997). Residual nitrogen effect of clover-ryegrass swards on yield and N uptake of a subsequent winter wheat crop as studied by use of ^{15}N methodology and mathematical modelling. *European Journal of Agronomy*, 6, pp. 235-243.

Høgh-Jensen, H., Sakala, W.D., Adu-Gyamfi, J.J., Kamalongo, D. & Myaka, F.A. (2006). Can modelling fill the gap in our knowledge of the nitrogen dynamics of the maize-pigeonpea intercrop? In: *Pigeonpea-based cropping systems for smallholder farmer's livelihood* (ed.: H. Høgh-Jensen), pp. 43-53, DSR Publishing, Copenhagen.

Høgh-Jensen, H., Kamalongo, D., Myaka, F.A. & Adu-Gyamfi, J.J. (2009). Multiple nutrient imbalances in ear-leaves of on-farm cultivated maize in Eastern Africa. *African Journal of Agricultural Research,* 4, pp. 117-112.

Høgh-Jensen,. H., Oelofse, M. & Egelyng, H. (2010). New challenges in underprivileged regions calls for people-centred research for development. *Society and Natural Resources*, 23, pp. 908-915.

Jensen, L.S., Mueller, T., Nielsen, N.E., Hansen, S., Crocker, G.J., Grace, P.R., Klír, J., Körschens, M. & Poulton, P.R. (1997). Simulating trends in soil organic carbon in long-term experiments using the soil-plant-atmosphere model DAISY. *Geoderma,* 81, pp. 5-28.

Jones, R., Freeman, H.A. & Monaco, G.L. (2002). *Improving the access of small farmers in eastern and southern Africa to global pigeonpea markets*. AGREN Network Paper No. 120. January 2002.

Kapkiyai, J.J., Karanja, N.K., Qureshi, J.N., Smitson, P.C. & Woomer, P.L. (1999) Soil organic matter and nutrient dynamics in a Kenyan nitisol under long-term fertilizere and organic matter input management. *Soil Biology & Biochemistry*, 31, pp. 1773-1782.

Khan, Z., Midega, C., Pittchar, J., Pickett, J. & Bruce, T. (2011). Push–pull technology: a conservation agriculture approach for integrated management of insect pests, weeds and soil health in Africa. UK government's Foresight Food and Farming Futures Project. *International Journal of Agricultural Sustainability*, 9, pp. 162-170.

Khan, S.A., Mulvaney, R.L., Ellsworth, T.R. & Boast, C.W. (2007). The myth of nitrogen fertilization for soil carbon sequestration. *Journal of Environmental Quality*, 36, pp. 1821-1832.

Kumar Rao, J.V.D.K., Dart, P.J. & Sastry, P.V.S.S. (1983). Residual effect of pigeonpea (*Cajanus cajan*) on yield and nitronge response of maize. *Experimental Agriculture*, 19, pp. 131-141.

Kumwenda, A.S. (1998). Soil Fertility Research for Maize-based Farming Systems in Malawi and Zimbabwe. In: *Soil Fertility Research for Maize-based Farming Systems in Malawi and Zimbabwe* (eds.: S.R. Waddington, H.K. Murwira, J.D.T. Kumwenda & F. Tagwira), pp. 263-269, Proceedings of the Soil Fert Net Results and Planning Workshop, 7-11 July 1997, Mutara, Zimbabwe. CIMMIT.

Laberge, G., Haussmann, B., Ambus, P. & Høgh-Jensen, H. (2011). Cowpea rhizodeposition and belowground transfer of nitrogen to millet in intercrop and rotation on a sandy soil of the Sudano-Sahelian eco-zone of Niger. *Plant and Soil*, 340, pp. 360-382.

Lim, J.T., Wilkerson, G.G., Raper, C.D. & Gold, H.J. (1990). A dynamic growht model of vegetative soya bean plants: Model structure and behaviour under varying root temperature and nitrogen concentration. *Journal of Experimental Botany*, 41, pp. 229-241.

Lupwayi, N.Z., Kennedy, A.C. & Chirwa, R.M. (2011). Grain legume impact on soil biological process in sub-Saharan Africa. *African Journal of Plant Science*, 5, pp. 1-7.

Mbilinyi, M. (1991). *Big Slavery. Agribusiness and the Crisis in women's employment in Tanzania.* Dar es Salaam University Press. Dar es Salaam.

McCown, R.L., Keating, B.A., Probert, M.E. & Jones, R.K. (1992). Strategies for sustainable crop production in semi-arid Africa. *Outlook on Agriculture*, 21, pp. 21-31.

Mergeai, M., Kimani, P., Mwang'ombe, A., Olubayo, F., Smith, C., Audi, P., Baudoin, J.-P. and A. L. Roi (2001). Survey of pigeonpea production systems, utilization and marketing in semi-arid lands of Kenya. *Biotechnology, Agronomy, Society and Environment*, 5(3), pp. 145-153.

Myaka, F.A., Sakala, W.D., Adu-Gyamfi, J.J., Kamalongo, D., Ngwira, A., Odgaard, R., Nielsen, N.E. & Høgh-Jensen, H. (2006). Yields and accumulations of N and P in farmer-managed maize-pigeonpea intercrops in semi-arid Africa. *Plant and Soil*, 285, pp. 207-220.

Mwanga W 2004 Low use of fertilizers and low productivity in sub-Saharan Africa. Nutr. Cycl Agroecosys. 45, 135-147.

Nene, Y.L. & Sheila, V.K. (1990). Pigeonpea: geography and importance. In: *The Pigeonpea* (eds.: Y.L. Nene, S.D. Hall & V.K. Sheila, pp. 1-14, CAB International and ICRISAT.

Nielsen, N.E. & Høgh-Jensen, H. (2006). Soil fertility evaluation of farmers' fields in semi-arid Tanzania and Malaiwi. In: *Pigeonpea-based cropping systems for smallholder farmer's livelihood* (ed.: H. Høgh-Jensen), pp. 43-53, DSR Publishing, Copenhagen.

Odeny, D.A. (2007). The potential of pigeonpea (*Cajanus cajan* (L.) Millsp.) in Africa. *Natural Resources Forum*, 31, pp. 297-305.

Palm, C.A., Myers, R.J.K. & Nandwa, S.M. (1997). Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. In: *Replenishing Soil Fertility in Africa* (Eds.: R.J. Buresh, P.A. Sanchez & F. Calhoun), pp. 193-217, SSSA Special Publication Number 51, Madison.

Palm, C.A., Murwira, H.K. & Carter, S.E. (1998). Organic matter management: from science to practice. In: *Soil Fertility Research for Maize-based Farming Systems in Malawi and Zimbabwe* (eds.: S. Waddington, H.K. Murwira, A.S. Kumwenda, D. Hikwa & F. Tagwira), pp. 21-27, Proceedings of the Soil Fert Net Results and Planning Workshop, 7-11 July 1997, Murara, Zimbabwe. CIMMIT.

Pinstrup-Andersen, P. & Pandya-Lorch, R. (2001). Meeting food needs in the 21st century. How many and who will be a risk? In: *Who will be fed in the 21st century? Challenges for Science and Policy* (eds.: K. Weibe, N. Ballenger & P. Pinstrup-Andersen), pp 3-14, IFPRI, Washington.

Postel, S.L. (2000) Entering an era of water scarcity: the challenge ahead. *Ecological Applications*, 10, pp. 941-948.

Radelet, S. (2010). *Emerging Africa. How 17 Countries are Leading the Way*. Center for Global Development, Washington.

Rogers, E. & Shoemaker, F. (1971). *Communication of Innovation*. Free Press, New York.

Rosegrant, M.W., Paisner, M.S., Meijer, S. & J. Witcover (2001). *Global Food Projections to 2002. Emerging Trends and Alternative Futures*. IFPRI, Washington, DC.

Ryle, G.J.A., Powell, C.E. & Gordon, A.J. (1979). The respiratory costs of nitrogen fixation in soyabean, cowpea, and white clover. I. Nitrogen fixation and the respiration of the nodulated root. *Journal of Experimental Botany*, 30, pp. 135-144.

Sakala, W.D., Kumwenda, J.D.T. & Saka, A.R. (2003). The potential of green manures to increase soil fertility and maize yields in Malawi. *Biological Agriculture and Horticulture*, 21, pp. 121-130.

Schlecht, E., Buerkert, A., Tielkes, E. & Bationo, A. (2006). A critical analysis of challenges and opportunities for soil fertility restoration in Sudano-Sahelian West Africa. *Nutrient Cycling in Agroecosystems*, 76, pp. 109-136.

Snapp, S.S. (1998). Soil nutrient status of smallholder farms in Malawi. *Communications in Soil Science and Plant Analysis*, 29, pp. 2571-2588.

Snapp, S.S. & Silim, S.N. (2002). Farmers preferences and legume intensification for low nutrient environments. *Plant and Soil*, 245, pp. 181-192.

Soussana, J.-F., Minchin, F.C., Macduff, J.H., Raistrick, N., Abberton, M.T. & Michaelson-Yeates, T.P.T. (2002). A simple model of feedback regulation for nitrate uptake and N2 fixation in contrasting phenotypes of white clover. *Annals of Botany*, 90, pp. 139-147.

Stützel, H. (1995). A simple model for simulation of growth and development in faba beans (*Vicia faba* L.) 1. Model description. *European Journal of Agronomy*, 4, pp. 175-185.

Sumberg, J. (2002). The logic of fodder legumes in Africa. *Food Policy*, 27, pp. 285-300.

Thies, J.E., Singleton, P.W. & Bohlool, B.B. (1995). Phenology, growht, and yield of field-grown soybean and bush bean as a function of varying modes of N nutrition. *Soil Biology & Biochemistry*, 27, pp. 575-583.

Twomlow, S., Rohrbach, D., Dimes, J., Rusiki, J., Mupangwa, W., Scube, B., Hove, L., Moyo, M., Masingaidze, N. & Mahposa, P. (2010). Micro-dosing as a pathway to Africa's green revolution: evidence from broad-scale on-farm trials. *Nutrient Cycling in Agroecosystems*, 88, pp. 3-15.

Unkovich, M.J., Baldock, J. & Peoples, M.B. (2010). Prospects and problems of simple linear models for estimating symbiotic N_2 fixation by crop and pasture plants. *Plant and Soil*, 329, pp. 75-89.

Urabe, K. (1988). Innovation and the Japanese management style. In: *Innovation and Management. International Comparisons* (eds.: K. Urabe, J. Child & T. Kagono), pp. 3-25, de Gruyter, Berlin.

Vesterager, J.M., Nielsen, N.E. & Høgh-Jensen, H. (2007). Nitrogen budgets in crop sequences with or without phosphorus-fertilised cowpea in the maize-based cropping systems of semi-arid eastern Africa. *African Journal of Agricultural Research*, 2 (6), pp. 261-268.

Versteeg, M.N. & Koudokpon, V. (1993). Participatory farmer testing of four low external input technologies, to address soil fertility decline in Mono Province (Benin). *Agricultural Systems*, 42, pp. 265-276.

Whiteside, M. (1998). *Living Farms. Encouraging Sustainable Smallholders in Southern Africa*. Earthscan Publications, London.

Wichern, F., Eberhardt, E., Mayer, J., Joergensen, R.G. & Müller, T. (2008). Nitrogen rhizodeposition in agricultural crops: Methods, estimates and future prospects. *Soil Biology & Biochemistry*, 40, pp. 30-48.

Walwort, J.L. & Summer, M.E. (1988). Foliar diagnosis: A review. In*: Advances in Plant Nutrition* (eds.: B. Tinker & A. Läuchli), pp. 193-241, Praeger Publishers.

Wen, Q.-X. (1984) Utilization of organic materials in rice production in China. In: *Organic Matter and Rice*, pp. 45-56. IRRI.

Woomer, P.L., Lan'gat M & Tungani J.O. (2004). Innovative maize-legume intercropping results in above- and below-ground competitive advantages for understorey legumes. *West African Journal of Applied Ecology*, 6, pp. 85-94.