Diversification and intensification of smallholder farming through intercropping with grain legumes in northern Tanzania

Esther Mugi

Propositions

1. Temporal and spatial diversification of component crops in an intercrop is key to ecological intensification of cropping systems.
(this thesis)
2. Residual benefits of maize-legume intercropping are amplified by addition of fertilizer.
(this thesis)
3. Climate change is an opportunity rather than a challenge for farmers to think outside the box.
4. The current publishing wave promotes fashionable topics while overlooking innovative ideas.
5. Technological advancements make people less creative.
6. Worrying takes up more of a PhD candidate’s energy than the actual research work.

Propositions belonging to the thesis entitled:

“Diversification and intensification of smallholder farming through intercropping with grain legumes in Northern Tanzania”

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Dedicated to the memory of my late father who was very happy when I began this adventure but did not live to witness its glorious end, my mother, my husband Daniel, daughter Natalie and son Nathan.

Abstract

Sustainable intensification and diversification of crop production is key to meeting higher future food demands while mitigating environmental impact of agriculture in smallholder farms. One way to achieve this is cereal-legume intercropping, as legumes incorporated into cereal-based systems have the ability to increase availability of nitrogen (N) from biological nitrogen (N_2) fixation. Other benefits associated with legumes inclusion includes the availability of legume grain yield, reduction in occurrence of pests and diseases, extended ground cover, better rooting ability, improved soil fertility in the long-term and the eventual increase in total yields. Productivity of intercrops depends on the balance between intra- and inter-specific competitions. This thesis focused on fine-tuning maize-legume intercropping systems in different agro-ecological zones, by working towards striking a balance between maximizing the benefits of inclusion of pigeonpea and lablab in maize systems, and minimizing potential disadvantages emanating from their competition with maize. A combination of farm surveys, on-farm trials and crop growth modelling were used on smallholder farms in northern Tanzania.

Socio-economic factors, field management characteristics, and their association with productivity of maize-pigeonpea intercrops were assessed through a survey of 277 farm households in northern Tanzania. Biomass production was 1.0-16.6 for maize, and 0.2-11.9 t ha^{-1} for pigeonpea (at maize harvest). The corresponding grain yield was 0.1-9.5 for maize, and 0.1-2.1 t ha^{-1} for pigeonpea. Factors that significantly affected maize grain yield were plant density at harvest, number of years the field had been cultivated, slope, weeding, soil fertility class, fertilizer and manure use, with interactions among the factors. Plant density at harvest was the key factor associated with pigeonpea yield. These results indicate that performance of intercrops can be enhanced through application of organic and inorganic nutrient sources, and agronomic interventions including weeding, implementing soil conservation measures on steep slopes and optimizing plant density.

Following the farm survey, on-farm experiments were conducted across three agro-ecological zones (Riroda, Arri and Dareda) within Babati district, Manyara region, northern Tanzania. The on-farm experiments were used to evaluate the growth and development of maize-pigeonpea and maize-lablab intercropping systems and their interaction with fertilizer and agro-ecological conditions. Additionally, residual effects from the grain legumes on the yields of a succeeding maize crop were assessed. Maize in intercrops was hardly affected by the presence of legumes, but the growth and yield of the intercropped legumes was negatively influenced by the presence of maize. The

productivity of maize was positively affected by N fertilization, but this was not the case for legumes, which responded positively to P fertilizer. Productivity of maize following two seasons of legumes or legumes intercropped with maize was larger than in plots that had been preceded by sole maize in the preceding seasons. Larger maize yields were observed in plots that had received fertilizer in the preceding seasons than the control plots. From the results, maize-legume intercropping systems are superior to maize pure stands, not only for the additional grain yield from legumes but also due to their residual effect in a succeeding cropping season.

The effect of cropping systems and fertilizer on N uptake by maize and legume, and N_2-fixation by grain legumes was evaluated. N_2-fixation differed among the legume species, with sole long-duration pigeonpea fixing 20 to 63 kg ha^{-1} more N_2 than all other cropping systems, corresponding to the higher shoot dry matter and N yield of this system. The combined N uptake of maize and legume in intercrops was consistently larger than that of pure stands of either maize or the legume. In the intercrops, the amount of N accumulated by maize was in most cases larger than that of the legume. Application of fertilizer resulted in enhanced N uptake both in the current season (up to 40 kg N ha^{-1}) and in a succeeding maize crop (up to 71 kg N ha^{-1}). We observed positive associations between grain yield, dry matter production and total N uptake of a succeeding maize crop, and the N-fixed by legume species in the preceding season.

Finally, we assessed the potential effects of water availability on the productivity of maize – grain legume systems in northern Tanzania, using a parameter-sparse model developed using Fortran Simulation Translator (FST) language. We observed that under rain-fed conditions, maize productivity is dependent on the amount of water available, while legumes are dependent on having a deep rooting system to access water from deeper soil horizons.

The results contribute to improved understanding of how cropping system diversification through cereal-legume intercropping can support sustainable intensification of food production in smallholder farming systems.

Contents

Chapter 1

General introduction

1.1 Background

Crop production in smallholder cropping systems in sub-Saharan Africa (SSA) frequently takes place in a situation of increasing pressure on available land where farm sizes are already small, with an approximated 4-6 persons ha^{-1} of cropland. Additionally, future projections point at the likelihood of population doubling by 2050, indicating a population pressure of 8-12 persons ha^{-1} of cropland when there will be no further expansion of cropland (Giller et al. 2021). Furthermore, crop productivity in these cropping systems is low, partly due to poor soil fertility as a result of continuous cropping, with little or no nutrient replenishment (Sanchez, 2002). In this regard, there is need to improve productivity sustainably, underscoring the importance of sustainable intensification (Pretty et al. 2011; Tilman et al. 2011). Sustainable intensification is defined as a set of agricultural practices and technologies that increase crop production and resource use efficiency on croplands, while reducing the negative environmental impacts of agriculture (Pretty et al. 2011). One potential pathway that can contribute to sustainable intensification is intercropping (Brooker et al. 2015; Lithourgidis et al. 2011), which involves cultivation of two or more crop species simultaneously in the same field (Vandermeer, 1989).

As in many parts of SSA, crop production in Tanzania is mainly based on smallholder farming (Mukasa 2018), characterized by poor management and limited access to resources and thus insufficient inputs (Masawe 1992), leading to low production. Nitrogen is among the most limiting plant nutrients in SSA, and has a crucial role in the plant growth and physiological processes (Anas et al. 2020). The most efficient way of adding nutrients to the soils is through inorganic amendments. However, this is an expensive method for small-holder farmers in Tanzania, thus threatening food security (Birech and Freyer 2007). Legumes are important sources of nitrogen and they also enhance P-availability, hence complement/ supplement inorganic fertilizers (Franke et al., 2018; Baldé et al. 2011; Sanginga 2003). They therefore contribute to improved soil fertility and enhanced yields of subsequent cereals (Peoples et al., 2009), often without compromising the yield of the main crop (Baldé et al. 2011; Rusinamhodzi et al. 2012).

1.2 Maize-grain legumes intercropping

Intercropping of grain legumes with maize (*Zea mays* L.) is common in Tanzania, mainly with pigeonpea (*Cajanus cajan* (L.) Millsp.), common bean (*Phaseolus vulgaris* L.), dolichos lablab (*Lablab purpureus* (L.) Sweet) and cowpea (*Vigna unguiculata* (L.) Walp) (Kimaro et al. 2009; Myaka et al. 2006b). Such intercrops have been reported to form the basis of smallholder family food security and have been identified as crucial for economic growth (Myaka et al. 2006a). Beyond their own yield, the grain legumes provide additional ecological benefits that enhance the productivity of maize in the short and long-term. Benefits of cereal-legume intercropping include greater ground cover and suppression of diseases, pests and weeds, and in subsequent seasons include the increase in supply of N from nitrogen (N_2) fixation, improved soil health, and increased maize yields (Giller 2001; Rusinamhodzi et al. 2012; Gu et al. 2021).

Among the legumes commonly intercropped with maize, pigeonpea has a slow early growth, limiting early competition with cereals in intercrops (Dalal, 1974; Silim et al., 2005). It has a longer growth cycle (up to 9 months) than maize (up to 6 months), and thus when the two are sown simultaneously, it continues to grow after maize harvest, producing copious vegetation (Myaka et al. 2006b). This extended period of growth also ensures that the greatest nutrient demand in pigeonpea occurs after the maize crop has been harvested (Dalal, 1974), resulting in temporal niche differentiation (TND). Also, most farmers can use their own pigeonpea seeds at low cost by using the previous year's stock, and in addition to its use as food, there is a market for green or dry grains (Löfstrand 2005). Pigeonpea stems can also be used as firewood, which is a scarce resource in many areas of Tanzania (Adu-Gyamfi et al. 2007; Myaka et al. 2006a). The strong contribution of atmospheric N_2 fixation associated with pigeonpea in intercropping systems has been demonstrated in several studies (Peoples et al., 1995; Giller, 2001; Myaka et al., 2006). Lablab also combines well in intercrops with maize (Cook et al., 2005). It has a sprawling habit, and is generally relay-planted to reduce competition with the cereal crop, allowing the cereal crop to germinate and establish before the closure of the lablab canopy (Cook et al., 2005). Similar to pigeonpea, lablab can contribute to soil fertility through N_2 fixation (Cook et al., 2005). In addition, its dense canopy soil-cover reduces soil moisture losses while the leaves are shed, providing mulch to the soil (Cook et al., 2005; Rapholo et al., 2020). With the help of a deep taproot, both pigeonpea and lablab can extract water at a soil depth of 2 m not accessible by maize, making them drought-tolerant thus enabling them to effectively withstand the lower soil moisture situation encountered at later stages of growth after maize is harvested (Kumar Rao et al., 2001; Cook et al., 2005). This results to both spatial and temporal niche differentiation.

1.3 Intercrop productivity

To improve on the benefits of intercrop systems by smallholder farmers, the systems require fine-tuning to enhance efficient use of available resources (i.e. radiation, water, space and nutrients) (Kihara et al. 2015; Li et al. 2014). This can be realized through complementarity between the component crops which is influenced by the choice and arrangement of intercrops, crop varieties and the timing of planting (Midmore 1993; Willey 1990). When the component crop species have complementary growth patterns (e.g. use different temporal niches by utilizing different periods of the season, or spatial niches through different rooting depths or canopy sizes), inter-specific competition tends to be weaker than intra-specific competition, and resources (sunlight, moisture and soil nutrients) will be acquired more efficiently (Lithourgidis et al., 2011). This results in relatively larger yields than pure crop stands (Willey, 1979). The extent of this over-yielding depends on crop management. The delay in sowing time of one component crop, so-called relay intercropping entails that crop periods only partially overlap, resulting in temporal niche differentiation. Managing the spatial arrangement of intercrops is also key to enhancing their productivity, as it determines the balance between intra- and inter-specific interactions. Greater productivity of maize-grain legume intercrops when sown within the same row compared with sole crops was reported in the Guinea savanna of northern Ghana (Kermah et al., 2017), southern Mali (Falconnier et al., 2016) and central Mozambique (Rusinamhodzi et al., 2012).

1.4 Residual effects of legumes on a succeeding maize crop

While within-season effects of intercropping are receiving increasing attention, they are rarely investigated across seasons, in spite of the benefits reported in the few studies. For example, Adjei-Nsiah et al. (2007) reported up to four times greater maize yield following sole cowpea than continuous maize. Further, sole maize grown in the third season in rotation with pigeonpea and without fertilizer application yielded eight times more than continuous maize (Rusinamhodzi et al., 2012). The increased productivity of a succeeding maize has been attributed to benefits associated with both N and non-N effects (Franke et al. 2018; Sanginga et al. 1999). The N-effects are those related to the improvement in N nutrition for the subsequent non-legume crop as well as reduced N fertilizer requirements as this is facilitated by the legumes included in the preceding seasons through biological N_2 fixation (BNF) (Ojiem et al., 2007; Giller, 2001). In cases where smallholder farmers remove most of the cereal and legume stover after grain harvest resulting in large quantities of fixed N being removed from the field, a considerable amount of residual N can become available in the soil through decomposition of roots, nodules and fallen leaves, which can benefit succeeding crops (van Kessel and Hartley, 2000). Where the amount of N available in the soil is very limited, the yield of the succeeding maize crop will be directly proportional to the amount of N_2 fixed (Giller, 2001). Other benefits accruing from grain legumes include enhanced P-availability, changes in soil moisture and organic matter, and changes in the occurrence of weeds, insect pests and diseases (Chan and Heenan, 1996; Schlecht et al., 2006; Rusinamhodzi et al., 2012; Franke et al., 2018).

1.5 Study rationale and objectives

Notwithstanding the potential benefits of intercropping, the current performance of maize-legume intercropping in northern Tanzania has been affected by poor management and other limiting factors (Amare et al. 2012). Yield advantage occurs when growth resources such as light, water and nutrients are used more efficiently by crops over time (Lithourgidis et al. 2011). Indeed, the ability of grain legumes to improve soil fertility through N_2 fixation depends on interaction between the genotype of the legume, the genotype of the rhizobia, the environment and the management of the crop and field; $(GL \times GR) \times E \times M$ (Giller et al., 2013). As such, contribution of legumes in maize-based systems should be considered across such factors to fully understand the legume's effect within the system. Additionally, a holistic assessment of component crops within intercrops accounting for multiple performance indicators such as grain and biomass, N_2 fixation potential and resource use efficiency is a requisite for a more robust assessment of the intercrops. Also, since the region has high diversity of agro-ecological zones (AEZs) (in terms of rainfall distribution/ amounts and temperature) (Myaka et al. 2006a), maize-legume intercropping systems need to be tailored to local conditions. Several management options have been used elsewhere to optimize intercropping systems such as choice of legume species, varying of sowing dates, spatial arrangements, fertilization, use of different crop varieties and sowing densities (Akanvou et al. 2002; Ghosh et al. 2006; Rusinamhodzi et al. 2012). In this respect, this study mainly aimed at exploring ways of fine-tuning the systems in different AEZs, by striking a balance between maximizing the benefits of inclusion of pigeonpea and lablab in the system and minimizing potential disadvantages emanating from their competition with maize. Specific objectives were:

1) To assess socio-economic factors, field management characteristics, and their association with productivity of maize-pigeonpea intercrops (*Chapter 2*).
2) To assess the productivity of maize-grain legume intercropping systems as a consequence of fertilizer use along an agro-ecological gradient, and residual effects from the grain legumes to yields of a succeeding maize crop (*Chapter 3*).
3) To evaluate the effect of cropping systems and fertilizer on N uptake by maize and legumes, N_2-fixation by the legumes and the extent to which residual effect can be explained by shoot N yield of the previous season (*Chapter 4*).

4) To ascertain to what extent the productivity of maize– grain legume systems in northern Tanzania is limited by water availability (*Chapter 5*).

1.6 Study setting

The study was conducted in the northern Highlands Zone (NHZ) of Tanzania. We used a combination of farm surveys and on-farm trials with crop growth modelling on small-holder farms in northern Tanzania. A farm survey was first conducted covering three regions of NHZ (Arusha, Kilimanjaro and Manyara), which lies between 3^o and 5^o South latitude, 35^o and 37^o East longitude and is at an elevation of 685 to 1920 m above sea level. Generally in NHZ, two rainy seasons are recognised: one from March-July and the other from October-December locally referred to as "long rains" or "*Masika*" and "short rains" or "*Vuli*", respectively. The rainfall is more intense and less variable during the long rains than during the short rains (Zorita and Tilya 2002). Predominant soil types range from humic nitosols that are well drained, to soils of volcanic origin (sandy loams to clay alluvial soils) (Mowo et al. 2006).

For the farm survey, farm households interviewed were randomly selected within the major agricultural areas of northern Tanzania. Following the stratified random approach developed by Africa Soil Information Service (AfSIS) (Huising 2012), twelve districts were selected in NHZ (3 in Arusha, 5 in Kilimanjaro and 4 in Manyara), within which a randomly selected 10 × 10 km grid was established per district. Within each of these 10 × 10 km grids, three 1 × 1 km clusters (wards) were randomly selected, where all farm households involved in farming were listed. Thereafter, within each cluster, eight farm households were randomly chosen. This translated into a sample size of 24 farm households per district (3 clusters × 8 farm households). Comprehensive data was collected using a semi-structured questionnaire in the form of an open data kit (ODK)-based survey instrument with the help of well-trained agricultural officers. Data collected included information on farm-household at plot level, reflecting the 2016/17 main agricultural season.

Following the farm survey, field experiments were conducted in three sites (Riroda, Arri and Dareda) within Babati district, Manyara region, an area with high diversity of agro-ecological zones (AEZs) and lies within 04^o 25'S, 35^o 60'E, at an altitude of 1300-1700 m above sea level. From each of the three AEZs, three farms were randomly selected to host experimental trials for three consecutive seasons (2017/2018- 2019/2020). Fields were ploughed and plots measuring 10 m long x 5 m wide marked just before planting. A path measuring 1m was left in between adjacent plots. Test crops used included: seed co. 513 maize (*Zea mays* L.) hybrid variety, lablab (*Lablab purpureus* (L.) Sweet)

"Selian-Rongai" variety and pigeonpea (*Cajanus cajan* (L.) Millsp.) long- duration ICEAP 00040 and medium-duration ICEAP 00557 varieties. Pure stands of maize, pigeonpea and lablab were planted at a spacing of 0.90 m × 0.50 m inter and intra-row respectively. Intercrops followed an additive design, with legumes planted in between maize hills, maintaining same plant population for each crop in sole and intercrops. Thus, the total plant population in intercrops was double that of sole crops. An intercrop model was applied to further analyse the data and ascertain to what extent the productivity of maize– grain legume systems in northern Tanzania is limited by water availability.

1.7 Outline of the thesis

This thesis consists of six chapters: a general introduction (Chapter 1), four research chapters (Chapter 2 to 5), and a general discussion (Chapter 6). Chapter 2 follows this general introduction. It provides an assessment of socio-economic factors, field management characteristics, and their association with productivity of maize-pigeonpea intercrops across three regions of northern Tanzania. We employed a farm household survey, where comprehensive socio-economic and plot-level production measurements were collected.

To understand the growth and development of maize-grain legume intercropping systems and their interaction with fertilizer application along an agro-ecological gradient, and the residual effects from the grain legumes to yields of a succeeding maize crop, field experiments were conducted in three sites (Riroda, Arri and Dareda) within Babati district, Manyara region, northern Tanzania. Pure stands of maize, pigeonpea and lablab, as well as intercrops of maize with the legumes were planted at a spacing of 0.90 m × 0.50 m inter and intra-row respectively, whereby the intercrops followed an additive design, with legumes planted in between maize hills. Grain yield and dry matter production data from the experimental trials for the first two seasons (2017/2018 and 2018/2019) is used. Additionally, data from a sole maize crop planted in the third season (2019/2020) is used to evaluate the residual N contributions from grain legumes to the yield of a succeeding maize crop (Chapter 3).

Chapter 4 uses data on N_2 fixation and nitrogen-uptake from the experiments containing sole crops and intercrops of maize, pigeonpea and lablab from the three seasons, to evaluate the effect of cropping systems and fertilizer on N uptake by maize and legumes, and N_2-fixation by grain legumes. We also assess the association between shoot N yield of legume species grown in the previous season, and grain yield, DM production and total N uptake of a succeeding maize crop.

In Chapter 5, a transparent, parameter- sparse model (Fortran Simulator Translator; FST model) is developed and extended with a soil water balance. The simplicity of the model allows its parameterization based on sole crops of maize, long and medium-duration pigeonpea, and lablab that were simultaneously grown with the intercrops, at one of the three sites (Arri site). Rather than a predictive tool, this model is designed as a tool for analysis to better appreciate the role of water as an important resource for productivity of the intercrop.

Chapter 6 synthesizes the results of Chapters 2 to 5, placing them into the broader context of smallholder farming systems in Tanzania, and by extension in SSA. The potential of maize-grain legume intercropping and the possible challenges and opportunities associated with it is discussed. Finally, the major conclusions drawn from the study are synthesised and recommendations for further research are presented.

Chapter 2

Farm-scale assessment of maize- pigeonpea productivity in northern Tanzania

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Abstract

Little is known about productivity of smallholder maize-pigeonpea intercropping systems in sub-Saharan Africa. We conducted a survey of 277 farm households in northern Tanzania to assess socio-economic factors, field management characteristics, and their association with productivity of maize-pigeonpea intercrops. On each farm, crop assessments were focused on a field that the farmer identified as most important for food supply. Variables associated with yields were evaluated using linear regression and regression classification. Biomass production ranged between 1.0 and 16.6 for maize, and between 0.2 and 11.9 t ha^{-1} for pigeonpea (at maize harvest). The corresponding grain yields ranged between 0.1 and 9.5 for maize, and between 0.1 and 2.1 t ha^{-1} for pigeonpea. Plant density at harvest, number of years the field had been cultivated, slope, weeding, soil fertility class, fertilizer and manure use were significantly associated with variation in maize grain yield, with interactions among the factors. Fields on flat and gentle slopes with plant density above 24,000 ha^{-1} had 28% extra yields when fertilizer was applied, while less than 24,000 plants ha^{-1} yielded 16% extra yield when manure was applied. Plant density at harvest was the key factor associated with pigeonpea yield; fields with densities above 24,000 plants ha^{-1} yielded an average of 1.4 t ha^{-1}, while less than 24,000 plants ha^{-1} yielded 0.5 t ha^{-1}. We conclude that performance of intercrops can be enhanced through application of organic and inorganic nutrient sources, and agronomic interventions including weeding, implementing soil conservation measures on steep slopes and optimising plant density.

Key words: Smallholder farms, Plant density, Intercrops, Fertilizer, Manure, Soil fertility

2.1 Introduction

Crop production in smallholder farming systems of the East African highlands is dominated by maize, which is the main staple and a food security crop (Arias et al., 2013). Intercropping of maize with grain legumes mainly pigeonpea, beans, dolichos lablab and cowpea is common (Myaka et al., 2006; Kimaro et al., 2009; Massawe et al., 2016; Ndungu-Magiroi et al., 2017). Such intercrops form the basis of smallholder family food security and are crucial for economic growth (Myaka et al., 2006). Legumes provide multiple benefits in intercrops in addition to the legume grain, both in the current and subsequent seasons. These include increase in availability of N from nitrogen (N_2) fixation, reduction in occurrence of pests and diseases, extended ground cover, better rooting ability, improved soil fertility and increase in maize yields (Giller, 2001; Mucheru-Muna et al., 2010; Li et al., 2013; Yu et al., 2015; Zhang et al., 2019).

Pigeonpea is well suited for intercropping with maize as it has an initial slow growth, avoiding competition with the primary maize crop (Silim et al., 2005). Pigeonpea has a longer growth cycle, and when sown simultaneously can continue to grow for up to three months after maize harvest (Myaka et al., 2006). The extended period of growth ensures that the greatest demand for water and nutrients in pigeonpea occurs after maize has been harvested (Dalal, 1974). The relatively deep root system enables pigeonpea to exploit moisture from deeper soil layers, effectively withstanding the dry conditions encountered at later stages of growth (Kumar Rao et al., 2001). In addition to direct consumption of green pigeonpea pods for food, there is a good market for the dry grain (Löfstrand, 2005). Pigeonpea has developed into an important cash crop in East and southern Africa which is mainly exported to India (Silim et al., 2005). After harvest, pigeonpea stems are used as firewood, which is a scarce resource in many areas of Tanzania (Myaka et al., 2006; Adu-Gyamfi et al., 2007). Furthermore, seed costs are low partly because farmers can retain seeds from the previous season (Sakala et al., 2003). Thus, maize-pigeonpea intercrops provide multiple benefits with minimal additional labour (Myaka et al., 2006).

In northern Tanzania, pigeonpea is frequently intercropped with maize, yet major gaps exist in the understanding of the characteristics of maize-pigeonpea intercropping systems and the key factors associated with their productivity. An agronomic survey by Kihara et al. (2015) assessed crop yield, controlling factors and management implications, where only maize crop was directly monitored through field measurements. Other studies have focused on limited components of the intercrops, including comparing maize-pigeonpea intercrops to sole maize in terms of yields and nutrient accumulation (Myaka et al., 2006), characterization of only the pigeonpea crop (Silim et al., 2005), quantifying the amount of atmospherically-derived N fixed by different pigeonpea varieties intercropped with maize (Adu-Gyamfi et al., 2007) or effects of competition between maize and pigeonpea on yields and nutrition of the crops (Kimaro et al., 2009). Owing to the potential complementarity of maize and pigeonpea in intercrops, our aim was to examine whether maize grain yield would be greater when intercropped with pigeonpea than in other intercrops, and whether factors associated with the yields were region-specific. To investigate this, we conducted a farm level agronomic survey to: (i) understand the socio-economic setting, structural and biophysical characteristics of farms and farming households across regions in northern Tanzania, (ii) assess the current field management and productivity of maize-pigeonpea intercrops and (iii) explore factors that are associated with productivity of maize-pigeonpea intercrops.

2.2 Materials and methods

2.2.1 Study site

The study was conducted in the northern Highlands Zone of Tanzania covering Arusha, Kilimanjaro and Manyara regions (Fig. 2.1).

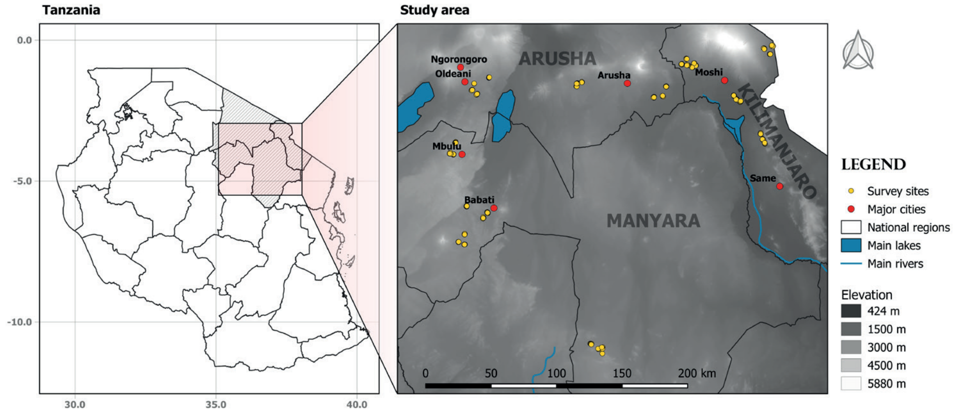

Fig. 2.1: Map showing survey sites in three regions of northern Tanzania where data was collected in the 2016 / 2017 main agricultural season.

The sampled area lies between 3° and 5° South latitude, 35° and 37° East longitude, and elevation within the ranges from 685 to 1920 m above sea level. The annual precipitation pattern is typically bi-modal: there being a relatively long rainy season (locally known as *Masika*") from March-July and a shorter one ("*Vuli*") from October-December. The mean seasonal rainfall in the 2016/ 2017 growing season was 474 mm, 434 mm and 387 mm in Kilimanjaro, Arusha and Manyara respectively. Temperature ranged from 20-28, 19-26 and 18-25 °C with means of 24, 22 and 21°C in Kilimanjaro, Arusha and Manyara respectively (https://power.larc.nasa.gov/data-access-viewer/). Predominant soil types range from well-drained humic nitosols to soils of volcanic origin (sandy loams to clay alluvial soils) (Mowo et al., 2006).

2.2.2 Sampling and farming systems characterization

Farm households interviewed were randomly selected following the stratified random approach developed by Africa Soil Information Service (AfSIS) (Huising, 2012). First, twelve districts were selected (3 in Arusha, 5 in Kilimanjaro and 4 in Manyara), within which a randomly selected 10,000 × 10,000 m grid was established per district. Then, within each of these 10,000 × 10,000 m grids, three 1,000 × 1,000 m clusters (wards) were randomly selected, where all farm households involved in farming were listed. Thereafter, within each cluster, eight farm households were randomly chosen. This translated into a sample size of 24 farm households per district (3 clusters × 8 farm households), giving a total of 288 farm households.

Comprehensive data was collected using a semi-structured questionnaire in the form of an open data kit (ODK)-based survey instrument, with the help of well-trained agricultural officers. Data collection involved first drawing a sketch of the farm with help of the farmer. Subsequently, all plots that were cultivated by the household during the 2016/ 2017 main agricultural season were numbered, and this coincided with the time the survey was conducted. Basic information on crops and production was collected for each plot managed by the household. In addition, the farmer was asked to identify the most important plot for food supply at household level, as maize is the predominant staple crop (Kaliba et al., 2000). The selected plot was treated as the focal plot from which very detailed agronomic management information was collected. Although our sampling strategy was fully randomised at the farm level, the plot for which information was collected was not sampled randomly. We chose to do this for two related reasons: First, it was not possible to collect such detailed information from all of the fields of each farm. Secondly, a purely random sampling would have led to selection of fallow land, or a field that was not being intensively managed as it is common that farmers plant a larger area than they are able to manage intensively. Earlier studies in East and southern Africa have identified strong spatial gradients of declining soil fertility with distance from the household due largely to allocation of animal manures to specific plots (Baijukya et al., 2005; Tittonell et al., 2005; Zingore et al., 2007). By contrast, little cattle manure is applied to fields in the study area, and these are also less intensively managed and no strong spatial patterns of soil fertility are observed such that we do not anticipate that this plot selection strategy introduced strong bias. We acknowledge that the non-random sampling of fields within the farms may introduce some bias which we cannot quantify.

Design of the questionnaire and topics were informed by literature review (Waithaka et al., 2007; Mugwe et al., 2008; Kihara et al., 2015; Silberg et al., 2017), and factors investigated were those commonly associated with yields and the agricultural practices under study. Farm - household information was obtained based on current data within the 2016/2017 main agricultural season. This included standard socio-economic and structural characteristics (age, gender, marital status and education level of household head, land size, household size, livestock ownership and extension service access). Focal plot information was based on current data and direct monitoring/ measurements targeting crops grown in the 2016/2017 main agricultural season. Crop cuts and soil samples were taken from these focal plots. Within each focal plot, three 5 m × 5 m square quadrats (centre and two corners) were demarcated to act as replicates. Information collected from the focal plot included weeding frequency, seed type used, distance from homestead, fertility level, slope, use of irrigation, fallow in the past 10 years, years the land had been under cultivation, GPS readings, fertilizer and manure use. From each quadrat of the focal plot (each focal plot had three quadrats), information on number of maize plants and maize cobs, number of pigeonpea plants (where present), plant spacing, number of plants per stand of maize and pigeonpea (where plants were planted in rows) and stage of development of pigeonpea at maize harvest (e.g. flowering or podding) was recorded. Thereafter, destructive sampling was done per quadrat, where three plants each for maize and pigeonpea were taken for determination of yield and yield components. To estimate maize production, measurements per quadrat involved separating cobs from stover and weighing the components separately. Thereafter, a sample of three cobs was taken (ensuring that they represented the sizes and moisture content of all the cobs), to be used in estimating maize grain yields. Maize stover was then chopped and weighed in the field, and a sub-sample taken. For pigeonpea, fresh weight of the selected plants from each of the 5 m × 5 m square quadrats was measured, the plants were chopped in the field, and a weighed sub-sample taken (the crop was either in the flowering or podding stage). Apart from maize cob sub-samples from the different quadrats which were considered separately (3 cobs from each quadrat considered as independent samples), other sub-samples from the three different quadrats were bulked to form a composite sample. The sub-samples were oven dried at 75 ^{o}C for 48 hours (stover) or 72 hours (grains) for determination of dry weight at Tanzania Agricultural Research Institute (TARI)-Selian, Arusha-Tanzania. To assess pigeonpea productivity after maize harvest, grain yields were monitored in the same quadrats where biomass measurements and management information had been taken when the crop attained physiological maturity. Whereas measurements for maize biomass and grain yield were taken in all fields where crop cuts were possible, pigeonpea yields were monitored from a proportion of fields (randomly sampled), due to labour limitations. This sample represented a third of the fields where pigeonpea biomass and management information had been taken previously.

Soil samples were collected when maize crop was at physiological maturity and pigeonpea was at reproductive stage (flowering / early podding). This was done using an auger from each quadrat (0 - 0.2 m) by taking two sub-samples from representative field positions comprising two corners of a quadrat. The sub-samples were then mixed to form a composite sample per quadrat. This was repeated in the other two quadrats, ending up with three composite samples (one for each quadrat). Finally, the three composite samples were bulked and a sample representative of the focal plot drawn for laboratory analyses. Soil samples were air-dried, passed through a 2 mm sieve and ground to <0.5 mm before analysis. Analyses were conducted by loading samples into micro-soil cups, scanning samples using alpha mid-infrared diffuse reflectance spectroscopy (MIR, 2.5-25 µm) and finally spectral prediction into various soil properties. Soil properties estimated included total carbon (C) and nitrogen (N) contents; available phosphorus (P); soil pH; exchangeable potassium (K), calcium (Ca) and magnesium (Mg) concentration (Table 2.2). Calibration samples were analysed by combustion method (for C and N), Electrodes (pH) and Mehlich 3 extraction (P, K, Ca and Mg) (Vagen et al., 2010). Processing and analyses of the samples was done at TARI-Selian, Arusha-Tanzania.

2.2.3 Data analysis

To understand the current biophysical factors and assess the current field management and productivity of maize-pigeonpea intercrops across regions in northern Tanzania, box plots and cumulative probability was used. Analysis of variance (ANOVA) was performed to test for differences in soil variables, biomass and grain yield among regions. Where a difference was significant, least significant difference test (LSD test) was used to separate means using the *agricolae* package (R Core Team, 2019).

To assess the association of field management factors with productivity of maize-pigeonpea intercrops, we modelled factors associated with maize and pigeonpea yields using a linear model and the *lm* function (R Core Team, 2019). The dependent variable was maize or pigeonpea grain yield and independent variables were field- specific characteristics and management factors. These included plant density at harvest, years the land has been under cultivation, slope, distance from homestead, weeding frequency, seed variety, fertility level, fertilizer and manure use. Factors which were found to be consistent across all sampled fields were not included in the model. This included irrigation which was not practiced in any field. Since the study was conducted in three sampling regions with varying rainfall and temperature conditions, the model were executed based on each sampling region. However, the statistical analyses per region were only possible for maize and not for pigeonpea. This was because contrasts can only be applied to independent categorical factors with two or more levels, and some of the factors for pigeonpea had only one level when considered on a regional basis. To further understand factors associated with maize grain yields, we classified the yields under different management options using regression classifications (Tittonell et al., 2008; Kihara et al., 2015), with ANOVA as the method of creating splits and the *rpart* function (R Core Team, 2019). Variables used were specific to the analysis conducted, so the number of observations (*n*) in the various tables and figures vary. This variation in *n* resulted from missing households, farmers who had already harvested their maize before crop cuts, while soil sampling was not permitted in all farms

2.3 Results

2.3.1 Socio-economic setting, field management and biophysical factors

A majority of farm households (HH) were male-headed (76-93%) (Table 2.1). Average household size was 5-6 persons per farm household with an average age of HH heads across the regions of 48-57 years. The majority of HH heads had attained primary level of education (68-85%) with only 6-13% being illiterate (no formal education). A majority of the HH heads were married (74-94%), with most of the remainder widowed. Average land size per household was 1.2-2.4 ha (Table 2.1). Assessment of the current field management of maize-pigeonpea intercrops across regions in northern Tanzania showed that farmers used both local and improved varieties, either recycled or purchased. For maize, a majority (≥55%) mainly purchased seed of improved varieties, while the rest used recycled seed of local varieties (Table 2.1). On the other hand, a majority (≥90%) used recycled seed of local pigeonpea varieties, and only few bought seed (Table 2.1).

Table 2.1: The socio-economic setting of farm households and variables used in the models from three regions of northern Tanzania during the 2016 / 2017 main agricultural season.

Data type	Variable	Unit	Direction	Summary statistics		
				Arusha (*n*=69)	Kilimanjaro (*n*=120)	Manyara (*n*=88)
				Mean		
Continuous	Maize/ pigeonpea grain yield	t ha^{-1}	-	-	-	-
Continuous	Density at harvest	Number of plants ha^{-1}	-	-	-	-
Continuous	HH head age	Years	-	48	57	48
Continuous	Household size	Number of persons	-	6	5	6
Continuous	Land size	ha	-	2.4	1.2	1.6
Continuous	Years under cultivation	Years	-	17	25	20
Continuous	Distance from homestead	Metres (m)	-	13000	6000	30000
Continuous	Weeding frequency	Numbers	-	1.3	1.5	1.7
				Proportion per region (%)		
Categorical	Gender of HH head	-	0=female	15	24	7
			1=male	85	76	93
Categorical	Marital status of HH head	-	0=others	12	26	6
			1=married	88	74	94
Categorical	Education level of HH head	-	0=none	13	6	13
			1=primary	68	85	78
			2=secondary	16	5	5
			3=post-secondary	3	4	4
Categorical	Slope	-	1=steep	10	14	17
			2=flat	18	26	14
			3=gentle	72	60	69
Categorical	Fallow practice in the past 10 years	-	0=no	81	94	97
			1=yes	19	6	3
Categorical	Maize/ pigeonpea seed variety	-	1=local	45 (90)	31 (100)	40 (92)
			2=improved	55 (10)	69 (0)	60 (8)
Categorical	Fertiliser use	-	0= no	90	59	89
			1=yes	10	41	11
Categorical	Manure use	-	0= no	11	78	14
			1=yes	89	22	86
Categorical	Fertility level	-	1= infertile	3	7	10
			2= moderate	81	86	65
			3=fertile	9	7	20
			4=very fertile	7	0	5

Values in brackets are for pigeonpea seed variety; Where summary statistics is not given, this is presented in the figures; HH = Household.

Farmers adopted different planting patterns: For maize, 87% used a well- defined row spacing with only 13% planting randomly, whereas for pigeonpea, 44% used well-defined spacing while 56% planted randomly. Additionally, 11% of the focal plots that had intercrop of maize and pigeonpea had both crops planted randomly. In cases where well-defined spacing was noted at the time of sampling, inter-row spacing for maize ranged from 0.6 to 1.15 m; average of 0.85 m, whereas intra-row spacing ranged between 0.25 and 0.75 m; average of 0.5 m. For pigeonpea, inter-row spacing ranged from 0.5 to 1 m; average of 0.8 m, while intra-row spacing ranged between 0.35 and 0.85 m; average of 0.55 m. Planting pattern varied among regions (Fig. 2.2), but only significantly for maize when Kilimanjaro and Manyara regions were compared.

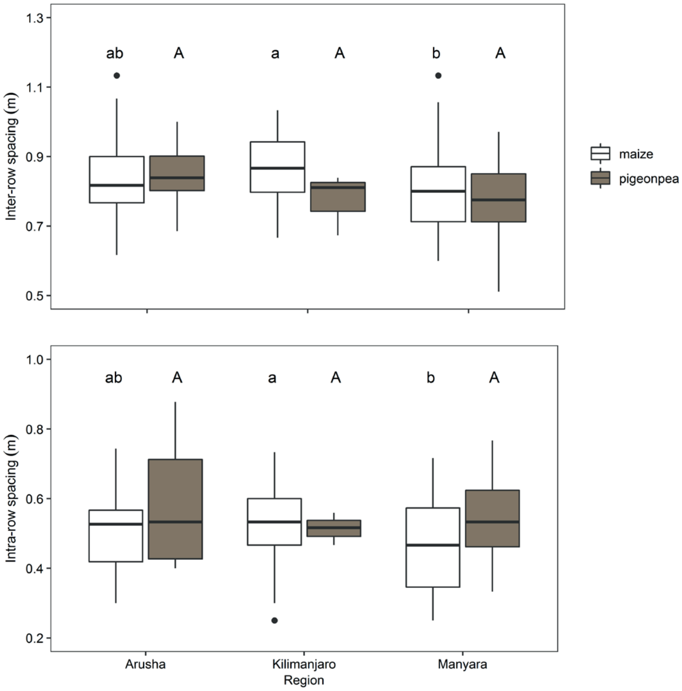

Fig. 2.2: Box plots showing measured inter and intra-row spacing (m) of maize and pigeonpea in the different regions of northern Tanzania in fields where seeds were not broadcast (maize *n* = 158 out of 182; pigeonpea *n* = 41 out of 90). Within the box plots, horizontal lines represent the median, lower and upper box plot boundaries represent the 25th and 75th percentiles respectively, lower and upper whiskers represent the minimum and maximum values respectively, while dots above and below whiskers represent outliers. Mean differences in spacing at 5% significance level in the different regions are indicated with different letters on the upper side of each box plot for maize (small letters) and pigeonpea (capital letters).

Measurements of plant density at harvest of the two crops across regions (Fig. 2.3) revealed that less than 20% of the farmers had a density above 40,000 plants/ha, which is the recommended plant density for intercropped maize in northern Tanzania (Kihara et al., 2015). Across regions, plant density at harvest ranged from 11,883 to 61,000 plants/ha for maize and 7,903 to 55,000 plants/ha for pigeonpea when crops were planted in rows. Where crops were planted randomly, plant density at harvest ranged between 5,200 and 48,800 plants/ha for maize and between less than 5,000 and 53,200 plants/ha for pigeonpea.

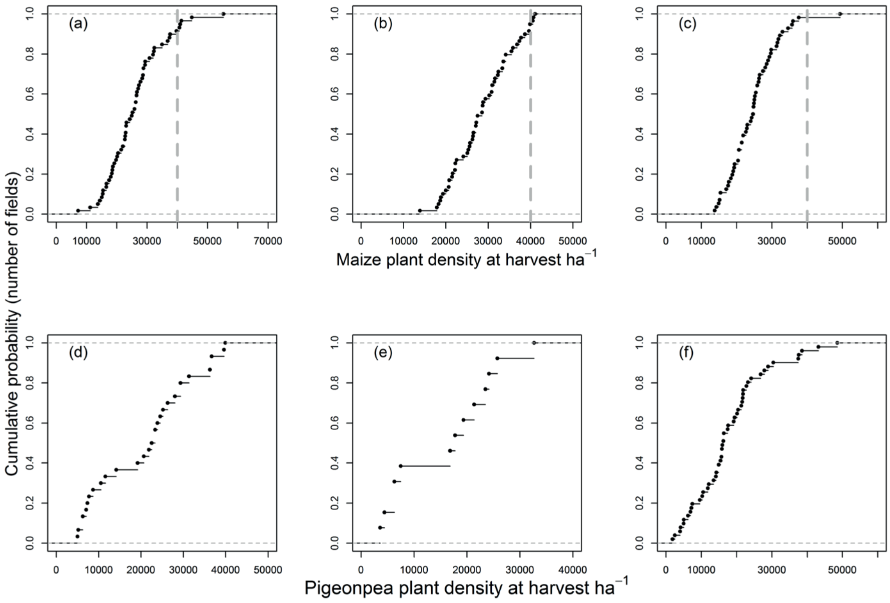

Fig. 2.3: Cumulative probability of maize and pigeonpea plant density in intercrops at maize harvest in the 2016/ 2017 main agricultural season across three regions of northern Tanzania. Maize = a, b and c in Arusha, Kilimanjaro and Manyara respectively; Pigeonpea = d, e and f in Arusha, Kilimanjaro and Manyara respectively.

Intercropping was practiced by all of the farmers interviewed. Intercrops included maize intercropped with pigeonpea (*Cajanus cajan*) (54%), common bean (*Phaseolus vulgaris*) (25%), sunflower (*Helianthus annuus*) (11%) and other crop mixtures (10%) of maize with lablab (*Lablab purpureus*), cowpea (*Vigna unguiculata*) and sorghum (*Sorghum bicolor*) (Fig. 2.4). It is notable that whereas maize-pigeonpea was well represented across the regions, other intercrop systems had very few cases recorded in some regions. For instance, fewer cases of maize-bean intercrop were found in Manyara and only one case of maize-sunflower and maize with other legumes in Arusha and Manyara respectively (Fig. 2.4).

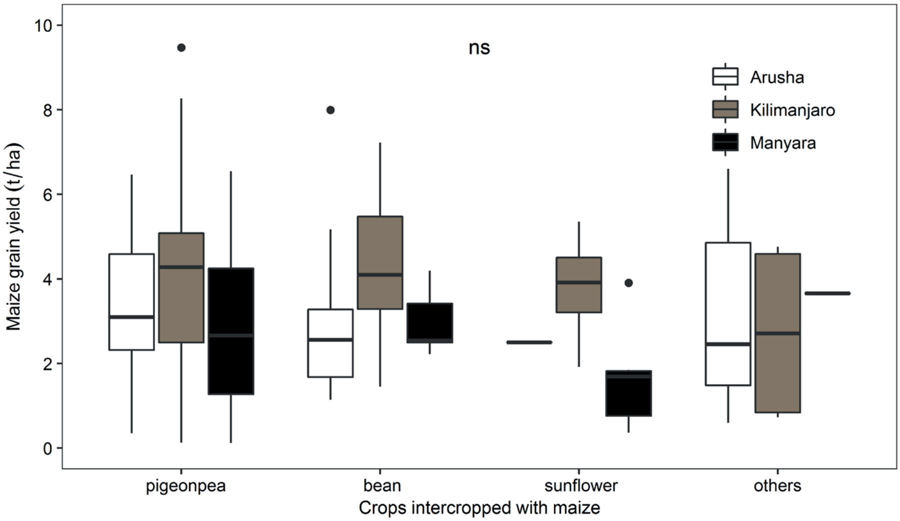

Fig. 2.4: Measured grain yield for maize in various intercrops in 2016/ 2017 cropping season in northern Tanzania. Mean differences in grain yield in the various intercrops were not significantly different at 5% significance level as indicated on the upper side of the box plots. Number of observations across regions: maize-pigeonpea *n* = 95, maize-bean *n* = 44, maize-sunflower *n* = 19, maize-others *n* = 18. Within the box plots, horizontal lines represent the median, lower and upper box plot boundaries represent the 25th and 75th percentiles respectively, lower and upper whiskers represent the minimum and maximum values respectively, while dots above the whiskers represent outliers. "Others" refers to intercrops of maize with crops such as lablab, cowpeas and sorghum.

Assessment of management practices for improving soil fertility in the 2016/ 2017 main agricultural season showed that on average, 51% of the sampled farm households used only manure, 18% used only fertilizer, 29% used both manure and fertilizer whilst 2% neither used manure nor fertilizer. A majority of farmers who did not use fertilizer (51%) reported that it was not needed due to a lack of crop response, 26% lacked cash to purchase while the rest (23%) gave reasons such as the commodity being expensive and not available.

Following Hazelton and Murphy (2016) to interpret the soil test results, available P values were small (>5-10 mg/kg) while soil carbon (C) was within a moderate range (Table 2.2) with significantly lower concentrations in Manyara than in the two other regions. The pH was between 6.0 and 6.5, being significantly lower in Kilimanjaro although soil acidity was not a problem in any of the regions. Exchangeable cations were above critical values and significantly greater in the Arusha region (Table 2.2).

Table 2.2: Concentration of key nutrients in the top soil (0-0.2 m) in northern Tanzania (total *n* = 284).

Region	Soil properties							
	pH	C	N	P	K	Ca	Mg	EC
	(water)	(%)		(mg kg^{-1})	(mmol kg^{-1})			dS m^{-1}
Arusha (*n*=72)	6.51_a	1.04_a	0.06_a	6.87_b	7.03_a	72.85_a	21.44_a	64.80_b
Kilimanjaro (*n*=119)	6.17_c	1.08_a	0.07_a	9.54_a	3.61_b	46.70_b	15.38_b	76.48_a
Manyara (*n*=93)	6.37_b	0.77_b	0.05_b	7.23_b	4.41_b	44.54_b	16.16_b	54.86_b

Means followed by different letters in the same column are significantly different at $p<0.05$.

We further compared our soil analysis results with farmers' own assessment of the soil fertility of their fields. Farmers used various indicators to distinguish fields as very fertile, fertile, moderately fertile or infertile. The main indicators used were production history (crop yield) of the field, soil colour and presence of certain weed species. A majority of farmers (79%) classified their soils as moderately fertile (Table 2.3). The pattern of measured soil properties followed that of the farmers, in that all variables decreased progressively with poorer soil fertility level, though the differences among levels were not significant (Table 2.3).

Table 2.3: Soil properties in different fertility levels as per farmers' subjective evaluation (total *n* = 234).

Fertility level	pH	C	N	P	K	Ca	Mg
	(water)	(%)		(mg kg^{-1})	(mmol kg^{-1})		
Very fertile (*n*=8)	6.35 (0.33)	1.23 (0.83)	0.06 (0.02)	9.60 (13.3)	4.3 (1.4)	55.9 (43.7)	19.1 (11.9)
Fertile (*n*=26)	6.46 (0.42)	1.10 (0.60)	0.07 (0.04)	7.99 (5.09)	5.1 (3.4)	71.3 (51.6)	19.3 (12.2)
Moderate (*n*=185)	6.31 (0.52)	0.97 (0.53)	0.06 (0.04)	7.97 (5.53)	4.8 (3.5)	52.9 (39.5)	17.5 (12.7)
Infertile (*n*=15)	6.29 (0.48)	0.82 (0.40)	0.04 (0.02)	7.88 (4.65)	3.2 (1.9)	40.5 (22.8)	14.8 (13.5)

Values in brackets are standard deviations. All means of soil properties across fertility levels were not significantly different at $p<0.05$.

2.3.2 Maize and pigeonpea production

The companion species intercropped with maize (i.e., pigeonpea, common beans, sunflower or other species) had no significant effect on maize grain yield (Fig. 2.4). There were significant differences in maize and pigeonpea biomass and grain yields among farms and regions (Fig. 2.5). Maize biomass production across regions ranged from 1.0 to 16.6 t ha^{-1}, whilst pigeonpea biomass production (when measured at the time of maize harvest) ranged from 0.2 to 11.9 t ha^{-1}, with means of 4.7 t ha^{-1} and 3.5 t ha^{-1}, respectively (Fig. 2.5a, c).

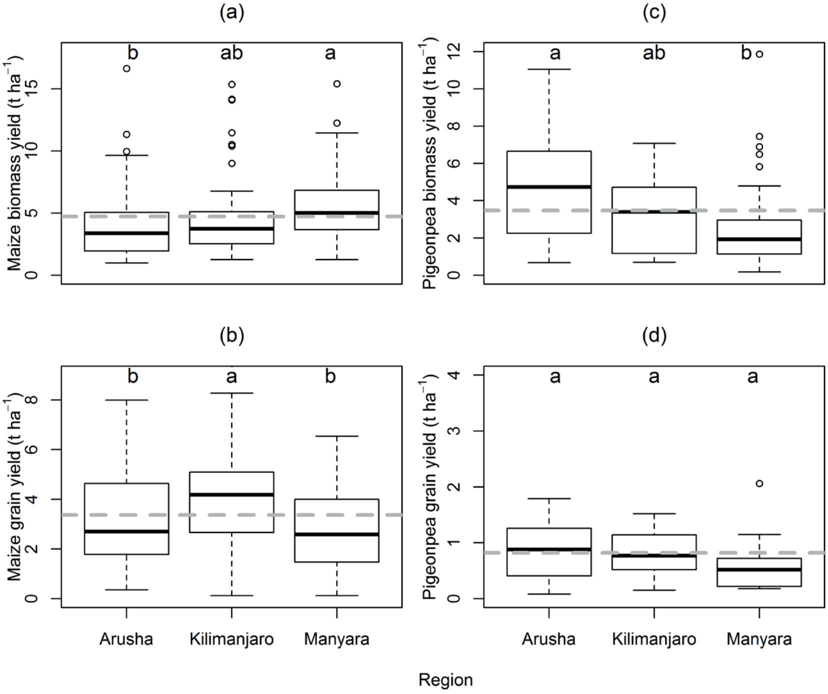

Fig. 2.5: Measured biomass production for maize and pigeonpea (a and c) and grain yields for maize and pigeonpea (b and d) in 2016/ 2017 cropping season in three regions of northern Tanzania (biomass measurements taken at maize harvest). Mean differences in biomass and grain yield at 5% significance level in the different regions are indicated with different letters on the upper side of each box plot. The horizontal dotted lines represent mean biomass and grain yield across regions. For biomass yield: Arusha; maize *n* = 57, pigeonpea *n* = 28; Kilimanjaro; maize *n* = 55, pigeonpea *n* = 13; Manyara; maize *n* = 56, pigeonpea *n* = 49). For grain yield: Arusha; maize *n* = 59, pigeonpea *n* = 9; Kilimanjaro; maize *n* = 61, pigeonpea *n* = 11; Manyara; maize *n* = 56, pigeonpea *n* = 11. Within the box plots, horizontal lines represent the median, lower and upper box plot boundaries represent the 25th and 75th percentiles respectively, lower and upper whiskers represent the minimum and maximum values respectively, while dots above the whiskers represent outliers.

Maize biomass production in Arusha was significantly smaller than in Manyara ($P < 0.05$) while pigeonpea biomass production in Arusha was significantly greater than in Manyara ($P < 0.05$). Furthermore, at physiological maturity, mean pigeonpea biomass production across regions was 3.4 t ha^{-1} (data not shown). The corresponding maize grain yield across regions ranged from 0.1 to 9.5 t ha^{-1} (mean of 3.3 t ha^{-1}) whilst pigeonpea yields ranged from 0.1 to 2.1 t ha^{-1} (mean of 0.8 t ha^{-1}) (Fig. 2.5b, d). Maize grain yields were significantly greater in the Kilimanjaro region than in Arusha and Manyara, whereas no significant differences in pigeonpea yield across regions were observed.

2.3.3 Factors associated with maize and pigeonpea production

An assessment of the association of field management factors with productivity of maize-pigeonpea intercrops showed that field characteristics (slope) and management factors (plant density at harvest, years under cultivation, weeding frequency, fertility level, seed variety used, fallow practice, fertilizer and manure use) were significantly associated with maize grain yields (Table 2.4), and plant density at harvest for pigeonpea grain yield (Table 2.5). Larger plant density at harvest resulted in greater maize and pigeonpea grain yields across regions. Maize yields declined with increasing number of years the field had been under cultivation in Arusha, where each additional year resulted in an average yield decline of 0.03 t ha^{-1}. In Arusha and Manyara, fields on gentle slopes had greater maize grain yields of 1.24 and 1.27 t ha^{-1} respectively, over yields on steep slopes. Weeding frequency had a positive effect on maize yields in Manyara region, where every additional weeding event resulted in a yield increase of 0.56 t ha^{-1} Manure application had a positive and significant impact on maize grain yields in Manyara, where its addition increased yield by 1.92 t ha^{-1}. Additionally, fertilizer use had a positive and significant impact on maize grain yields (Table 2.4), where its addition increased yield by 1.54, 1.62 and 1.17 t ha^{-1} in Arusha, Kilimanjaro and Manyara respectively. Yields on fields that farmers rated as very fertile in Arusha obtained an extra 2.59 t ha^{-1} over yields on infertile fields. Fields where improved maize seed variety was used recorded a 0.84 t ha^{-1} more yield over local seed variety in Arusha, while fallow practice in the past ten years resulted in 1.06 t ha^{-1} increase in yields in Manyara region.

Table 2.4: Linear model parameters for the management factors associated with maize grain yield in three regions of Northern Tanzania during 2016/ 2017 main agricultural season

Independent variables	Arusha			Kilimanjaro			Manyara		
	Estimate	S.E.	Sig	Estimate	S.E.	Sig.	Estimate	S.E.	Sig.
Density at harvest (plants ha^{-1})	**.00009**	.00002	<.001	**.0001**	.00005	.03	**.000001**	.00002	.04
Years under cultivation (years)	**-.03**	.01	.02	-.02	.02	.19	-.007	.009	.46
Slope: flat	.78	.63	.22	.45	1.08	.68	.33	.46	.48
Slope: gentle	**1.24**	.58	.04	.61	1.08	.58	**1.27**	.31	< .001
Distance from homestead (m)	-.006	.008	.42	-.03	.04	.38	-.001	.006	.84
Weeding frequency (numbers)	.007	.32	.98	.06	.54	.92	**.56**	.27	.04
Fallow practised	.08	.40	.06	.18	1.27	.89	**1.06**	.47	.03
Seed variety: improved	**.84**	.32	.01	.03	.88	.71	.04	.27	.87
Fertiliser use	**1.54**	.54	.006	**1.62**	.73	.04	**1.17**	.32	< .001
Manure use	.23	.34	.50	.85	.66	.21	**1.92**	.31	< .001
Fertility level: moderate	1.14	.82	.17	.45	1.32	.74	.19	.36	.59
Fertility level: fertile	1.19	.94	.21	.02	1.53	.99	.47	.42	.26
Fertility level: very fertile	**2.59**	.96	.009	-	-	-	.02	.83	.98

Dependent Variable: Maize grain yield (t ha-1). Bold estimate values are significant at ≤5% probability level. S.E. is the standard error of the mean.

Table 2.5: Linear model parameters for the management factors associated with pigeonpea grain yield in Northern Tanzania during 2016/ 2017 main agricultural season

Independent variables	Estimate	S.E.	Sig.
Density at harvest (plants ha^{-1})	**.00005**	.00001	< .001
Years under cultivation (years)	-.004	.005	.41
Slope: flat	-	-	-
Slope: gentle	-.09	.20	.65
Distance from homestead (m)	-.0005	.009	.96
Weeding frequency (numbers)	.28	.21	.20
Fallow practised	-.14	.37	.71
Seed variety: improved	-.05	.25	.84
Fertiliser use	.03	.20	.88
Manure use	-.02	.19	.91
Fertility level: moderate	-	-	-
Fertility level: fertile	-.05	.20	.82
Fertility level: very fertile	-.02	.26	.42

Dependent Variable: Pigeonpea grain yield (t ha-1). Bold estimate values are significant at ≤5% probability level . S.E is the standard error of the mean.

Classification trees were used to further understand the interaction of various factors associated with maize yields. Results showed that although maize grain yields on steep slopes were significantly smaller than on flat and gentle slopes, distance from the homestead also explained a proportion of these patterns. Yields on more steep slopes that were < 3,500 m from the homestead produced 55% more yields than those that were > 3,500 m from the homestead (Fig. 2.6).

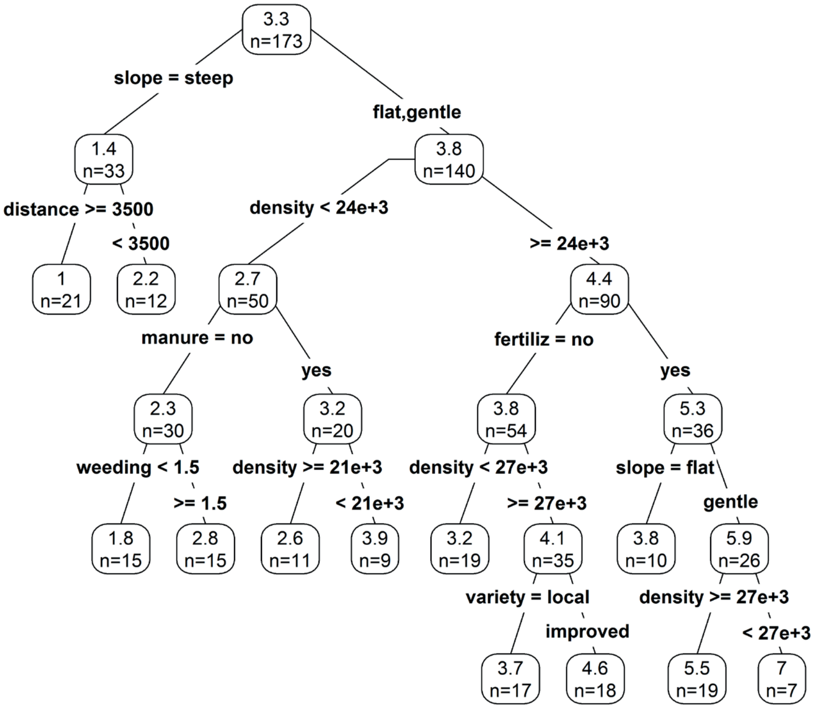

Fig. 2.6: Association of key management parameters with maize grain yield as observed from various farmer fields ($n = 173$) in northern Tanzania. Enclosed is yield t ha^{-1}; n = number of farms. Considered factors: slope = slope of the field (steep, flat or gentle); distance = field distance from the homestead (m); density = plant density at harvest (plants ha^{-1}); manure = manure use (yes or no); fertiliz = fertiliser use (yes or no); weeding = weeding frequency (numbers); variety = maize seed used (local or improved). Mean squared error (MSE) of the model = 3.55.

Similarly, yields on flat and gentle slopes with plant density below 24,000 plants ha^{-1} had 16% higher yields when manure was applied compared with fields that received no manure. For fields with plant density higher than 24,000 plants ha^{-1} on flat and gentle slopes, fertilizer use increased yields by 28% (Fig. 2.6). In contrast to maize yields, only plant density at harvest was a significant factor in explaining pigeonpea yields (Table 2.6). Plots with higher plant density at harvest gave larger pigeonpea grain yield; fields with plant density > 24,000 plants ha^{-1} had an average of 1.4 t ha^{-1} while those with plant density < 24,000 plants ha^{-1} yielded on average 0.5 t ha^{-1}.

2.4 Discussion

The majority of sampled farmers (≥55%) planted seed of improved maize varieties mainly purchased from agro-dealers whereas for pigeonpea, a majority (≥90%) relied on saved seeds. This is a common situation in northern Tanzania where previous studies have reported that 79% of farmers used improved maize seed varieties (Kihara et al., 2015), whereas a majority relied on saved pigeonpea seeds (Silim et al., 2005). Intercropping was ubiquitous across all sampled fields in northern Tanzania. The most common intercropping system was maize-pigeonpea which was practiced by more than 50% of the sampled farmers. Although far less frequent, maize was also intercropped with beans (25%), sunflower (11%) and other crop species (10%). Long-duration pigeonpea varieties were most common (data not shown), which are preferred due to their greater yield potential (Shiferaw et al., 2007). In general, maize yielded more grain when intercropped with pigeonpea than when intercropped with other crop species. The slow initial growth of pigeonpea makes it well suited for intercropping as there is little competition with the primary maize crop (Silim et al., 2005). Even when sown simultaneously with maize, pigeonpea has a longer growth cycle and can continue to grow for up to three months after maize harvest (Myaka et al., 2006). With the extended period of growth, the greatest demand for water and nutrients in pigeonpea occurs after maize has been harvested (Dalal, 1974). As such, pigeonpea does not affect the yield of the companion maize crop (Myaka et al., 2006; Kimaro et al., 2009). The greater maize yield when intercropped with pigeonpea was not significantly different from other intercrops (Fig. 2.4), probably due to the large difference in the number of observations (*n*) of the various intercrop systems, where the number of cases for maize-pigeonpea intercrops was substantially larger. We attribute the popularity of maize-pigeonpea intercrops to their multiple benefits, among others the use of green pods for food, the good market for dry grain (Löfstrand, 2005; Silim et al., 2005), and the stems remaining after harvest are used for fencing or as firewood (Myaka et al., 2006; Adu-Gyamfi et al., 2007).

Maize grain yields were significantly greater in the Kilimanjaro region than in Arusha and Manyara regions, while pigeonpea grain yield was comparable across regions (Fig. 2.5). This significantly greater yield in maize in the Kilimanjaro region was associated with the more fertile soils with larger soil C and N concentrations (Table 2.2), which are important indicators of soil quality. In relation to this, it is notable that 41% of the farmers sampled in Kilimanjaro used fertilizer as compared with only 10-11% in Arusha and Manyara (Table 2.1). The biomass of pigeonpea at the time of maize harvest was 3.5 t ha^{-1}, while at physiological maturity it was 3.4 t ha^{-1}. Pigeonpea grows for an extended period of three to four months after maize harvest by accessing sub-soil moisture due to its deeper rooting system (Mafongoya et al., 2006). The reduction in pigeonpea biomass observed in this study at the time of harvest is due to the fact that despite the longer growth period, pigeonpea plants shed large amounts of leaves as they approach maturity. The fallen pigeonpea leaves were not included in the samples for determining final aboveground biomass, which is known to lead to underestimates of overall biomass production for pigeonpea (Sheldrake and Narayanan, 1979). This leaf litter can contribute greatly to soil fertility; 75-95 kg N ha^{-1} was added to the soil from senescent pigeonpea leaves in maize-pigeonpea intercrops in Malawi (Sakala, 1998).

The most important factors associated with variability in yield were plant density at harvest, fertilizer use and slope, as these were significant across more than one region (Table 2.4). Other factors included manure use, years the land had been under cultivation, weeding frequency, seed variety used, fallow practice and fertility level. Yield variability is often attributed to heterogeneity and differences in landscapes and soils, and the corresponding agronomic and management practices (Njoroge et al., 2019; Tamene et al., 2016). There was wide variability of plant spacing and plant density, with a median value of 26,000 and 18,000 plants ha^{-1} for maize and pigeonpea respectively. In our study, denser plant densities at harvest gave larger yields for both maize and pigeonpea, as observed elsewhere (Fanadzo et al., 2010). The wide variability in plant spacing and low plant densities at harvest is partly associated with the use of ox-drawn ploughs and the broadcasting of seeds leading to random arrangement of the crops. Each additional year that fields had been cultivated in Arusha led to a decrease in maize yields, suggesting decline in soil fertility as a cause especially given that only 10% of the farmers used fertilizer in the region. The reasons highlighted for not using fertilizer included lack of cash, low response rate and high prices. The sparse use of fertilizer has also been attributed to lack of information on its benefits and the absence of input suppliers (Mowo et al., 2006; Adu-Gyamfi et al., 2007). Additionally, Mapila et al. (2012) found that smallholder maize farmers in Southern Africa (Malawi, Mozambique and Zambia) did not use fertilizer due to a perception that it would have detrimental effects on their soils, and they attributed such perceptions to a lack of farmer training on fertilizers. The extra yield realized due to addition of fertilizer or manure (1.5 t ha^{-1} and 0.9 t ha^{-1} respectively) underscores the importance of replenishment of the nutrients removed through harvest of grains, maize stover for livestock feed and pigeonpea stems for fuel wood (Kihara et al., 2015). Indeed, manure has multiple benefits on soil fertility (Zingore et al., 2008) which explains its role in increasing yield. More frequent weeding had a positive effect on maize yields, where each additional weeding event resulted in 0.39 t ha^{-1} extra yield. Yields on fields that farmers rated as very fertile were 1.62 t ha^{-1} greater than infertile fields (Table 2.4), which is unsurprising given that crop yields were among the criteria used to rate the fertility of fields. Larger total carbon (C) and available P concentrations were also found in fields that farmers considered to be fertile (Table 2.3). Maize yielded poorly on steep slopes as compared to flat and gentle slopes and this was even exacerbated where the steep slopes were farther from the homestead; yields on more steep slopes that were closer to the homestead produced higher yields than those that were farther away (Fig. 2.6). This could be attributed to the fact that fields that are farther from the homestead are often located on steeper slopes and more prone to erosion risks (Giller et al., 2011; Mowo et al., 2006). Further, fields that are farther from the homestead often receive less nutrient inputs (Zingore et al., 2008).

2.5 Conclusions

This study systematically illustrates current practices in maize- pigeonpea intercrops by combining agronomic, structural and socio-economic information in three regions of northern Tanzania. We identify promising interventions to increase yields of intercrops. Improved soil fertility management using manure where it is available and supplementing with mineral fertilizers will enhance yields of the intercrops. Greater awareness through training farmers on balanced nutrition and fertilizer use is needed. The importance of optimising plant density and implementing soil conservation measures on steep slopes is also clear. The large amount of pigeonpea leaf fall which is left in the field after harvest can contribute greatly to soil fertility through nutrient cycling and maintenance of soil organic matter for long term sustainability. Residual benefits that the intercropped legume crops and in particular pigeonpea provide to the subsequent maize crop deserve more detailed investigation. Furthermore, since intercrops are known to increase aggregate yields per unit input through complementarity in utilization of nutrients, water and solar radiation, studies to assist in quantification of such benefits are strongly recommended.

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Chapter 3

Immediate and residual-effects of sole and intercropped grain legumes in maize production systems under rain-fed conditions of northern Tanzania.

This chapter is published in slightly refined form as:

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Abstract

Intercropping of maize with grain-legume crops predominates on smallholder farms in East Africa. However, the growth and development of crops and their interaction with fertilizer in intercropping systems are not well understood. We sought to answer the questions: (i) what are the effects of fertilizer on the growth and development of maize-pigeonpea and maize-lablab intercropping systems under variable agroecological conditions? (ii) what are the residual effects of two seasons of sole and intercrops of maize, pigeonpea and lablab on a succeeding maize crop? We studied pure stands of maize, long-duration pigeonpea, medium-duration pigeonpea and lablab, and additive intercropping combinations on eight farms in Babati, northern Tanzania. The intercropping combinations studied were: maize-long duration pigeonpea, maize-medium duration pigeonpea and maize-lablab. Three fertilizer levels were applied: no fertilizer; 40 kg P ha^{-1}; and 90 kg N ha^{-1} + 40 kg P ha^{-1}. The P was applied at planting in the form of triple superphosphate to both maize and legumes, thus in intercrops the 40 kg P ha^{-1} was shared between maize and legume. The N was spot-applied in the form of urea in three equal splits, only on maize. The trials were implemented for two consecutive cropping seasons (2017/2018 and 2018/2019), without changing treatments and plot locations. To evaluate the residual effect of grain legumes, we planted a sole crop of maize in the third season (2019/2020) in all plots, with no addition of fertilizer. Maize and pigeonpea were sown simultaneously, while lablab was relay-planted one month after maize. Maize dry matter (DM) and grain yield were not significantly affected by the presence of legumes, but were about twice as large in 2017/2018 as in 2018/2019 season, likely due to the considerably higher rainfall in the 2017/2018 season. Legume productivity was more consistent across the two seasons. Legume crops in the intercrops produced significantly less DM and grain yield than in their respective pure stands, but maize yield did not differ significantly between sole and intercrops. The productivity of maize was significantly increased by N fertilization, but the legumes responded positively only to P fertilizer in the 2017/2018 season. Land-equivalent and area-time-equivalent ratios of intercropping systems were consistently greater than one. The DM and grain yield of maize following two seasons of legumes was consistently larger than in plots where maize was grown continuously. The P-fertilizer applied in the preceding seasons had significant residual effects on the yield of the succeeding maize crop. The temporal niche complementarity of pigeonpea and lablab with maize minimized competition in the intercrops, although intercrops are clearly more demanding in labour at planting and harvest. Overall, our results showed the superior performance of maize-legume intercropping over sole maize, both in terms of additional grain yield within a season and the residual effects in the succeeding season. Maize-legume intercropping with fertilizer application was effective in enhancing the productivity of smallholder cropping systems.

Key words: Cropping system, Fertilizer, Residual effect, Pigeonpea, Lablab

3.1 Introduction

Smallholder crop production systems in much of the East African highlands are dominated by maize (*Zea mays* L.) which is commonly intercropped with grain legumes, mainly pigeonpea (*Cajanus cajan* (L.) Millsp.), common bean (*Phaseolus vulgaris* L.), dolichos lablab (*Lablab purpureus* (L.) Sweet) and cowpea (*Vigna unguiculata* (L.) Walp) (Myaka et al., 2006; Kimaro et al., 2009; Mugi-Ngenga et al., 2021). Beyond direct yield benefits, the grain legumes can provide additional ecological benefits that may enhance the productivity of maize in the short and long-term. Within-season benefits of cereal-legume intercropping include greater ground cover and suppression of diseases and pests. Residual benefits that accrue in subsequent seasons include supply of nitrogen (N) from N_2-fixation, improved soil health, weed (*Striga*) suppression and increased maize yields (Giller, 2001; Rusinamhodzi et al., 2012; Zhang et al., 2019).

Productivity of intercrops depends on the balance between intra- and inter-specific competitions. When the component crop species have complementary growth patterns (e.g., use different temporal niches by utilizing different periods of the season, or spatial niches through different rooting depths or canopy sizes), inter-specific competition will tend to be weaker than intra-specific competition, and resources (sunlight, moisture and soil nutrients) will be acquired more efficiently (Lithourgidis et al., 2011). This results in relatively greater yields in intercrops than in pure crop stands (Willey, 1979). The extent of this improvement in yields depends on crop management. Relay intercropping entails that crop growth phases only partially overlap, resulting in temporal niche differentiation (TND). Managing the spatial arrangement of intercrops is also key to enhancing their productivity, as it dictates the balance between intra- and inter-specific interactions. Greater productivity of maize-grain legume intercrops when sown within the same row compared with sole crops was reported in the Guinea savanna of northern Ghana (Kermah et al., 2017), southern Mali (Falconnier et al., 2016) and central Mozambique (Rusinamhodzi et al., 2012).

Pigeonpea is drought-tolerant due to its relatively deep root system, enabling it to exploit moisture from deep soil layers (Kumar Rao et al., 2001) than e.g., maize. It improves soil fertility through high biomass production and soil nutrient contribution. The litter fall plays a significant role in the recycling of nutrients and improving soil organic matter (Sakala, 1998). Pigeonpea has slow early growth, which limits early competition with cereals in intercrops (Silim et al., 2005). It also has a longer growth cycle than maize, and when sown simultaneously continues to grow for up to three months after maize harvest (Myaka et al., 2006). This ensures that the greatest demand for water and nutrients occurs after maize has been harvested (Dalal, 1974). The strong contribution of atmospheric N_2 fixation associated with pigeonpea in intercropping systems has been demonstrated in several studies (Peoples et al., 1995; Giller, 2001; Myaka et al., 2006). Lablab also complements well with maize in intercrops (Cook et al., 2005). However, it has a spreading growth habit and is generally relay-planted to reduce competition. In addition, it has a dense canopy that reduces soil moisture losses and adds significant mulch to the soil while the lower leaves are shed (Cook et al., 2005; Rapholo et al., 2020). With the help of a deep taproot, both pigeonpea and lablab can extract water at a soil depth of 2 m, which allows them to grow during the dry season after maize is harvested (Kumar Rao et al., 2001; Cook et al., 2005), resulting in both spatial and temporal niche differentiation.

While within-season effects of intercropping are receiving increasing attention, the rotational performance is rarely investigated across seasons, even though the two are complementary strategies in the sense that they provide spatial (intercropping) and temporal (rotations) crop diversification. For example, Adjei-Nsiah et al. (2007) reported up to four times greater maize yield following sole cowpea than continuous maize, but did not consider the possibility of intercropping in this respect. The benefits accruing from grain legumes are associated with N and non-N effects (Sanginga et al., 1999; Franke et al., 2018). The N benefits are related to the improvement in N nutrition (Giller, 2001). The non-N effects include enhanced P-availability, improved soil moisture and organic matter, and suppression of weeds, pests and diseases (Chan and Heenan, 1996; Schlecht et al., 2006; Rusinamhodzi et al., 2012; Franke et al., 2018).

Farmer management practices and agroecological conditions are critical factors that influence grain legume productivity. Poor soil fertility and low water availability are well known to reduce yields of both legumes and maize, resulting in smaller returns on land and labour. A better understanding of the influence of agroecological conditions on the performance of intercrops is particularly pertinent in northern Tanzania, due to the wide diversity of climatic conditions and soils. Furthermore, most studies on maize-legume intercropping have neither considered the season-to-season temporal performance of rotations, nor the effects of local variation in agro-ecological conditions. This study aimed to: (i) evaluate the growth and development of maize-pigeonpea and maize-lablab intercropping systems and their interaction with fertilizer and agroecological conditions; and (ii) evaluate the residual effects of the grain legumes on the yields of the succeeding maize crop. We hypothesized that: (i) growth and development of legumes (pigeonpea and lablab) in intercrops will be suppressed when maize is present, but partial compensation will occur after maize harvest; and (ii) intercropping maize with pigeonpea and lablab confers residual benefits that are amplified by nutrient application.

3.2 Materials and methods

3.2.1 Study site characterization

The study was conducted in Babati district, northern Tanzania (Fig. 3.1). The district is located within 04° 20-29’S, 35° 56-71’E, at 1300-1700 m above sea level, and covers five agroecological zones (AEZs). Our study was concentrated within 3 AEZs, hereafter referred to as sites (Riroda, Arri and Dareda) (Fig. 3.1).

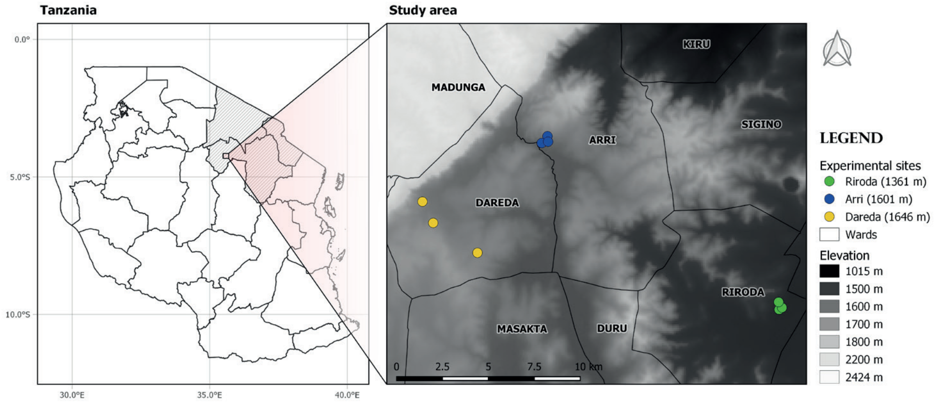

Fig. 3.1: Map showing the location of the three sites (Riroda, Arri and Dareda) in Babati, northern Tanzania (left panel) and the location of the on-farm experimental trials (three replicate farms, dots) in each of the three sites and the range in altitude (right panel).

The district was chosen due to the widespread practice of maize-legume intercropping, following a farm-scale survey in northern Tanzania (Mugi-Ngenga et al., 2021). Due to area constraints on smallholder farms, only three farms were selected in each site, making an initial sample size of nine farms. Each farm acted as a replicate (one farm-one replicate design).

Annual rainfall distribution varies among sites and seasons, while topographical changes result in gradients in temperature and soil fertility (Kihara et al., 2015). Annual rainfall ranges from 600 to 1100 mm and the area has a single growing season from November/December to April/May, although pigeonpea continues to grow into the dry season until September. The rains typically begin early November, but farmers commonly delay planting until mid-December to early January, to ensure that the critical growth stage of maize does not coincide with a dry spell that often occurs between February and March.

Prior to establishment of the experiments, soils were sampled to determine the initial soil fertility status. In each farm, one field of approximately 0.13 ha was sub-divided into four sections of approximately 0.03 ha each. Subsequently, four sub-samples were taken in each section following a 'Y frame' sampling approach using an Edelman auger (7 cm diameter), at a depth of 0-20 cm. The four sub-samples from each of the four sections (thus a total of 16 sub-samples per field) were placed in a basin and thoroughly mixed to create a composite sample. Samples were dried to constant weight and passed through a 2 mm sieve prior to chemical analysis at Yara U.K. Limited. Soil organic carbon (SOC), total nitrogen (N) and available phosphorus (P) were analysed by Walkley-Black, Kjeldahl, and modified Olsen methods, respectively (Anderson and Ingram, 1993). The exchangeable bases comprising of Ca, Mg, and K were determined using atomic absorption spectrometry, with ammonium nitrate as the extracting agent. Soil pH was determined in water using the pH electrode method; ratio of 1:2.5, while soil texture was determined using the improved hydrometer method (Bouyoucos, 1962). Daily rainfall was recorded at each experimental field using simple rain gauges, and temperature was monitored using Thermochron® iButton® device (DS1921G).

3.2.2 Experimental set-up and management

The experiment was conducted for three consecutive cropping seasons (2017/2018-2019/2020), but one farmer in the Riroda site withdrew from the study after the 2017/2018 season. In each of the selected farms, fields were ploughed, and thirteen or eighteen plots measuring 10 × 5 m delineated at planting. Paths measuring 1 m wide were left in between plots. Test crops used included maize Seed Co. 513 hybrid variety, dolichos lablab "Selian-Rongai" variety and pigeonpea long ICEAP 00040 and medium duration ICEAP 00557 varieties. Pure stands of maize, pigeonpea and lablab were planted at a spacing of 0.90 m × 0.50 m inter- and intra-row, respectively. Each plot was thus composed of 11 rows with a length of 5 m. Cereal legume intercrops followed an additive design, with legumes planted in the maize rows, in-between maize hills (Fig. 3.2). Three seeds were planted per hill for both maize and legumes and later thinned to two at 2 weeks post-emergence to achieve the target planting density. Plant populations of approximately 40,000 plants ha^{-1} for each crop were maintained in both pure stands and intercrops, thus the population in intercrops was double that of sole crops.

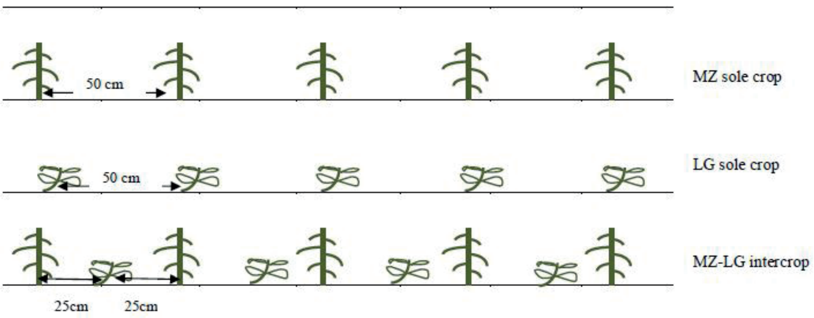

Fig. 3.2: An illustration of the composition of a single row in sole stands of maize and legumes (long and medium-duration pigeonpea and lablab) and intercrops of maize with the legumes in the on-farm experiments in Babati, northern Tanzania. MZ= Maize; LG= Legume.

In the first two seasons of experimentation (2017/2018 and 2018/2019), the plots on each farm consisted of a unique set of two factor treatment combinations. A treatment combination was characterised by species composition as the first factor at seven levels:

i. Pure stand of maize.
ii. Pure stand of long-duration pigeonpea.
iii. Pure stand of medium-duration pigeonpea.
iv. Pure stand of lablab.
v. Maize – long duration pigeonpea intercrop.
vi. Maize – medium duration pigeonpea intercrop.
vii. Maize - lablab intercrop.

Fertilizer treatment was the second factor, applied at three levels: (i) no fertilizer, (ii) P fertilizer only and (iii) NP fertilizer. Pure stands of legumes did not receive the NP fertilizer. For this reason, trial farms with all species composition at seven levels had 18 treatment plots, three less than the 21 plots that would have been achieved with a full-factorial design (7 × 3). Pure stands and intercrops containing lablab were only included in one farm per site. Therefore the farms where lablab was omitted had a total of 13 treatment plots, as the NP fertilizer was also not applied to pigeonpea pure stands. An overview of all treatments and their frequency per site is provided in Table 3.1. To evaluate residual benefits of the grain legumes to the yield of a succeeding maize crop, a third season (2019/2020) was included, where a sole maize crop was planted in all treatments. No fertilizer was applied to the maize crop in the third season.

Table 3.1: Description and frequency of occurrence of treatments in on-farm experimental trials in each of the three sites (Riroda, Arri and Dareda) in Babati, northern Tanzania

Species combination	**Fertilizer**		
	Control	**+P**	**+NP**
Maize (MZ)	3/3[a.]	3/3	3/3
Long-duration pigeonpea (ldP)	3/3	3/3	-
Medium-duration pigeonpea (mdP)	3/3	3/3	-
Lablab (LB)	1/3	1/3	-
MZ- ldP intercrop	3/3	3/3	3/3
MZ- mdP intercrop	3/3	3/3	3/3
MZ- LB intercrop	1/3	1/3	1/3

[a.] 3/3 indicates that this treatment combination was present in all three of the trial farms within a site.

The P fertilizer was applied at planting in the form of triple superphosphate (TSP) at the rate of 40 kg P ha^{-1} to both maize and legumes. Fertilizer N was spot-applied in the form of urea at the rate of 90 kg N ha^{-1} in three equal splits only on maize; one third at planting, one third at four weeks after planting and one third at eight weeks after planting. The combination of cropping system (various sole and intercrops) and fertilizer (control, +P and +NP) were randomly assigned within each farm per site. Pigeonpea (both long and medium duration varieties) were planted simultaneously with maize, whilst lablab was relay-planted one month later. Individual plots were maintained and treatments (cropping systems and fertilizer) allocated to the same plots in the 2017/2018 and 2018/2019 seasons. Maize was harvested 3-4 months before the legumes (Fig. 3.3).

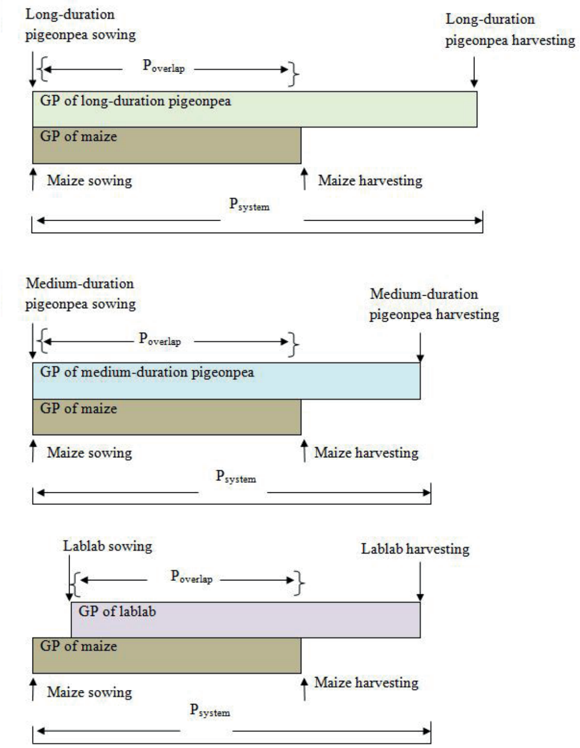

Fig. 3.3: An illustration of temporal niche differentiation for maize-legume intercrops in Babati, northern Tanzania. GP=Growing period of the component crop; D_{system}=Total system duration; $D_{overlap}$=Overlap duration (duration when the two crops were growing together).

General crop management was optimal to prevent yield losses to weed and pests. Weeding was done manually twice during the period when maize was growing, while after harvesting maize weeds were eliminated by uprooting. Chemical pest control was used to control fall armyworm. Multi-alpha plus 150 EC (Emamectin Benzoate 50g/l + Alphacypermethrin 100g/l) was applied on all plots containing maize, at least twice during the vegetative growth of the crop, at the rate of 450 ml ha^{-1}.

3.2.3 Determination of dry matter and grain yield

At physiological maturity of each crop (150-180, 210, 240 and 270 days after sowing for maize, lablab, medium-duration pigeonpea and long-duration pigeonpea respectively), all plants within the net plot were harvested by cutting at ground level. The net plot comprised of four centre rows with a length of 2.5 m in each plot, leaving at least 1.25 m on each side of the centre rows to minimize edge effects. For plots with intercrops, the legume crop was maintained after maize harvest until final harvest. Total fresh weight of maize and legume plants were separately taken in the field. Maize cobs were manually separated from the stover and hand threshed. Legumes were also threshed manually to separate grains and haulms. After threshing, total fresh weight of maize and legume grains were separately taken in the field. Thereafter, 3-5 plants of maize and legumes were taken after removal of grains, cut into small pieces and weighed in the field to form a sub-sample whose fresh weight was 400-500 g. The sub-samples were oven dried at 75 °C for 48 hours, for correction of moisture content and determination of dry weight. Moisture content of the grains (%) was determined using a moisture meter (Dickey John Mini GAC, Minneapolis USA), and grain yields corrected to 12.5% and 13% moisture content for maize and legumes, respectively.

3.2.4 Leaf fall measurements

During the first season, sub-plots measuring 1 m × 1 m were demarcated in the net plot on all plots containing legumes. Wire-mesh litter traps were placed on the ground to capture fallen leaves. The litter traps were stolen before the first sampling could be done. Consequently, fallen leaves were not quantified in the first season. In the second season, we installed similar sub-plots in all plots (1 m × 1 m), with no wire mesh. Every two weeks we collected the leaves from the ground to minimize decomposition, weighed and included them in the final determination of biomass yield.

3.2.5 Calculations and statistical analysis

The final dataset used in the analyses was derived from eight farms, since one farm in Riroda was excluded due to lack of data for the 2018/2019 and 2019/2020 seasons, following farmer withdrawal from the study after the first season. For maize and legumes, the grain yields obtained in pure stands were averaged per site, before they were used to calculate the Land Equivalent Ratio (LER) and Area Time Equivalent ratio (ATER).

LER was calculated as:

$$LER = \frac{Y_{MZi}}{Y_{MZs}} + \frac{Y_{Li}}{Y_{Ls}} = RY_{MZ}\ (partial\ LER\ of\ maize) +\ RY_{L}\ (partial\ LER\ of\ legume)$$

Where Y_{MZi} and Y_{MZs} represent yield of maize in intercrop and sole stand, respectively, and Y_{Li} and Y_{Ls} represent yield of the legume in intercrop and sole stand, respectively.

ATER was calculated as:

$$ATER = \frac{(RY_{MZ} \times t_{MZ}) + (RY_L \times t_L)}{T}$$

Where t_{MZ} and t_L represent duration (in days) from planting to harvest taken by maize and legume, and T represents duration (days) of the whole intercropping system.

All statistical analyses were performed in RStudio Version 1.0.143 (R Core Team, 2021), separately for maize and legume, per season. Since the treatments for sole and intercropped legumes did not overlap completely (sole crops did not have a "+NP" treatment), analysis for legumes was executed in two contrasts: (i) a contrast of all systems (both sole and intercrops) but only including control and +P fertilizer, and (ii) a contrast of only intercrop systems but including all three fertilizer levels: control, +P and +NP fertilizer. To assess the effects of various treatments on DM and the grain yield of maize and legumes, mixed effects models were fitted using the *lme4* package in R software. The DM or grain yield was used as the response variable, while site, cropping system and fertilizer were used as fixed effects. To account for variation in DM and grain yield due to differences in farms, a variable 'farm' was included as a random effect in the mixed model. Significance of effects of model parameters on DM and grain yield were evaluated using the *lmerTest* package available in R software. Where mean differences were significant, least significant difference test (LSD test) was used to separate means using the *agricolae* package and reported at a significance level of $P<0.05$.

3.3 Results

3.3.1 Soil characterization and weather attributes

Baseline soil properties varied among sites (Table 3.2). Following Hazelton and Murphy. (2016) to interpret the soil test results, significantly larger concentrations of available P (P=0.04) were recorded in Riroda than in the other sites, with below critical P-concentrations (9-15 mg kg^{-1}) in all locations in Arri and some locations in Dareda. There was no indication of K deficiency, as all sites had concentrations well above the critical threshold of 0.2 cmol kg^{-1}. A consistent pattern was observed for SOC and total N in the different sites, in the order of Riroda<Dareda<Arri, with significant differences between these sites (P=0.003 for SOC and 0.002 for total N). The soil was slightly acidic (pH<6) in Dareda and neutral in Riroda and Arri. Soils at the Riroda site had significantly larger sand content (P=0.008) and smaller silt (P=0.02) and clay content (P=0.01) than at the Arri and Dareda sites (Table 3.2).

Table 3.2: Means and range of soil properties (0-20 cm depth) at the start of the on-farm experimental trials across three sites in Babati, northern Tanzania

Site	Soil properties										
	pH (water)	SOC (%)	N (%)	C:N (ratio)	P (mg kg^{-1})	K (cmol kg^{-1})	Ca (cmol kg^{-1})	Mg (cmol kg^{-1})	Sand (%)	Silt (%)	Clay (%)
Riroda (1361 masl)	6.4 (6.0-6.6)	0.76^{c} (0.60-0.90)	0.06^{c} (0.05-0.08)	12.6 (10.1-16.2)	33.9^{a} (22.0-45.0)	0.51^{b} (0.40-0.70)	4.42 (3.50-5.20)	1.12 (0.80-1.50)	67.3^{a} (56.0-80.3)	20.7^{b} (15.5-26.1)	12.0^{b} (2.40-18.0)
Arri (1601 masl)	6.1 (5.8-6.9)	1.69^{a} (1.50-2.00)	0.14^{a} (0.12-0.15)	12.3 (11.2-13.9)	4.25^{b} (1.00-10.0)	0.93^{a} (0.40-1.30)	6.06 (4.90-8.30)	2.48 (1.60-4.00)	30.8^{b} (22.1-42.4)	35.2^{a} (30.7-40.0)	34.0^{a} (26.1-39.6)
Dareda (1646 masl)	5.8 (5.6-6.8)	1.10^{b} (0.90-1.50)	0.10^{b} (0.08-0.13)	10.7 (9.40-11.8)	12.3^{b} (1.00-32.0)	0.63^{b} (0.50-1.30)	4.04 (2.90-6.90)	1.66 (1.20-2.40)	40.1^{b} (25.9-61.7)	30.6^{a} (18.4-38.3)	33.7^{a} (19.9-68.2)
P-value	ns	0.003	0.002	ns	0.04	0.04	ns	ns	0.008	0.02	0.01

Values in brackets represent range. Mean values within the same column followed by a different superscript are significantly different at $P < 0.05$. masl = metres above sea level.

Rainfall amounts were up to 551 mm in 2017/2018 and up to 236 mm in the 2018/2019 season. In both seasons, there was a severe dry spell in the first half of the season, where no rainfall was received for 1-2 months. In 2017/2018, the dry spell between 40-70 days after sowing (DAS) coincided with the vegetative growth stage of maize and legumes. However, in the 2018/2019 season, the dry spell which occurred between 30-90 DAS extended into the reproductive phase of maize. As expected, the highest-elevation site, Dareda, recorded the lowest temperature in most cases throughout the growing period and across the two seasons. Whereas in 2017/2018 the temperature started to decline at 60 DAS, in the 2018/2019 season, the temperature remained high and dropped only at 120 DAS. This coincided with the extended dry spell, an indication that cloudiness had a dampening effect on temperature. We do not have detailed rainfall and temperature data for the 2019/2020 season, but it was similar to the 2017/2018 season.

3.3.2 Dynamics of dry matter production and grain yield of maize

Significant main effect of fertilizer was found for maize dry matter (DM) and grain for both seasons. The effect of site was significant for maize grain yield only in the second season (2018/2019). Addition of NP fertilizer significantly enhanced maize DM (P<0.001 and =0.01 in 2017/2018 and 2018/2019 respectively) and grain yield (P<0.001 and =0.009 in 2017/2018 and 2018/2019 respectively) compared with the control plots and/ or +P plots (Table 3.3, Fig. 3.4). In the 2017/2018 season, the effects of nitrogen fertilizer were evident, as +NP plots produced more maize DM and grain yield than +P (+1.5 t ha^{-1} DM, +0.8 t ha^{-1} grain) and control plots (+2.5 t ha^{-1} DM, +1.2 t ha^{-1} grain). In 2018/2019 season, maize production in control plots was significantly less than +P (-1.1 DM, -0.7 grain) and +NP plots (-1.9 DM, -0.9 grain) (P=0.01 and 0.009 for DM and grain yield respectively) (Table 3.3, Fig. 3.4).

Table 3.3: Dry matter yield (t ha^{-1}) of maize at final harvest in the various cropping systems as affected by fertilizer, from on-farm experimental trials in Babati, northern Tanzania. Results are averaged over three sites (Riroda, Arri and Dareda).

Season	Fertilizer	Cropping system				Mean
		MZ sole	MZ- ldP	MZ- mdP	MZ- LB	
2017/2018	C	8.7	8.2	10.4	9.4	9.2c
	+P	10.0	10.5	9.3	10.8	10.2b
	+NP	11.4	11.7	11.8	11.9	11.7a
	Mean	10.0	10.1	10.5	10.7	
	SED (Cropping system)					ns
	SED (Fertilizer)					0.50
2018/2019	C	3.8	4.4	4.9	4.5	4.4b
	+P	5.8	5.6	5.2	5.2	5.4a
	+NP	6.9	6.7	5.9	5.8	6.3a
	Mean	5.4	5.4	5.2	5.2	
	SED (Cropping system)					ns
	SED (Fertilizer)					0.48

Means per season followed by different letters are significantly different at $P \leq 0.05$ (ns = not significant). MZ = maize, ldP = long-duration pigeonpea, mdP = medium-duration pigeonpea, LB = Lablab.

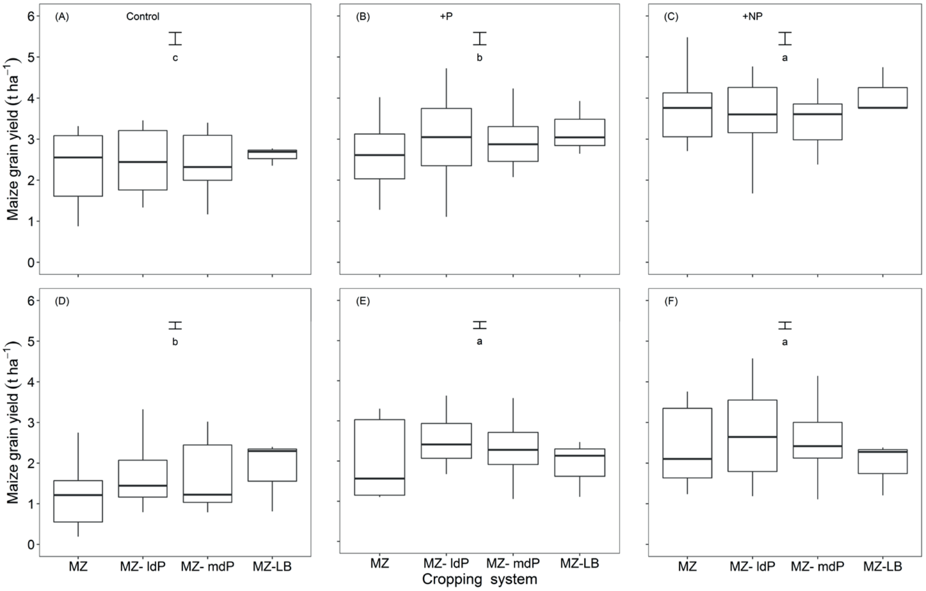

Fig. 3.4: Maize grain yield in various cropping systems as affected by fertilizer from on-farm experimental trials during the 2017/2018 (A-C) and 2018/2019 (D-F) seasons in Babati, northern Tanzania. MZ= maize; ldP= long-duration pigeonpea; mdP= medium-duration pigeonpea; LB= lablab. Error bars indicate the standard error of means. Mean differences of fertilizer treatments at 5% significance level in the various box plots are indicated with different small letters on the upper side of the box plot.

In the 2018/2019 season, grain yield of maize across the various cropping systems was significantly smaller (*P*=0.01) in Riroda than Arri (-26% DM, -43% grain) and Dareda (-32% DM, -52% grain) (Fig. 3.5). Maize growth was in most cases not affected by the presence of legumes, as it produced similar DM and grain yield in sole- and intercrops (Table 3.3 and Figs. 3.4, 3.5).

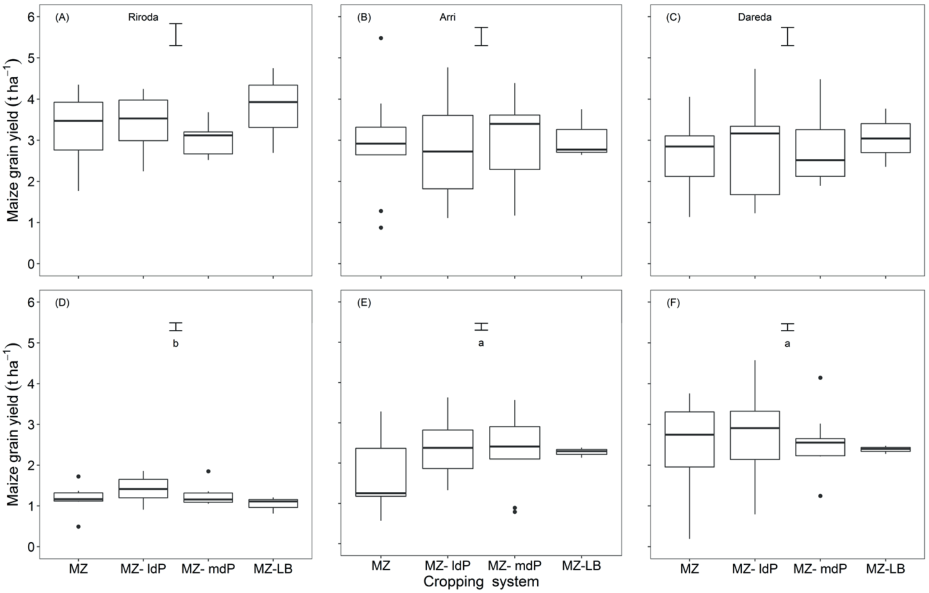

Fig. 3.5: Maize grain yield in various cropping systems as affected by site from on-farm experimental trials during the 2017/2018 (A-C) and 2018/2019 (D-F) seasons in Babati, northern Tanzania. MZ= maize; ldP= long-duration pigeonpea; mdP= medium-duration pigeonpea; LB= lablab. Mean differences of site at 5% significance level in the various box plots are indicated with different small letters on the upper side of the box plot. Error bars indicate the standard error of means.

3.3.3 Dynamics of dry matter production and grain yield of legumes

3.3.3.1 Legume dry matter

Compared with medium-duration pigeonpea (240 days) and lablab (180-210 days), the growth duration was longest for long-duration pigeonpea (270 days). During the co-growth stage in the intercrops (from at least 120 up to 180 days after sowing), the growth of legumes in intercrops was suppressed by maize. This is reflected by the greater biomass production in sole legume crops than the intercrops, which was statistically significant ($P<0.001$) in the 2018/2019 season (Table 3.4). Within this data set, contrasts were made for sole and intercrop systems combined with control and +P fertilizer (referred to as contrast 1), and for intercrop systems combined with control, +P and +NP fertilizer (referred to as contrast 2).

At the time of maize harvest, under both contrasts, the DM production was significantly different across sites ($P=0.02$ or 0.01) in the 2017/2018 season, where legumes in Riroda site produced greater DM than Dareda. Under contrast 1 (all systems but only including control and +P fertilizer), DM production of pigeonpea was greater (*P*<0.001) in pure stand than in intercrop with maize in the 2018/2019 season. Both in pure stand and in the intercrop, the DM production of lablab was significantly less than that of the two sole pigeonpea varieties (*P*<0.001). Under contrast 2 (intercrop systems with control, +P and +NP fertilizer), significantly greater DM (*P*<0.001) was produced in Riroda than the Arri and Dareda sites in the 2018/2019 season (Table 3.4). Furthermore, intercropped lablab produced significantly less DM (*P*=0.003) than the two pigeonpea intercrops (Table 3.4).

Table 3.4: Above-ground dry matter yield (t ha^{-1}) of legumes at the time of maize harvest as affected by site and cropping system, from on-farm experimental trials over two seasons in Babati, northern Tanzania. Contrasts were made for (1) sole and intercrop systems with control and +P fertilizer and (2) intercrops only at control, +P and +NP fertilizer. Results for site were averaged over cropping system and two fertilizer levels. Results for cropping system were averaged over sites and fertilizer treatments. The SED shows standard error of difference between means.

Season	Site	Contrasts	
		Sole and intercrops with control and +P fertilizer (t ha^{-1})	Intercrop systems with control, +P and +NP fertilizer (t ha^{-1})
2017/2018	Riroda	3.98a	3.58a
	Arri	3.09ab	2.80a
	Dareda	2.36b	2.11b
	SED (Site)	0.34	0.27
2018/2019	Riroda	3.11	2.59a
	Arri	2.38	1.93b
	Dareda	2.32	1.71b
	SED (Site)	ns	0.21
	Cropping system		
	ldP sole	3.55a	-
	ldP inter	2.13b	2.13a
	mdP sole	3.24a	-
	mdP inter	2.06b	2.16a
	LB sole	1.77bc	-
	LB inter	1.28c	1.39b
	SED (Cropping system)	0.39	0.21

Means within the same column under site or cropping system followed by different letters per contrast are significantly different at *P*<0.05. Inter = intercropped with maize; ldP = long-duration pigeonpea, mdP = medium-duration pigeonpea, LB = Lablab.

Leaf fall was quantified in the 2018/2019 season (Table 3.5), and included in determination of DM production of legumes at final harvest (Table 3.6). While pigeonpea plants shed leaves from the beginning of the reproductive stage (starting from 150 DAS), lablab plants did so only at physiological maturity. Under contrast 1 (all systems but only including control and +P fertilizer), a significant main effect of site (*P*=0.02) and cropping system (*P*<0.001) was observed for the overall amount of senesced leaves (Table 3.5). Plants at the Riroda site produced more senesced leaves than those at Arri (30% greater) and Dareda (45% greater) (Table 3.5). Furthermore, sole long-duration pigeonpea produced more senesced leaves than the pure stands of medium-duration pigeonpea and lablab. Intercropped with maize and both pigeonpea varieties produced less senesced leaves than in pure stand, but for lablab this difference was not observed (Table 3.5).

Under contrast 2 (intercrop systems at control, +P and +NP fertilizer), a significant site × cropping systems effect was observed (*P*=0.03). In Riroda and Arri sites, significant differences were observed among the three legumes, with long-duration pigeonpea>medium-duration pigeonpea>lablab (Table 3.5). In Dareda site, long-duration pigeonpea produced the largest amounts of senesced leaves. For long-duration pigeonpea, leaf fall differed with site (Riroda>Arri>Dareda), while production of medium-duration pigeonpea was greater in Riroda than at the other two sites. For lablab no site differences were observed (Table 3.5).

Table 3.5: Amount of fallen leaves (t ha^{-1}) as affected by site and cropping systems from on-farm experimental trials in the 2018/2019 season, in Babati, northern Tanzania. Contrasts were made for 1) sole and intercrop systems with control and +P fertilizer and 2) intercrops only at control, +P and +NP fertilizer. Results for site are averaged over cropping systems and fertilizer levels. Results for cropping system are averaged over sites and fertilizer treatments. The SED shows standard error of difference between means.

Cropping system	Sole and intercrops with control and +P fertilizer (t ha^{-1})				Intercrop systems with control, +P and +NP fertilizer (t ha^{-1})			
	Riroda	Arri	Dareda	Mean	Riroda	Arri	Dareda	Mean
ldP sole	2.86	1.98	1.64	2.16a	-	-	-	
ldP inter	2.22	1.46	0.84	1.51b	2.21a	1.45b	0.81c	1.49
mdP sole	1.86	1.25	1.19	1.43b	-	-	-	
mdP inter	1.30	0.79	0.53	0.87c	1.21b	0.76cd	0.55de	0.84
LB sole	0.82	0.72	0.57	0.70c	-	-	-	
LB inter	0.68	0.63	0.58	0.63c	0.65cde	0.53e	0.58de	0.59
Mean	1.62a	1.14b	0.89b		1.36	0.91	0.65	
SED (Site)				0.17				-
SED (Cropping system)				0.12				-
SED (Site×Cropping system)				ns				0.12

Means within the same column followed by different letters are significantly different at *P*<0.05. Inter = intercropped; ldP = long-duration pigeonpea, mdP = medium-duration pigeonpea, LB = Lablab.

At final harvest of the legumes in the 2017/2018 season, intercrops with medium-duration pigeonpea and lablab produced significantly smaller legume DM (*P*<0.001) than intercropped long-duration pigeonpea under both contrasts (Table 3.6).

Table 3.6: Dry matter yield (t ha^{-1}) of legumes at final harvest, as affected by cropping system and fertilizer from on-farm experimental trials over two seasons in Babati, northern Tanzania. Contrasts were made for 1) sole and intercrop systems with control and +P fertilizer and 2) intercrops only at control, +P and +NP fertilizer. Results for cropping systems were averaged over sites and fertilizer levels. Results for fertilizer were averaged over sites and cropping systems. The SED shows standard error of difference between means.

Season	Cropping system	Contrasts			
		Sole and intercrops with control and +P fertilizer (t ha^{-1})	Intercrop systems with control, +P and +NP fertilizer (t ha^{-1})		
2017/2018	ldP sole	2.48a	-		
	ldP inter	2.37a	2.28a		
	mdP sole	2.51a	-		
	mdP inter	1.57b	1.56b		
	LB sole	2.36a	-		
	LB inter	1.62b	1.70b		
	SED (Cropping system)	0.23	0.20		
	Fertilizer				
	Control	2.03b	1.83		
	+P	2.36a	2.00		
	+NP	-	1.83		
	SED (Fertilizer)	0.13	ns		
2018/2019 (minus leaf fall)	Cropping system				
	ldP sole	3.04a	-		
	ldP inter	2.54bc	2.67a		
	mdP sole	3.26a	-		
	mdP inter	2.43c	2.39a		
	LB sole	2.96ab	-		
	LB inter	1.72c	1.80b		
	SED (Cropping system)	0.30	0.25		
2018/2019 (plus leaf fall)	Cropping system			Site	
			Riroda	Arri	Dareda
	ldP sole	5.11a	-	-	-
	ldP inter	3.96b	4.61a	4.43a	3.33abc
	mdP sole	4.64a	-	-	-
	mdP inter	3.25c	4.01ab	2.90bc	2.93bcd
	LB sole	3.66bc	-	-	-
	LB inter	2.34d	2.62cd	2.07d	2.49bcd
	SED (Cropping system)	0.34		ns	
	SED (Site × Cropping system)	ns		0.69	

Means within the same column under site, cropping system or fertilizer per season followed by different letters are significantly different at $P<0.05$. Inter = intercropped with maize; ldP = long-duration pigeonpea, mdP = medium-duration pigeonpea, LB = Lablab.

Under contrast 1 (all systems but only including control and +P fertilizer), significant main effects of cropping system (both seasons) and fertilizer (2017/2018) were found for DM yield of legumes (Table 3.6). All sole legumes produced similar amounts of DM. Furthermore, control plots produced significantly less DM (P=0.006) than plots where P was added. In the 2018/2019 season, sole crops consistently produced more biomass (*P*<0.001) than the intercrops with maize irrespective of whether or not fallen leaves were included in the biomass. No significant differences were observed among the three legumes in pure stand, with exception of lablab (when fallen leaves were included) which was smaller (*P*<0.001) than the other two legumes. Production including leaf fall of the legumes in intercrop with maize was significantly different (*P*<0.001) in the order; long-duration pigeonpea>medium-duration pigeonpea>lablab.

Under contrast 2 comparing only intercrop systems but including all three fertilizer treatments, significant main effect of cropping system (both seasons) and significant site × cropping system effect (2018/2019 with leaf fall) were found for DM yield of legumes (Table 3.6). No significant difference was recorded between any of the three fertilizer levels. When fallen leaves were excluded, the DM of the legumes in intercrop with maize did not differ significantly, except for lablab which produced less DM (*P*<0.001).

3.3.3.2 Legume grain yield

Legumes tended to produce greater grain yield in sole than in the corresponding intercrops, but the difference was significant (*P*<0.001) only for medium-duration pigeonpea (Fig. 3.6A). Under contrast 1 (all systems but only including control and +P fertilizer), a significant main effect of cropping system (*P*<0.001) was observed in the 2017/2018 season (Fig. 3.6A). Additionally, significant site × fertilizer (*P*=0.03) (2017/2018) (Fig. 3.6B) and site × cropping system (*P*=0.001) (2018/2019) (Fig. 3.6C) effects were observed. In the 2017/2018 season, sole lablab produced a significantly greater grain yield (0.6-1 t ha^{-1} more) than all other systems except for intercropped lablab (Fig. 3.6A). Control plots in Riroda site produced a significantly greater grain yield (0.6-0.8 t ha^{-1} more) than control plots in other sites and +P plots in Dareda site (Fig. 3.6B). In the 2018/2019 season, sole long-duration pigeonpea produced significantly greater grain yield in the Arri site (0.6-1.3 t ha^{-1} more) than all other intercrops (Fig. 3.6C).

Under contrast 2 comparing only intercrop systems but including all three fertilizer treatments, significant main effects of cropping system (2017/2018; *P*=0.04 and 2018/2019; *P*<0.001) and fertilizer (2017/2018; *P*=0.03) were observed (Fig. 3.6). In the 2017/2018 season, intercropped lablab had a grain yield 0.5 t ha^{-1} greater than intercropped medium-duration pigeonpea (Fig. 3.6D). Plots with +NP fertilizer produced significantly smaller grain yields (0.2 t ha^{-1} smaller) than control and +P plots (Fig. 3.6E). In the 2018/2019 season, intercropped long-duration pigeonpea produced 0.3-0.4 t ha^{-1} more grain than other intercrops (Fig. 3.6F).

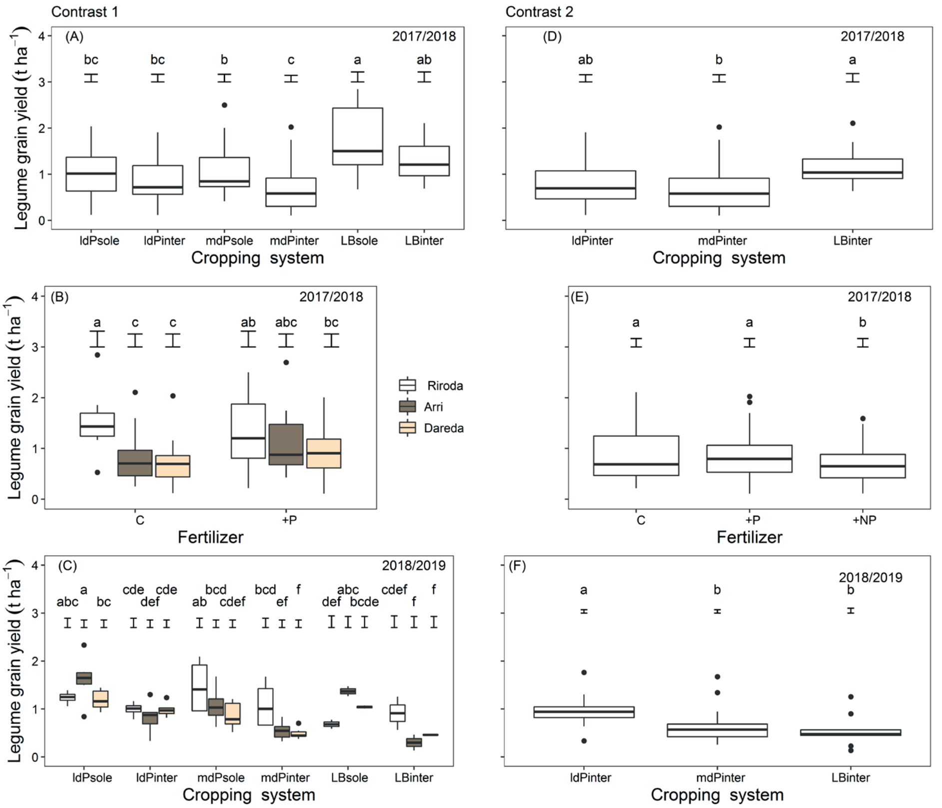

Fig. 3.6: Legume grain yields as affected by cropping system from on-farm experimental trials during the 2017/2018 (A, B, D, E) and 2018/2019 (C&F) seasons in Babati, northern Tanzania. Contrasts were made for 1) sole and intercrop systems with control and +P fertilizer (A, B, C) and 2) intercrops only at control, +P and +NP fertilizer (D, E, F). ldP= long-duration pigeonpea; mdP= medium-duration pigeonpea; LB= lablab; inter= intercrop. Mean differences at 5% significance level in the various box plots are indicated with different small letters on the upper side. Error bars indicate the standard error of means.

3.3.4 Assessing intercrop productivity

The land equivalent ratio (LER) and area time equivalent ratio (ATER) were substantially greater than one for all intercropping systems (Fig. 3.7), demonstrating a relative yield advantage of intercropping over sole cropping. Large variation in LER and ATER was observed, with average values of 1.81 and 1.85 for LER, and average of 1.39 and 1.40 for ATER in 2017/2018 and 2018/2019 seasons respectively. Significant main effects of fertilizer were observed for both LER and ATER in the two seasons ($P<0.05$).

In the 2017/2018 season, the +NP plots exhibited significantly smaller LER and ATER values than the unfertilized control (16 and 18% smaller respectively) and +P plots (18% smaller) (Fig. 3.7A, C). In the 2018/2019 season, +NP plots recorded significantly smaller LER and ATER values than control plots (22 and 23% smaller respectively) (Fig. 3.7B, D).

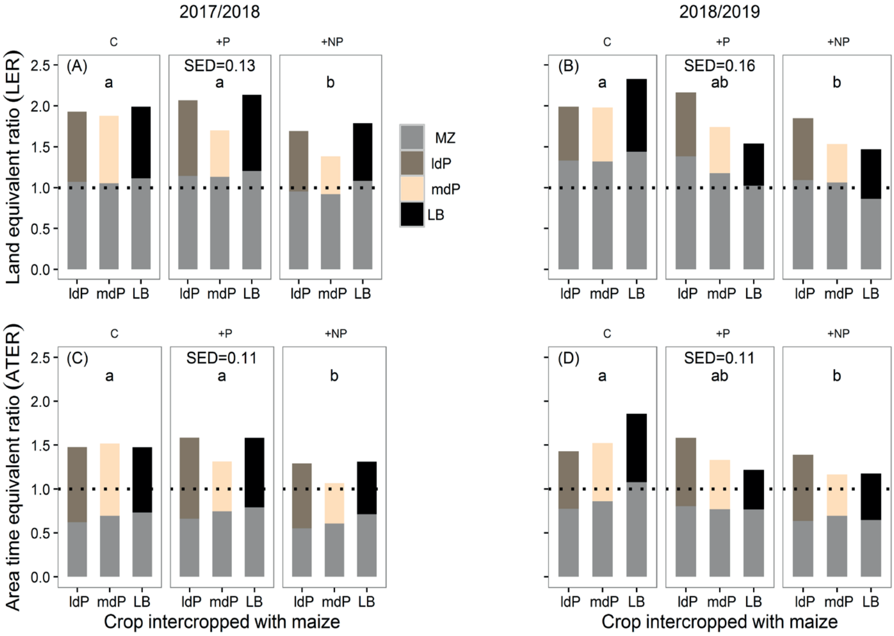

Fig. 3.7: Land equivalent ratio (LER) (A, B) and Area time equivalent ratio (ATER) (C, D) in the various cropping systems as affected by fertilizer from on-farm experimental trials during the 2017/2018 and 2018/2019 seasons in Babati, northern Tanzania. Mean differences at 5% significance level in the various fertilizer inputs are indicated with different small letters on the upper side of each box plot, per season. ns= not significant. MZ= maize; ldP= long-duration pigeonpea; mdP= medium-duration pigeonpea; LB= lablab. The black dotted horizontal line shows LER/ATER value of one. Note that for the calculations in the +NP systems, the legume pure stands in the +P treatment were used as reference. The SED shows standard error of difference between means of fertilizer treatments (C, +P and +NP).

No significant effects of site and cropping system were observed for LER and ATER. In none of intercrop systems did the species grow for exactly the same time period; LER values were always greater than the equivalent ATER value. Notably, the partial LER of maize exceeded one in almost all cases, whereas partial LER for legumes was smaller than for maize and less than one in all cases (Fig. 3.7). By contrast, average partial ATER values for maize were smaller than partial ATER for long-duration pigeonpea. This discrepancy arises because the growth time of long-duration pigeonpea was equal to that of the intercrop system, while that of maize was much shorter.

3.3.5 Residual effects of two seasons of maize-legume intercropping on maize

In the third season of experimentation, pure stands of maize were grown on all plots to investigate the residual effects of the two preceding cropping seasons. For the contrasts, a distinction was made between 1) pure stands and intercrop systems with control and +P fertilizer (all systems) and 2) pure stand of maize and intercrops that included maize at control, +P and +NP fertilizer (maize systems).

Significant main effects of site (*P*=0.04 under both contrasts), cropping system (*P*=0.003 under all systems and *P*=0.02 under maize systems), and fertilizer (*P*=0.002 under maize systems) were found for DM of the succeeding maize crop after two seasons (Fig. 3.8). The DM yield in Arri was significantly greater than in Riroda (43% and 44% greater under all systems and maize systems, respectively) (Fig. 3.8A, B). DM yield following two seasons of continuous maize was smallest and significantly less (1.6-2.5 t ha^{-1} less) than in plots that followed pure stand legumes or maize intercropped with legumes, except for maize-long duration pigeonpea (Fig. 3.8C). Within the maize systems and averaged over three fertilizer levels, yields in the continuous maize treatment were 0.9-1.3 t ha^{-1} less than in plots following maize intercropping with a legume (Fig. 3.8D). The effect of fertilizer application was evident when comparing only maize systems; plots that had no fertilizer applied (control plots) in the first two seasons produced significantly less (1.4-1.7 t ha^{-1} less) DM yield in the third season than where fertilizer was applied (Fig. 3.8F).

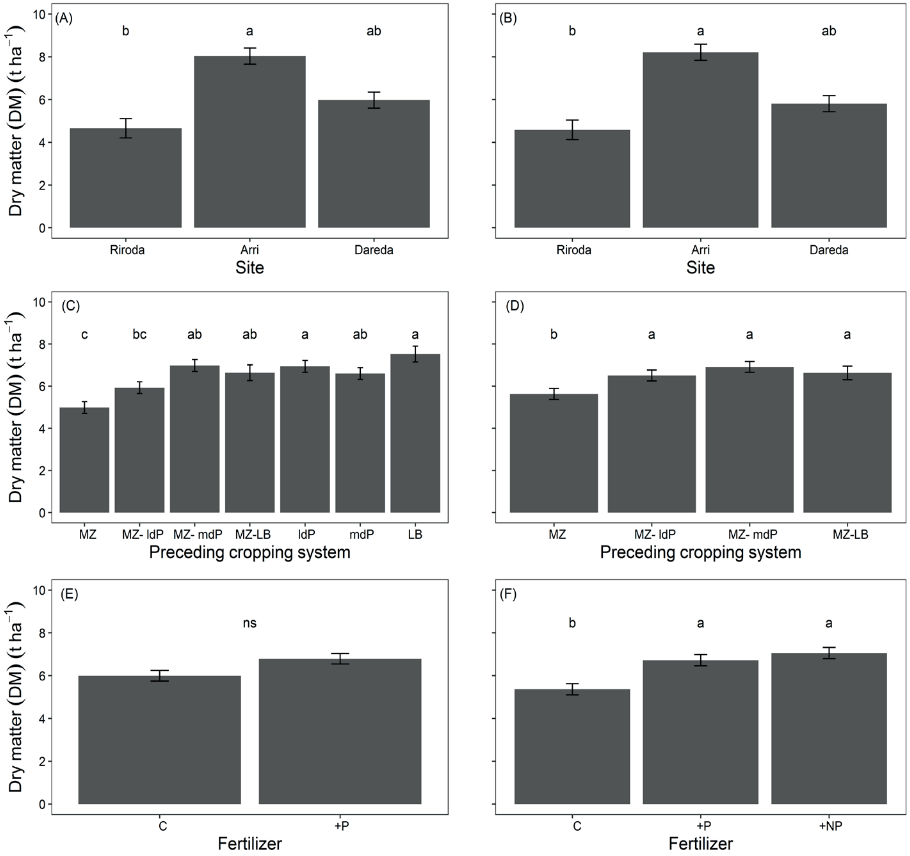

Fig. 3.8: Above ground dry matter production of a succeeding maize crop as affected by the site (A, B), preceding crop combination (C, D) and fertilizer applied in the preceding seasons (E, F) from on-farm experimental trials during the 2019/2020 season in Babati, northern Tanzania. Mean differences at 5% significance level in the various box plots are indicated with different small letters on the upper side. ns= not significant. Graphs A, C and E include all systems at two fertilizer levels (control; C and +P), while B, D and F include only systems that had maize in the preceding seasons, at all three fertilizer levels (control; C, +P, and +NP). The separation was made to account for the effect of the +NP treatment which was only present in maize-based systems. MZ= maize; LB= lablab; ldP= long-duration pigeonpea; mdP= medium-duration pigeonpea. Error bars indicate the standard error of means.

A similar pattern was observed for maize grain yield, where significant main effects of site (P=0.03 under all systems; P=0.04 under maize systems), cropping system (P<0.001 under both comparisons), and fertilizer (P<0.001 under both comparisons) were found for grain yield of the succeeding maize crop after two seasons (Fig. 3.9). Grain yield was significantly greater in Arri than in Riroda and Dareda sites (all systems: 42 and 47% greater; maize systems: 47 and 52% greater) (Fig. 3.9A, B). Grain yield following two seasons of continuous maize was smallest and significantly less (0.8-1.9 t ha^{-1} less) than in all other systems (Fig. 3.9C), and significantly less (1.0 t ha^{-1} less) than in maize-long duration pigeonpea plots (under maize systems) (Fig. 3.9D).

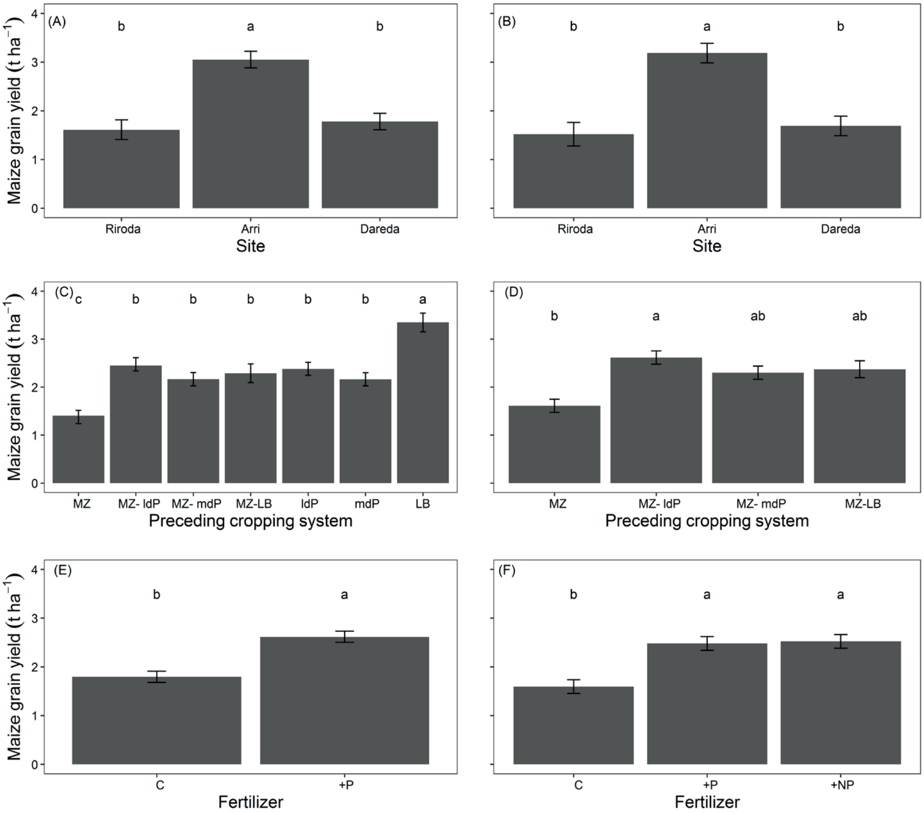

Fig. 3.9: Grain yield of a succeeding maize crop as affected by site (A, B), preceding crop combination (C, D) and fertilizer (E, F) from on-farm experimental trials during the 2019/ 2020 season in Babati, northern Tanzania. Mean differences at 5% significance level in the various box plots are indicated with different small letters on the upper side. ns= not significant. Graphs A, C and E include all systems at two fertilizer levels (control; C and +P), while B, D and F include only systems that had maize in the preceding seasons, at all three fertilizer levels (control; C, +P, and +NP). The separation was made to account for the effect of the +NP treatment which was only present in the maize-based systems. MZ= maize; LB= lablab; ldP= long-duration pigeonpea; mdP= medium-duration pigeonpea. Error bars indicate the standard error of means.

Notably, maize after lablab sole cropping exhibited the largest grain yields (0.9-1.4 t ha^{-1} larger) than those of the other two sole legume crops and the intercrops. The effect of fertilizer application was evident; plots that had no fertilizer applied (control plots) in the preceding seasons yielded significantly less grain yield in the succeeding maize crop than where fertilizer was applied under all systems (0.8 t ha^{-1} less) and maize systems (0.9 t ha^{-1} less) (Fig. 3.9E, F).

3.4 Discussion

The productivity and yields of maize in intercrops was unaffected by the presence of legumes. Although pigeonpea was sown simultaneously with maize, its slow initial growth resulted in little competition. By contrast relay-planting of lablab one month after maize was effective at managing the expected strong competitive interaction with maize. The growth and yield of the intercropped legumes was negatively influenced by the presence of maize, and full recovery of the legume between the time of maize harvest and final harvest only occurred for long-duration pigeonpea in the 2017/2018 season. However, at the aggregate system level, all intercrops performed better than sole crops as shown by the consistent LER and ATER of greater than 1. Productivity of maize following two seasons of legumes or legumes intercropped with maize was larger than in plots that had been preceded by sole maize. Furthermore, maize yields were larger in plots that had received fertilizer in the preceding seasons than control plots that had received no fertilizer.

3.4.1 Seasonal and site effects

Maize was strongly affected by the differences in rainfall between the two seasons, but the yields of the legumes were more stable. While legumes had similar grain yields in the two seasons (Table 3.6), grain yield of maize was much smaller in 2018/2019 than 2017/2018 (Figs. 3.4, 3.5). The differences were associated with differences in total rainfall (2017/2018: 467-551 mm; 2018/2019: 230-236 mm), and also possibly with differences in within season rainfall distribution. Maize is particularly drought-sensitive during the critical reproductive phase (tasselling to grain filling) (Daryanto et al., 2016), which in our study occurred at 70-90 days after sowing (DAS). This was after the drought period in 2017/2018 season, but partly coincided with the drought period in the 2018/2019 season. Legumes were less affected by dry spells than maize, presumably due to their deeper rooting (Rusinamhodzi et al., 2012). Indeed, an inspection of root profiles in this study at the reproductive growth stage of the legumes showed that both pigeonpea and lablab had a deep taproot which extended beyond 2 m depth (data not shown). Pigeonpea grown for 5 months had a taproot extending for at least 2 m below the soil surface as reported in Sekiya and Yano (2004), allowing it to extract water from deep soil layers.

The significantly smaller productivity of maize in Riroda in the 2018/2019 season is possibly due to the substantially larger sand content observed in the Riroda site (Table 3.2), as such soils are characterized by low moisture-holding ability (Nkurunziza et al., 2019). Additionally, the SOC content and total N in Riroda site were significantly smaller than at the other sites (Table 3.2), which likely resulted in low nutrient supply. Notably, the harvest index for maize in Riroda site was smaller than in the other sites in the 2018/2019 season (Fig. 3.5). This is possibly due to the extended drought period, which depressed maize growth during the reproductive stage. Contrary to maize, the productivity of legumes at final harvest was in most cases significantly larger in Riroda than in the other sites (Table 3.6, Fig. 3.6). For intercrops in 2018/2019, the significantly larger yields of legumes in Riroda could be associated with the low maize productivity in this site. However, pure legume stands in Riroda were also more productive, suggesting a more structural difference between sites. Particularly relevant is that, despite the differences in productivity, general trends related to the effects of cropping system and fertilizer use were largely consistent across sites.

3.4.2 Effects of cropping system

As noted, maize growth and yield was in most cases not affected by the presence of legumes. This is consistent with previous research on maize-pigeonpea systems showing insignificant effects of pigeonpea on maize (Myaka et al., 2006; Waddington et al., 2007; Kimaro et al., 2009; Rusinamhodzi et al., 2012). The growth duration of pigeonpea was 3-4 months longer than that of maize. Consequently, the greatest demand for water and nutrients in pigeonpea occurred after maize was harvested (Dalal, 1974), which is a form of temporal niche differentiation (TND) (Yu et al. 2015; Li et al., 2020). Relay-planting of lablab one month after maize planting allowed the maize crop to establish well before the closure of the lablab canopy. Our results demonstrate that a one-month delay in planting of lablab is sufficient to avoid the negative competitive effects on growth and yield of maize, but we cannot rule out that a slightly shorter delay would have given a similar result. Relay planting of cowpea in intercrop with maize has been shown to be an effective TND strategy (Jeranyama et al., 2000). By contrast, there was a significant reduction in legume biomass production in the intercrops at the time of maize harvest in the 2018/2019 season (Table 3.4).

The legume crop in intercropping systems only recovered partially after the removal of maize, as legume plants were released from competition. The larger yields of legumes in pure stands than intercrops can partly be attributed to the reduced radiation reaching the lower part of the intercrop canopy occupied by the legumes before maize harvest. Indeed, legumes such as lablab have a high demand for light (Cook et al., 2005). Our results revealed large differences in leaf fall between legumes; whilst pigeonpea plants shed leaves from the beginning of reproductive stage, lablab plants shed leaves only at physiological maturity when the canopy closes (data not shown). Additionally, both pigeonpea varieties produced greater senesced leaves when grown as pure stand than when intercropped with maize, and this was greater than for pure and intercropped lablab. Differences in DM production between legumes may thus be obscured if fallen leaves are omitted.

3.4.3 Effects of fertilizer

Maize and legumes showed contrasting patterns of response to fertilizer. In most cases, maize yields increased strongly in response to direct N fertilization. Although integration of legumes contributes N through atmospheric N_2-fixation, it clearly did not contribute enough to preclude the need for applying N fertilizer to maize (cf. Jeranyama et al., 2000; Giller, 2001). The increased maize growth with application of fertilizer N resulted in stronger competition with the legumes, resulting in less pigeonpea and lablab grain yield in intercrops where N fertilizer was added (Fig. 3.6). As commonly observed in SSA (Sanginga et al., 2003; Vanlauwe et al., 2019), application of P fertilizer led to increased yields (Tables 3.3, 3.6 and Fig. 3.4).

3.4.4 Intercrop productivity

Improved productivity of cropping systems is often observed when cereals are intercropped with grain legumes due to differences in functional traits and TND. In particular, differences in growing period allow complementarity in resource capture of light, water and nutrients (Li et al., 2020). In our study, establishment of the intercrop systems was timed to minimize the competitive effects of legumes on maize, with legumes benefiting from the release of competition after maize harvest. This resulted in partial LER values of maize ≥ 1 in almost all cases, whereas partial LER for legumes were always < 1. As this was an additive design, the legumes provided a supplementary yield benefit. The LER values partly reflect TND between the companion crops; productivity of intercrops increases with greater TND (Yu et al., 2015; Li et al., 2020). The positive relationship between LER and TND does not consider that the system requires a larger part of the growing season, whereas ATER accounts for the extended growth duration and provides a more meaningful comparison. The recorded ATER values > 1 indicate the suitability of the investigated cropping systems. Significantly greater LER and ATER were observed in control plots compared with plots that received N-fertilizer. This finding supports the observation that relative productivity of intercrops is usually greater at lower N- input, and TND is required to achieve greater yield at high nutrient availability (Rao et al., 1987; Li et al., 2020). Weaker growth in the control plots leads to reduced shading of the legume by the intercropped maize as reported by Kermah et al. (2017). Feng et al. (2021) also reported that in a maize-peanut intercrop, high N-input led to the vigorous growth of maize, which negatively affected peanut due to competition for light.

3.4.5 Residual effects of two seasons of maize-legume intercropping on a succeeding maize crop

The DM and grain yield of maize following two seasons of sole or intercropped legumes was up to 25 and 43% larger, respectively, than in plots with continuous maize in the preceding seasons (Figs. 3.8, 3.9). The residual benefits of maize-legume intercropping were in most cases similar to the residual benefits of pure stand legumes. The greater DM and grain yield in plots where a legume was included during the preceding seasons can be attributed to benefits associated with both residual N and non-N effects (Sanginga et al., 1999; Franke et al., 2018). In our study, we did not observe significant biotic constraints in the succeeding maize crop. Since we did not retain maize and legume stover in the field, we attribute any residual N effects to the decomposition of the legumes' roots, nodules, and fallen leaves (Ledgard and Giller, 1995). Indeed, other studies have found that contributions from fallen leaves are more important than retaining the grain legume stover after harvest (Ncube et al., 2007). Fallen pigeonpea leaves have been reported to contribute 75-95 kg N ha^{-1} to the soil in maize-pigeonpea intercrops in Malawi (Sakala, 1998). The residual effect of fertilizer was evident; in most cases, plots with +P or +NP fertilizer in the preceding seasons yielded significantly more DM and grain yield in the succeeding maize crop than control plots where fertilizer was omitted. In the control plots, the lack of fertilizer addition for three consecutive seasons could have led to soil nutrient depletion, thus reducing productivity of maize crop planted in the third season. For maize, no difference was observed between the +P and +NP fertilizer, indicating that there was no residual effect of N fertilizer from the previous seasons. In addition to the direct effects of increasing available soil P with P-fertilizer application, indirect residual benefits on the maize crop were also expected to accrue from increased biomass yields of the legumes (Sanginga et al., 2003). The DM and grain yield of the maize crop in the third season was greater in Arri than the other two sites, and the difference was significant in some cases (Figs. 3.8, 3.9 A&B). This significantly greater yield of the succeeding maize crop following two consecutive seasons of sole and intercropped legume crops at Arri is associated with the more fertile soils with larger soil organic C and N at this site (Table 3.2). Notably, no interactions were observed between site × preceding cropping system and site × fertilizer input level, indicating that the positive effects of including a legume in the maize cropping system and addition of fertilizer were robust and valid for all three sites.

3.5 Conclusions

Maize-legume intercropping systems were superior to sole maize crops, not only for the additional grain yield from legumes, but also due to their residual effect which resulted in greater productivity of the succeeding maize crop. Legumes continued to grow in the dry period after maize harvest due to their deep rooting. This contributed to consistent legume crop yields across the two seasons, whereas maize production was strongly affected by variation in seasonal rainfall. The yields of maize were increased by N-fertilizer, whereas legume yield were enhanced by P-fertilizer. Both pigeonpea varieties produced more senesced leaves when grown as pure stand than when intercropped with maize. This underscores the importance of quantifying senesced leaves for future intercropping trials, especially using methods that completely eliminate decomposition. All intercrops were relatively more productive than sole crops, with LER and ATER values consistently > 1. The effects were more evident in control plots, highlighting the advantage of intercropping under low input systems. Significant residual benefits on maize grain yields were observed after two consecutive seasons of sole and intercropped legume crops. P-fertilizer applied in the previous seasons also showed strong residual benefits. Assessment of the non-N effects of grain legumes to the associated or succeeding cereal crop which was not covered in the current study is highly recommended. Overall, our results confirm that when the component crop species in an intercrop have complementary growth patterns, temporal and spatial diversification provides a plausible pathway for ecological intensification of smallholders cropping systems.

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Chapter 4

The role of nitrogen fixation and crop N dynamics on performance and legacy effects of maize-grain legumes intercrops on smallholder farms in Tanzania

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Abstract

Maize-grain legume intercrops form an important component of the cropping systems of smallholder farmers in many parts of sub-Saharan Africa. However, the effects of cropping system and fertilizer use on nitrogen fixation and nitrogen uptake of component crops in maize-legume intercrops are not well understood. Our study sought to answer the questions: (i) what is the capacity of pigeonpea and lablab to fix atmospheric nitrogen (N_2) in sole crop and when intercropped with maize on smallholder farms across different agro-ecological conditions?; (ii) how does productivity and N-uptake by sole and intercropped maize and legumes respond to N and P fertilizer?; (iii) what are the residual effects of the sole crops, intercrops and fertilizer treatments on the productivity of a succeeding maize crop? We studied additive intercropping systems on eight farms in Babati, northern Tanzania: maize-long duration pigeonpea, maize-medium duration pigeonpea and maize-lablab, with separate pure stands for each crop, at three fertilizer rates: no fertilizer; 40 kg P ha^{-1}; and 90 kg N ha^{-1} + 40 kg P ha^{-1}. Whereas P fertilizer was applied on maize and the legumes, the N fertilizer was only applied on maize. Maize and pigeonpea were sown simultaneously, while lablab was relay-planted one month after maize. N_2-fixation was quantified using the ^{15}N natural abundance method. N_2-fixation differed among the legume species. Sole long-duration pigeonpea fixed significantly more N_2 (+20 to 63 kg ha^{-1}) than all other cropping systems, corresponding to the higher shoot dry matter and N yield of this system. The combined N uptake of maize and legume in intercrops was consistently larger than that of pure stands of either maize or the legume. In the intercrops, the amount of N accumulated by maize was in most cases larger than that of the legume. Furthermore, sole legumes had consistently larger total N uptake than the intercropped legume, whereas such consistency was lacking for maize. Application of fertilizer resulted in enhanced N uptake both in the current season (up to 40 kg N ha^{-1}) and in a succeeding maize crop (up to 71 kg N ha^{-1}). We observed positive associations between grain yield, dry matter production and total N uptake of a succeeding maize crop, and the N-fixed by legume species in the preceding season. Each kg of legume shoot N yield was associated with up to 14 kg ha^{-1} extra grain yield, 29 kg ha^{-1} extra dry matter and 0.5 kg ha^{-1} extra total N uptake of the succeeding maize crop. Our results show that inclusion of grain legumes either as pure stand or intercropped with maize has a direct positive effect on maize productivity, which is carried over into the subsequent season.

Key words: Intercropping, Pigeonpea, Lablab, Biological nitrogen fixation, N-uptake, ^{15}N natural abundance

4.1 Introduction

Smallholder farmers in sub-Saharan Africa (SSA) commonly grow grain legumes in intercrops with cereals (Myaka et al., 2006; Mugi-Ngenga et al., 2021). Legume-based cropping systems confer benefits that contribute to increased yield of succeeding cereal crops, including the contribution of N through biological N_2-fixation (Ojiem et al., 2007; Giller, 2001). The presence of a cereal exploiting soil mineral N may stimulate legumes to fix N_2 by depleting the available soil-N pool (Giller, 2001; Sanginga, 2003). This leads the legume to rely primarily on symbiotic fixation of atmospheric N_2 for its N supply, and thus to a high proportion of plant N being derived from N_2-fixation (%Ndfa) (Cardoso et al., 2007; Corre-Hellou et al., 2006; Jensen, 1996). When various cropping systems are compared, the larger amount of N derived from N_2-fixation in sole legume crops compared with intercropped legumes is mainly attributed to larger biomass accumulation in the sole legume crops (Kermah et al., 2018). Where the amount of N available in the soil is very limited, the legume yield is directly proportional to the amount of N_2 fixed (Giller, 2001).

Smallholder farmers remove most of the cereal and legume stover after grain harvest, which leads to removal of large amounts of nutrients (Bationo and Mokwunye, 1991; Giller and Cadisch, 1995). However, even where large quantities of fixed N are removed from the field with the harvested grain and stover, a considerable amount of residual N can become available in the soil through decomposition of fallen leaves, roots and nodules which can benefit succeeding crops (van Kessel and Hartley, 2000).

Legume species and varieties differ in their N_2-fixation potential. Pigeonpea (*Cajanus cajan* (L.) Millsp.) for instance is considered to have greater N_2-fixation rates compared with other legume species (Chikowo et al., 2004; Peoples et al., 2021). Pigeonpea can nodulate well and has been estimated to fix up to 90% of its N from the atmosphere (Kumar Rao et al., 1987). The greatest biomass accumulation and N_2-fixation for pigeonpea has been observed in long-duration varieties (Kumar Rao and Dart, 1987). The litter fall, which under a good pigeonpea stand could be 1-2 t ha^{-1} (Sakala, 1999; Mugi-Ngenga et al., 2022), plays a significant role in the recycling of nutrients and helps to improve soil organic matter. Lablab (*Lablab purpureus* (L.) Sweet) is another N_2-fixing legume that can be incorporated into cereal cropping systems (Cook et al., 2005). Lablab has a sprawling habit, and is generally relay-planted to reduce competition with the cereal crop. In addition, its dense canopy covers the soil thus reducing soil moisture losses while the lower leaves are shed, providing mulch to the soil (Cook et al., 2005; Rapholo et al., 2020).

In addition to the influence of legume species and variety, and cropping system (i.e., sole or intercropping), the amount of N contributed through N_2-fixation potential depends on the production environment (Giller, 2001). Environmental conditions such as temperature, rainfall, soil pH and the availability of mineral nutrients in the soil can strongly affect N_2-fixation (Peoples et al. 2009). For instance, soils low in mineral N favour an effective legume-rhizobia symbiosis (Peoples et al., 2009). On the contrary, a lack of soil available P strongly limits N_2-fixation due to reduction of root growth, photosynthesis, translocation of sugars and other functions (Giller and Cadisch, 1995; Hardarson and Atkins, 2003). Consequently, the effects of such environmental factors must be considered when developing management recommendations to optimize the growth of grain legume and enhance their contribution to soil fertility.

In SSA, grain legumes are frequently intercropped with maize, yet there remain major knowledge gaps on the influence of species and variety, cropping system (sole vs intercrop), soil conditions and fertilizer application on the performance of grain legumes and their contribution of N through N_2-fixation. To address these critical knowledge gaps, we sought to: (i) assess the capacity of pigeonpea and lablab, to fix atmospheric nitrogen (N_2) when grown in sole crop or intercropped with maize under different agro-ecological conditions; (ii) quantify the influence of N and P fertilizer on N-uptake by sole and intercropped maize and legumes (pigeonpea and lablab); (iii) assess the residual effects of the sole crops and intercrops on N uptake and associated productivity of a succeeding maize crop. We hypothesized that: (i) N_2-fixation by grain legumes is a function of legume biomass production and will therefore be larger in pure legume stands than in maize-legume intercrops; (ii) the combined N uptake of maize and legume in intercrops will be larger than that in pure stands of either maize or legumes and will be influenced by availability of soil nutrients; (iii) the productivity of a succeeding maize crop grown after two seasons of grain legumes will be related to the amount of nitrogen fixed by the preceding legumes. Experiments were conducted on smallholder farms across different agroecological zones in northern Tanzania.

4.2 Materials and methods

4.2.1 Study area description

The study was conducted in Babati district, northern Tanzania, within 04° 20-29'S, 35° 56-71'E, and elevation from 1300-1700 m above sea level (Fig. 3.1). The district was chosen due to the widespread frequency of maize-pigeonpea intercropping, following a farm-scale survey (Mugi-Ngenga et al., 2021). Three agro-ecological zones (sites) were selected, namely Riroda, Arri and Dareda. Due to constraints of area on smallholder farms, three farms were chosen per site to host the on-farm experimental trials, providing an initial sample size of nine farms, where each farm acted as a replicate (one farm-one replicate design). Annual rainfall ranges from 600 to1100 mm and the area has a single growing season from November/December to April/May. Legumes such as pigeonpea and lablab continue to grow into the dry season until September.

4.2.2 Experimental set-up and management

The experimental trials were conducted for three consecutive cropping seasons (2017/2018, 2018/2019, 2019/2020), but one farmer withdrew from the study after the 2017/2018 season. In each of the selected farms, fields were ploughed and plots measuring 10 m × 5 m delineated at planting. Paths measuring 1 m wide were left between plots. Test crops used included maize (*Zea mays* L.) Seed Co. 513 hybrid variety, dolichos lablab (*Lablab purpureus* (L.) Sweet) "Selian-Rongai" variety, and pigeonpea (*Cajanus cajan* (L.) Millsp.) long-duration ICEAP 00040 and medium-duration ICEAP 00557 varieties. Pure stands of maize, pigeonpea and lablab were planted at a spacing of 0.90 m × 0.50 m inter- and intra-row, respectively. Cereal-legume intercrops followed an additive design (i.e., plant densities of each crop being the same as in its respective sole crop), with legumes planted in the maize rows, in-between maize hills. Trials were planted with three seeds per hill for both maize and legumes and later thinned to two at two weeks after emergence. Remaining plant populations of approximately 44,444 plants ha^{-1} per crop were maintained in both pure stands and intercrops.

In the first two seasons of experimentation (2017/2018 and 2018/2019), treatment combinations comprising of cropping system (seven levels: sole crops of maize, long-duration pigeonpea, medium-duration pigeonpea, lablab and intercrops of maize with each of the three legumes) and fertilizer (three levels: control, +P and +NP) were assigned randomly to the plots within each farm per site. The NP fertilizer was not applied to the pure legume stands. Furthermore, due to constraints of area on smallholder farms, sole lablab and maize-lablab intercrops were included in only one of the three farms within a site (Table 3.1). For this reason, farms that had lablab contained a total of 18 plots, while farms where lablab was omitted had a total of 13 plots.

Pigeonpea (both long and medium duration varieties) were planted simultaneously with maize, whilst lablab was relay-planted one month after maize. Individual plots were maintained and treatments (cropping systems and fertilizer) allocated to the same plots in 2017/2018 and 2018/2019. The P fertilizer was applied at sowing in the form of triple superphosphate (TSP) at a rate of 40 kg P ha^{-1} to both maize and legumes. The N was spot-applied in the form of urea at a rate of 90 kg N ha^{-1} in three equal splits only on maize; one third at sowing, one third at four weeks after sowing, and one third at eight weeks after sowing. The residual effects of the grain legumes on the yield of a succeeding maize crop were evaluated in the third season (2019/2020), where a sole maize crop was planted on all plots following similar spacing as pure stands of the previous seasons, with no fertilizer addition.

The crops were well managed to ensure adequate control of weeds and pests. Weeding was done manually with hand hoes twice during the period when maize was growing, while after maize harvest, weeds were eliminated by uprooting. Chemical pest control was used to control fall armyworm.

4.2.3 Estimating inputs from nitrogen fixation

N_2-fixation in pigeonpea and lablab was determined by destructive sampling of legume aboveground biomass at mid-pod filling stage from a 1 m^2 sub-plot, outside the 9 m^2 net plot which was later used to determine yields at physiological maturity in both 2017/2018 and 2018/2019 seasons. The plants from the 1 m^2 sub-plot were cut at ground level, and both the total and sub-sample fresh weights were taken in the field. Sub-samples, 400-500 g in fresh weight, were taken to the laboratory at TARI-Selian, Tanzania for drying to constant weight. Ratio of dry weight over fresh weight of the sub-sample taken in the field was used to estimate shoot dry matter (DM) (kg ha^{-1}) at mid-pod filling stage. At the same time when legume samples were taken, maize and a weed species, *Commelina benghalensis* L. growing along the borders of the experimental fields were taken as reference plants in the 2017/2018 season. In the 2018/2019 season, two extra reference plants, *Bidens pilosa* L. and *Oxygonum sinuatum (*Hochst. & Steud. ex Meisn.) were collected from the experimental fields. The reference plants were used to represent the $\delta^{15}N$ of the soil N available to the legume test crops (Unkovich et al., 2008). Plant samples were dried and ground at TARI-Selian, Tanzania. Ground samples were then sent to KU-Leuven, Belgium for analysis of the N content and $\delta^{15}N$ natural abundance by isotope ratio mass spectrometer. Based on the $\delta^{15}N$ values of legumes and reference plants, the percentage of N derived from atmosphere (%Ndfa) was estimated as:

$$\%\mathrm{Ndfa} = ((\delta^{15}\mathrm{N}_{\mathrm{ref}} - \delta^{15}\mathrm{N}_{\mathrm{leg}}) / (\delta^{15}\mathrm{N}_{\mathrm{ref}} - B)) \times 100$$

where subscript ‘ref’ refers to the non-fixing reference plant species, and subscript ‘leg’ denotes the nitrogen fixing legume. Parameter B is the $\delta^{15}N$ of the same legume species reliant upon N_2 as the sole nitrogen source for growth. Following Peoples et al. (2002), the *B* value for each legume species was set equal to the smallest δ^{15}N obtained for each legume crop over the two seasons. The amount of nitrogen fixed (N_2-fixed; kg ha^{-1}) by the legume species in either pure stand or intercrop was then estimated as:

$$\mathrm{N_2fixed} = \mathrm{\%Ndfa}/100\ \times \mathrm{Shoot\ N}$$

where Shoot N (kg ha^{-1}) refers to total nitrogen in the shoot of the legume crop, which was calculated as the product of the N-content (g N/g DM) and shoot dry matter yield (Shoot DM; kg ha^{-1}):

$$\mathrm{Shoot\ N}\ = \mathrm{N\ content}\ \times \mathrm{Shoot\ DM}$$

4.2.4 Nitrogen (N) uptake

At physiological maturity of each crop (150-180, 240 and 270 days after sowing for maize and lablab, medium-duration pigeonpea and long-duration pigeonpea, respectively), all plants within the net plot were harvested by cutting them at ground level. For plots with intercrops, the legume crop was maintained after maize harvest until legume maturity. The net plot comprised of four centre rows with a length of 2.5 m in each plot, leaving at least 1.25 m on each side of the centre rows to minimize edge effects. Total fresh weight of maize and legume plants were separately taken in the field. In the 2018/2019 season, fresh weight of legumes included fallen leaves which were measured from 1m^2 sub-plots in all plots. The fallen leaves were collected every two weeks from the ground to minimize decomposition, weighed and included in the total biomass at final harvest. Maize cobs were manually separated from the stover and hand threshed. Legumes were also threshed manually to separate grains and haulms. After threshing, total fresh weight of maize and legume grains were separately taken in the field. Thereafter, 3-5 plants of maize and legumes were taken after removal of grain, cut into small pieces and weighed in the field to form a sub-sample of 400-500 g. A sub-sample for grains was also taken in the field. The sub-samples were taken to the laboratory at TARI-Selian, Tanzania for drying to constant weight for correction of moisture content and grinding. The nitrogen (N) uptake in grain (Grain N uptake; kg ha^{-1}) and total shoot (Total N uptake; kg ha^{-1}) of maize, pigeonpea and lablab was computed as:

$$\text{Grain N uptake} = \text{N content}_{\text{grain}} \times \text{dry matter of grain } (\text{DM}_{\text{grain}})$$

$$\text{Total N uptake} = \text{Grain N} + (\text{N content}_{\text{stover}} \times \text{DM}_{\text{stover}})$$

4.2.5 Calculations and statistical analysis

The legumes had different fertilizer treatments in sole and intercrops (sole crops did not have "+NP"), hence the statistical analysis for legumes was executed in two contrasts: (i) a contrast of all systems (both sole and intercrops) but only including control and +P fertilizer, and (ii) a contrast of only intercrop systems but including all three fertilizer levels: control, +P and +NP fertilizer. Mixed effects models were fitted to assess the effects of the various treatments on $\delta^{15}N$, %Ndfa, dry matter (DM) production, shoot N yield, N_2 fixed and N uptake, using the *lme4* package in R software (R Core Team, 2021). The $\delta^{15}N$, %Ndfa, DM production, shoot N yield, N_2 fixed and N uptake were used as the response variables, while site, cropping system and fertilizer were treated as fixed effects. Additionally, to account for variation in the response variables due to differences in farms, a variable 'farm' was included as a random effect in the mixed model. Significant effects of model parameters on response variables were evaluated using the *lmerTest* package available in R software (R Core Team, 2021). Significant mean differences were separated using least significant difference test (LSD test) (R Core Team, 2021) and reported at a significance level of $P < 0.05$.

To assess the association of shoot N yield of legume species measured at final harvest in the 2018/2019 season across sites and grain yield, DM production and total N uptake of a succeeding maize crop grown in the 2019/2020 season at final harvest, a linear model and the *lm* function was used. Dependent variables were grain yield/ DM production/ total N uptake of a succeeding maize crop grown in the 2019/2020 season, measured at final harvest. The independent variables were shoot N yield of legume species measured at final harvest in the 2018/2019 season, and site. All statistical analyses were performed in RStudio Version 1.0.143 (R Core Team, 2021).

4.3 Results

4.3.1 The δ15N enrichment of different species of non N_2-fixing reference plants and grain legumes

The $\delta^{15}N$ signatures of reference plants varied among species and across sites (Table 4.1). In both 2017/2018 and 2018/2019 seasons, the $\delta^{15}N$ of maize was considerably smaller than that of the weed species (*Commelina benghalensis* in 2017/2018 and *C. benghalensis*, *Bidens pilosa* and *Oxygonum sinuatum* in 2018/2019) (Table 4.1).

Table 4.1: The $\delta^{15}N$ natural abundance signatures (‰) of maize and broad-leaved non-N_2-fixing reference plants from on-farm experimental trials sampled at mid-pod filling growth stage of the legume crops during the 2017/2018 and 2018/2019 seasons in Babati, northern Tanzania.

Site	Reference plant	2017/2018		2018/2019	
		$\delta^{15}N$ (‰)		$\delta^{15}N$ (‰)	
		Maize	Weeds	Maize	Weeds
Riroda	*Zea mays*	4.57	-	6.62	-
	Commelina benghalensis	-	6.96	-	8.33
	Bidens pilosa	-	-	-	9.57
	Oxygonum sinuatum	-	-	-	11.17
	Average				9.69
Arri	*Zea mays*	5.47	-	3.05	-
	Commelina benghalensis	-	5.51	-	7.04
	Bidens pilosa	-	-	-	8.16
	Oxygonum sinuatum	-	-	-	7.16
	Average				7.45
Dareda	*Zea mays*	3.66	-	2.98	-
	Commelina benghalensis	-	7.94	-	6.29
	Bidens pilosa	-	-	-	7.36
	Oxygonum sinuatum	-	-	-	6.61
	Average				6.75

The $\delta^{15}N$ of the various legume species varied within and between sites, with larger values in 2018/2019 than 2017/2018 (Table 4.2). Notably, the use of maize as reference plant consistently resulted in values of % N derived from N_2-fixation (% Ndfa) that were smaller or equal to values obtained using broad-leaved weed species as reference, with many negative values especially in the 2018/2019 season (87% of the cases). Based on this, weed reference plants were considered more realistic for estimation of N_2-fixation than maize and were used in subsequent calculations.

Table 4.2: Shoot ^{15}N natural abundance and estimates of %N derived from atmosphere (%Ndfa) for grain legumes at mid-pod filling stage from on-farm experimental trials in the 2017/2018 and 2018/2019 seasons in Babati, Northern Tanzania. *B*-values used were set equal to the smallest values obtained per legume species over the two seasons.

				Riroda			Arri			Dareda	
Grain legumes	System	Fertilizer	Shoot $\delta^{15}N$ (‰)	% N from N_2-fixation ^{1}Mean weeds	^{2}Weeds range	Shoot $\delta^{15}N$ (‰)	% N from N_2-fixation ^{1}Mean weeds	^{2}Weeds range	Shoot $\delta^{15}N$ (‰)	% N from N_2-fixation ^{1}Mean weeds	^{2}Weeds range
2017/2018 Long-duration pigeonpea	Sole	Control	6.48	7	-	0.36	93	-	1.66	79	-
		+P	0.64	91	-	3.35	39	-	2.38	70	-
	Intercropped	Control	**-0.02**	100	-	0.52	90	-	1.01	87	-
		+P	2.27	67	-	1.63	70	-	0.62	92	-
		+NP	0.91	87	-	0.47	91	-	0.62	92	-
Medium-duration pigeonpea	Sole	Control	-0.24	88	-	1.51	60	-	1.08	75	-
		+P	0.71	77	-	1.65	58	-	**-1.18**	100	-
	Intercropped	Control	1.69	65	-	3.42	31	-	1.23	74	-
		+P	0.96	74	-	1.96	53	-	-0.40	91	-
		+NP	1.27	70	-	1.72	57	-	-0.57	93	-
Lablab	Sole	Control	2.62	54	-	2.53	45	-	1.55	71	-
		+P	1.96	63	-	5.87	-6	-	-0.50	94	-
	Intercropped	Control	1.89	63	-	0.07	83	-	-0.05	89	-
		+P	4.35	33	-	3.73	27	-	**-1.03**	100	-
		+NP	3.83	39	-	2.60	45	-	2.28	63	-
2018/2019 Long-duration pigeonpea	Sole	Control	2.89	70	65-74	2.03	73	71-75	2.47	63	61-66
		+P	3.78	61	54-66	3.38	55	52-58	0.85	87	86-88
	Intercropped	Control	1.72	82	79-84	1.91	74	73-76	0.26	96	96-96
		+P	3.67	62	56-67	3.46	53	51-57	3.38	50	46-54
		+NP	3.61	63	57-68	4.34	42	38-47	1.38	79	78-81
Medium-duration pigeonpea	Sole	Control	8.49	11	-2-22	3.36	47	45-51	4.62	27	22-32
		+P	8.33	13	0-23	5.18	26	23-32	3.42	42	38-46
	Intercropped	Control	4.10	51	44-57	4.25	37	34-42	3.28	44	40-48
		+P	3.72	55	48-60	4.80	31	27-36	3.26	44	40-48
		+NP	4.51	48	40-54	3.62	44	42-49	2.95	48	45-52
Lablab	Sole	Control	3.95	54	47-59	3.48	47	44-51	3.32	44	41-48
		+P	3.13	61	56-66	7.25	2	-3-10	1.24	71	69-73
	Intercropped	Control	3.29	60	54-65	4.75	32	28-37	0.56	80	78-81
		+P	2.76	65	60-69	5.16	27	23-33	0.54	80	79-81
		+NP	4.74	46	38-53	3.91	42	39-46	0.71	78	76-79

^{1} %Ndfa calculated using the mean shoot $\delta^{15}N$ values of the broad-leaved weed reference plants collected in that year and presented in Table 4.2. ^{2}Range of %Ndfa values calculated using individual broad-leaved weed species presented in Table 4.2 as reference plants. The *B*- values used in estimation of % N from N_2-fixation were -0.02, -1.18 and -1.03 for long-duration pigeonpea, medium-duration pigeonpea and lablab respectively (values in bold in the table).

4.3.2 Differences in %Ndfa between legumes

In the 2018/2019 season, %Ndfa differed significantly among cropping systems ($P<0.05$) for both contrasts. Under contrast 1 comparing all systems (both sole and intercrops) but only including control and +P fertilizer, mean %Ndfa of long-duration pigeonpea in pure stand and intercropped with maize (68-69%) was larger ($P<0.05$) than that of sole lablab (46%) and medium-duration pigeonpea (28-44%) in the 2018/2019 season (Fig. 4.1a). Under contrast 2 (intercrop systems with control, +P and +NP fertilizer treatments), mean %Ndfa of intercropped long-duration pigeonpea (67%) and lablab (56%) was larger ($P<0.05$) than that of intercropped medium-duration pigeonpea (45%) in the 2018/2019 season. Further, in the 2017/2018 season, mean %Ndfa of long-duration pigeonpea (86%) was larger ($P<0.05$) than that of medium-duration pigeonpea (67%) and lablab (60%) (Fig. 4.1b).

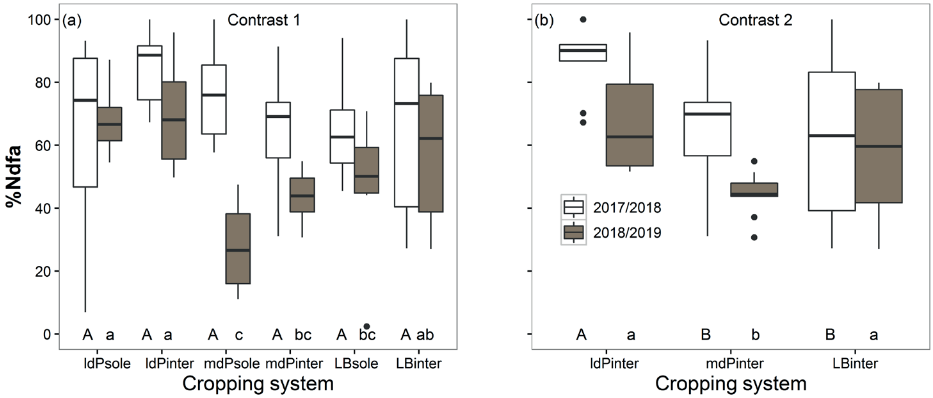

Fig. 4.1: The % N derived from atmosphere (%Ndfa) in grain legumes in sole stands and intercrops for two contrasts measured at mid-pod filling stage of legumes from on-farm experimental trials during the 2017/2018 and 2018/2019 seasons in Babati, northern Tanzania. Contrast 1 (a) represents sole and intercrops averaged over control and +P fertilizer. Contrast 2 (b) represents intercrop systems averaged over control, +P and +NP fertilizer. ldP = long-duration pigeonpea; mdP = medium-duration pigeonpea; LB = lablab; inter = intercropped. Mean differences at 5% significance level are indicated below each box plot, with upper case for 2017/2018 and lower case for 2018/2019.

In the 2018/2019 season, a significant sampling time × cropping system interaction was observed for %Ndfa of legumes. The shoot %Ndfa was larger ($P < 0.05$) at final harvest than at mid-pod filling stage for medium-duration pigeonpea under both contrasts (Fig. 4.2).

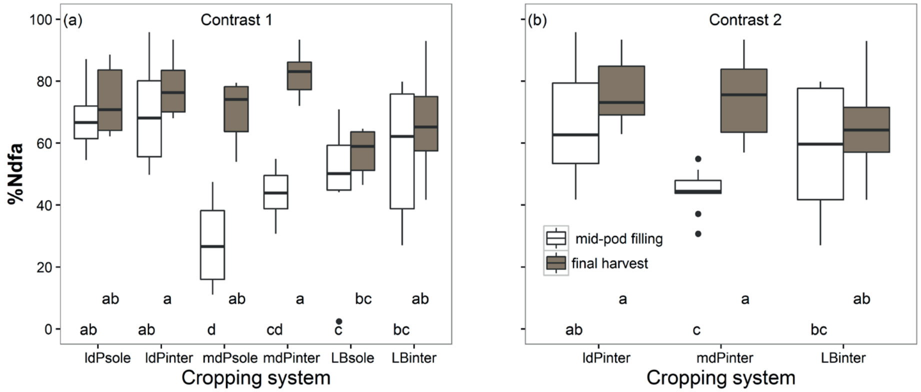

Fig. 4.2: Comparison of the percentage of N derived from atmosphere (%Ndfa) in sole stands and intercrops of grain legumes measured at mid-pod filling and final harvest stage of legumes. Data was collected from on-farm experimental trials during the 2018/2019 season in Babati, northern Tanzania. Contrast 1 (a) represents data for sole and intercrops averaged over control and +P fertilizer. Contrast 2 (b) represents intercrop systems averaged over control, +P and +NP fertilizer. ldP = long-duration pigeonpea; mdP = medium-duration pigeonpea; LB = lablab; inter = intercropped. Mean differences at 5% significance level are indicated on the lower side of each box plot.

Further, in the 2018/2019 season, a significant sampling time × cropping system interaction was observed for shoot N yield of the legumes under contrast 1 comparing all systems (both sole and intercrops) but only including control and +P fertilizer. The shoot N yield for sole long-duration pigeonpea was larger ($P < 0.05$) at mid-pod filling stage than at final harvest, while the opposite was true for sole lablab (Fig. 4.3).

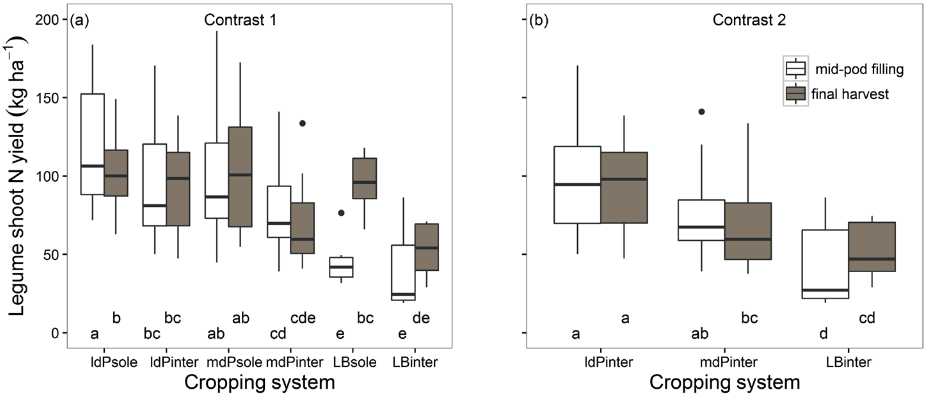

Fig. 4.3: Comparison of shoot N yield in sole stands and intercrops of grain legumes measured at mid-pod filling and final harvest stage of legumes (including fallen leaves). Data was collected from on-farm experimental trials during the 2018/2019 season in Babati, northern Tanzania. Contrast 1 (a) represents data for sole and intercrops averaged over control and +P fertilizer. Contrast 2 (b) represents intercrop systems averaged over control, +P and +NP fertilizer. ldP = long-duration pigeonpea; mdP = medium-duration pigeonpea; LB = lablab; inter = intercropped. Mean differences at 5% significance level are indicated on the lower side of each box plot.

4.3.3 Shoot N and N_2-fixed at mid-pod filling stage

A significant main effect of site was observed for shoot DM, shoot N yield and N_2-fixed in the 2017/2018 season under both contrasts, whereby the values were significantly larger in Riroda than in Arri and Dareda (Table 4.3). Between the Arri and Dareda sites, a significantly larger shoot N-yield was observed in the former.

Under contrast 1, comparing all systems (both sole and intercrops) but only including control and +P fertilizer, a significant main effect of cropping system was found for shoot DM and shoot N yield in both seasons. Such a significant main effect was also observed for the amount of N_2-fixed in the 2018/2019 season (Table 4.3). In the 2017/2018 season, shoot DM and N-yield of sole long-duration pigeonpea was significantly larger than that of all other cropping systems (0.98 to 1.76 t ha^{-1} DM and 27 to 49 kg ha^{-1} N-yield). In the 2018/2019 season, sole long-duration pigeonpea had significantly larger shoot DM (0.78 to 2.74 t ha^{-1}), N-yield (33 to 86 kg ha^{-1}), and N_2-fixed (20 to 63 kg ha^{-1}) in almost all cases. In the 2017/2018 season, there was no direct effect of fertilizer for each of the cropping systems, but depending on the fertilizer treatment, there was a difference across cropping systems; In control plots, intercropped long-duration pigeonpea fixed a significantly larger amount of N_2 than medium-duration pigeonpea (up to +48 kg ha^{-1}) and sole lablab (+42 kg ha^{-1}). Additionally, sole long-duration pigeonpea fixed significantly more N_2 than intercropped medium-duration pigeonpea (+31 kg ha^{-1}). With the addition of P fertilizer, sole long-duration pigeonpea fixed significantly more N_2 than lablab (up to +51 kg ha^{-1}), while intercropped long-duration pigeonpea fixed 39 kg ha^{-1} more N_2 than intercropped lablab.

Under contrast 2 (intercrop systems with control, +P and +NP fertilizer treatments), significant main effects of site (for shoot N yield and N_2-fixed) and cropping system (for shoot DM and shoot N) were observed in the 2018/2019 season (Table 4.3). Shoot N yield and N_2-fixed were significantly larger in Riroda than in Dareda. Further, intercropped long-duration pigeonpea had a significantly larger shoot DM (0.75 and 1.52 t ha^{-1}) than the other two intercrops, but its shoot N-yield was only significantly larger than that of intercropped lablab (50 kg ha^{-1}). Furthermore, significant cropping system × fertilizer interaction was observed for N_2-fixed in both seasons (Table 4.3). In the 2017/ 2018 season, with no fertilizer addition, intercropped long-duration pigeonpea fixed significantly greater amount of N_2 than medium-duration pigeonpea (+48 kg ha^{-1}) and lablab (+27 kg ha^{-1}). With addition of P-fertilizer, intercropped long-duration pigeonpea fixed significantly greater amount of N_2 than intercropped lablab (+39 kg ha^{-1}). In the 2018/2019 season, a significantly greater amount of N_2 was fixed in control plots, than in plots where fertilizer was applied to intercropped long-duration pigeonpea (up to +32 kg ha^{-1}). Furthermore, intercropped long-duration pigeonpea fixed significantly more N_2 than intercropped lablab with no fertilizer (+60 kg N ha^{-1}) and with NP fertilizer (+29 kg N ha^{-1}). With no fertilizer addition, long-duration pigeonpea also fixed significantly more N_2 (+50 kg N ha^{-1}) than medium-duration pigeonpea.

Table 4.3: Shoot dry matter (shoot DM), shoot N and amount of nitrogen fixed (N_2-fixed) by long-duration pigeonpea, medium-duration pigeonpea and lablab at three sites (S; Riroda, Arri and Dareda), as sole crop or intercropped with maize (Cropping system; CS), at three fertilization levels (F; Control(C), +P and +NP)) measured at mid-pod filling stage in the 2017/2018 and 2018/2019 seasons in Babati, Northern Tanzania. Contrast 1 represents data for sole and intercrops averaged over control and +P fertilizer, while contrast 2 represents intercrop systems averaged over control, +P and +NP fertilizer.

Season	Treatment	Contrast 1 Sole and intercrops with control and +P fertilizer Shoot DM (t/ha)	 Shoot N (kg ha^{-1})	 N_2-fixed (kg ha^{-1})		Contrast 2 Intercrop systems with control, +P and +NP fertilizer Shoot DM (t/ha)	 Shoot N (kg ha^{-1})	 N_2-fixed (kg ha^{-1})		
2017/2018	*Site*									
	Riroda	3.64a	107a	71a		3.16a	98a	72a		
	Arri	2.45b	79b	47b		2.25b	76b	50b		
	Dareda	2.04b	59c	49b		1.84b	52c	45b		
	Cropping system			C	+P	ns	ns	Control	+P	+NP
	ldP sole	3.69a	111a	63abc	74ab	-	-	-	-	-
	ldP inter	2.71b	84b	80a	62abc	2.56	82	80a	62ab	69ab
	mdP sole	2.30b	64c	49bcd	48bcd	-	-	-	-	-
	mdP inter	2.14b	63c	32d	50bcd	2.16	71	32c	50bc	45bc
	LB sole	2.26b	77bc	38bcd	34cd	-	-	-	-	-
	LB inter	1.93b	62c	53abcd	23d	2.21	64	53bc	23c	44bc
2018/2019	*Site*	ns	ns	ns		ns				
	Riroda	3.00	107	56		3.00	112a	67a		
	Arri	2.28	68	33		2.31	74ab	36b		
	Dareda	2.38	71	41		1.93	63b	39b		
	Cropping system							Control	+P	+NP
	ldP sole	4.02a	126a	85a		-	-	-	-	-
	ldP inter	2.92b	93bc	65b		2.91a	94a	81a	49bc	57b
	mdP sole	3.24b	104ab	28c		-	-	-	-	-
	mdP inter	2.05c	78cd	34c		2.16b	79a	31c	37bc	38bc
	LB sole	1.77c	46de	22c		-	-	-	-	-
	LB inter	1.28c	40e	24c		1.39c	44b	21c	28c	28c

ns = not significant; inter = intercropped; Means within the same column per shoot DM, shoot N and N_2-fixed under site or cropping system followed by different letters per contrast are significantly different at $P<0.05$.

4.3.4 Grain N and total N uptake in the 2018/2019 season

Under contrast 1 comparing all systems but only including control and +P fertilizer, significant main effects of fertilizer use were found for total N uptake (Table 4.4). P-fertilized plots had larger total N uptake values than control plots (+14 kg N ha^{-1}). Furthermore, a significant site × cropping system interaction was observed for grain and total N uptake (Table 4.4). The effect of site was significant, but this differed among cropping systems for both grain and total N uptake. Grain N uptake for maize-long duration pigeonpea was significantly larger in Dareda than in the other sites (up to +16 kg N ha^{-1}), while that of sole medium-duration pigeonpea was larger in Riroda than in Dareda (+18 kg N ha^{-1}). Sole long-duration pigeonpea had larger total N uptake in Riroda than in Dareda (+43 kg N ha^{-1}). Similarly, sole medium-duration pigeonpea had larger total N uptake in Riroda than in Dareda (+78 kg N ha^{-1}). Notably, the combined total N uptake by maize and legume in intercrops was significantly larger than that of their respective sole crops in most cases, in Arri and Dareda sites.

Table 4.4: Grain and total N uptakes (kg ha^{-1}) of long-duration pigeonpea (ldP), medium-duration pigeonpea (mdP), lablab (LB) and maize (MZ) under different cropping systems and fertilizer across three sites, measured at respective final harvest of each crop species in the 2018/2019 season in Babati, northern Tanzania. The N uptake of intercrops is computed using the combined uptake by maize and legume.

Treatment	Contrast 1						Contrast 2	
	Sole and intercrops with control and +P fertilizer						Systems that had maize with control, +P and +NP fertilizer	
	Grain N			[1]Total N			Grain N	[1]Total N
	(kg ha^{-1})							
Cropping system	Riroda	Arri	Dareda	Riroda	Arri	Dareda		
Sole ldP	33bcde	37bcd	28cde	129cde	102efgh	86fgh	-	-
Intercropped	43b	42b	58a	181ab	184ab	188a	55a	198a
ldP + MZ	(25,18)	(19,23)	(23,35)	(117,64)	(99,85)	(73,115)	(24,31)	(93,105)
Sole mdP	39bc	26cdef	21ef	148bcd	110defg	70gh	-	-
Intercropped	41bc	38bcd	42b	159abc	138cd	155bc	43b	156b
mdP + MZ	(26,15)	(15,23)	(11,31)	(100,59)	(62,76)	(56,99)	(15,28)	(67,89)
Sole LB	22cdef	42bc	28cde	107defg	106defgh	74fgh	-	-
Intercropped	42bc	40bc	38bcd	119cdef	152bcd	113cdefg	40b	134b
LB + MZ	(29,13)	(10,30)	(12,26)	(69,50)	(50,102)	(41,72)	(16,24)	(53,81)
Sole MZ	11f	22def	28cde	56h	79fgh	89fgh	24c	89c
Fertilizer	ns							
Control	32			114b			35b	127b
+P	36			130a			39b	145b
+NP	-			-			47a	167a

ns = not significant. [1]Total N computed as sum of grain and stover N uptake. Means within the same column per yield component (grain and total N) under cropping system or fertilizer followed by different letters per contrast are significantly different at $P<0.05$. Values in brackets represent contribution of component crops to N uptake in intercrops; first value in the brackets is for the legume and second value is for maize. MZ = Maize, ldP = long-duration pigeonpea, mdP = medium-duration pigeonpea, LB = Lablab.

In intercrops, the contribution of maize to total N uptake was larger than that of legume in almost all cases, except in Riroda site. Additionally, while there was no consistent pattern in total N uptake by sole and intercropped maize, sole legumes had consistently larger total N uptake values than intercropped legumes (Table 4.4).

Under contrast 2 comparing systems that had maize as a sole crop or intercropped with a legume with control, +P and +NP fertilizer, significant main effects of cropping system and fertilizer use were found. Grain and total N uptake for maize-long duration pigeonpea was significantly larger than for all other maize systems (up to +31 kg ha^{-1} grain N and +109 kg ha^{-1} total N), with sole maize recording the lowest N uptake. Plots with NP fertilizer had larger grain and total N uptake than control and +P plots (up to

+12 kg ha^{-1} grain N and +40 kg ha^{-1} total N, respectively), with the least total N uptake in the control plots (Table 4.4).

4.3.5 Residual effect of two seasons of legumes on N uptake of a succeeding maize crop

In the third season of experimentation (2019/2020 season), a sole crop of maize was grown on all plots with no fertilizer addition, to investigate residual effects of the treatments implemented in the two preceding cropping seasons. Under contrast 1 comparing all systems included in the preceding seasons but only control and +P fertilizer plots, significant main effects of cropping system and fertilizer use were found for grain N uptake (kg ha^{-1}) by a succeeding maize crop (Table 4.5). Grain N uptake of succeeding maize was significantly less following two seasons of continuous maize than in plots that had sole or intercropped legume (up to -23 kg N ha^{-1}) in almost all cases. Additionally, maize crop grown in plots where no fertilizer had been applied in the preceding seasons (control plots) had significantly less grain N uptake (-10 kg N ha^{-1}) than where P fertilizer had been applied. Furthermore, significant site × cropping system and cropping system × fertilizer interactions were found for total N uptake (kg ha^{-1}) of the succeeding maize crop (Table 4.5). There was an effect of site, which differed per cropping system; total N uptake of maize following two seasons of sole and intercropped pigeonpea and sole lablab was significantly larger in Arri than in Riroda site. The effect of previous fertilizer application differed between cropping systems; previous +P plots recorded larger uptake than control plots, in most cases. Notably, maize following two seasons of sole maize was consistently among the systems with lowest total N uptake, regardless of fertilizer treatment (Table 4.5).

Table 4.5: Grain and total N uptakes (kg ha^{-1}) of a succeeding maize crop after two seasons of legumes' inclusion, measured at final harvesting in the 2019/2020 season in Babati, northern Tanzania.

Treatments in the preceding seasons	Contrast 1				Contrast 2			
	Sole and intercrops with control and +P fertilizer				Systems that had maize with control, +P and +NP fertilizer			
	Grain N (kg ha^{-1})	[1]Total N (kg ha^{-1})			Grain N (kg ha^{-1})	[1]Total N (kg ha^{-1})		
		Riroda	Arri	Dareda		Riroda	Arri	Dareda
Cropping system (CS)								
Sole ldP	24b	63de	111bc	103bc	-	-	-	-
Intercropped ldP + MZ	26b	58de	105bc	76cde	27a	58d	116b	80cd
Sole mdP	23b	57de	100bc	62de	-	-	-	-
Intercropped mdP + MZ	23b	57de	127ab	63de	26a	53d	157a	70cd
Sole LB	37a	66de	156a	113abc	-	-	-	-
Intercropped LB + MZ	21bc	72cde	98bcd	89bcde	23ab	68cd	108bc	88bcd
Sole MZ	14c	46e	72cde	65de	17b	47d	86cd	67d
Fertilizer (F)						Riroda	Arri	Dareda
Control	18b	[2]NA			16b	47d	81c	64cd
+P	28a	[2]NA			27a	65cd	121b	76c
+NP	-	-			27a	52d	152a	81c
CS × F	-	Control		+P	-		-	
Sole ldP	-	104a		88bc	-		-	
Intercropped ldP + MZ	-	67de		98ab	-		-	
Sole mdP	-	80bc		70cd	-		-	
Intercropped mdP + MZ	-	74cd		97ab	-		-	
Sole LB	-	110a		114a	-		-	
Intercropped LB + MZ	-	76cd		97ab	-		-	
Sole MZ	-	54e		72cd	-		-	

Means within the same column per yield component (grain N and total N) under cropping system or fertilizer followed by different letters per contrast are significantly different at $P<0.05$. MZ = Maize, ldP = long-duration pigeonpea, mdP = medium-duration pigeonpea, LB = Lablab. [1] Total N computed as sum of grain and stover N uptake. [2] NA shows that main effects are significant, but interactions are also significant and therefore main effects are not presented.

Under contrast 2 comparing systems that had sole or intercropped maize with control, +P and +NP fertilizer plots in the preceding seasons, significant main effects of cropping system and fertilizer use were found for grain N uptake (kg ha^{-1}) by a succeeding maize crop (Table 4.5). A trend similar to contrast 1 was observed, where grain N uptake of a succeeding maize crop following two seasons of continuous maize was significantly less than in plots that followed maize intercropped with pigeonpea (up to -10 kg N ha^{-1}).

Additionally, succeeding maize crop in plots that had no fertilizer in the preceding seasons had significantly less grain N uptake (up to -11 kg ha^{-1}) than where fertilizer had been applied. Furthermore, significant site × cropping system and site × fertilizer interactions were found for total N uptake (kg ha^{-1}) of the succeeding maize crop (Table 4.5). There was an effect of site, which differed per cropping system; total N uptake of maize following two seasons of intercropped pigeonpea was significantly larger in Arri than in Riroda site. Additionally, total N uptake at the Arri site differed significantly across plots that had different fertilizer treatments in the order of +NP>+P>control, and was significantly larger than in Riroda (across all fertilizer treatments), and Dareda (in +P and +NP plots).

4.3.6 The N residual effect of two seasons of legumes inclusion on a succeeding maize crop

There were positive associations between shoot N yield of legume species measured at final harvest in the 2018/2019 season and grain yield, DM production and total N uptake of a succeeding maize crop grown in the 2019/2020 season at final harvest (Fig. 4.4). Plots that had a larger amount of legume-N in the previous season yielded larger grain, DM and N uptake of maize in the succeeding season. The association of shoot N yield of legumes and grain yield, DM production and total N uptake of a succeeding maize crop varied from one site to another (Fig. 4.4). Each kg of legume shoot N yield was associated with about 14, 14 and 5 kg ha^{-1} grain, 29, 19 and 11 kg ha^{-1} DM, 0.47, 0.27 and 0.13 kg ha^{-1} of total N uptake of a succeeding maize crop in Arri, Dareda and Riroda site, respectively. Notably, grain yield, DM production and total N uptake of a succeeding maize crop was consistently largest in the Arri site and smallest in the Riroda site (Fig. 4.4).

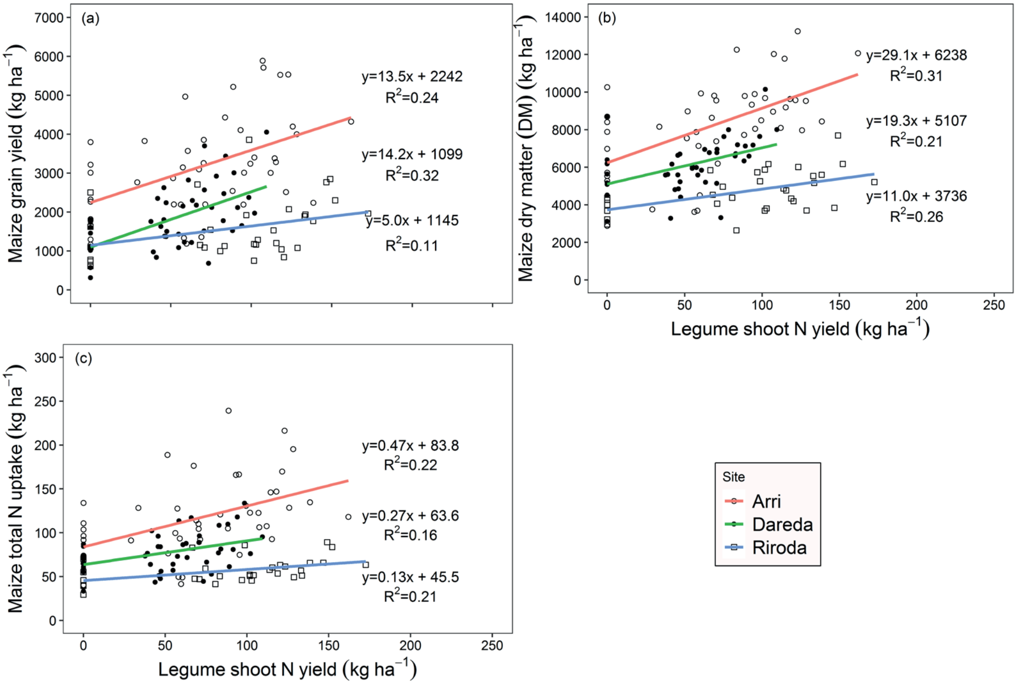

Fig. 4.4: Relationship between shoot N yield of legumes and the grain yield (a), DM production (b) and total N uptake (c) of maize. The shoot N yield of legumes was measured at final harvest of legumes during the 2018/2019 season, while grain yield, DM production and total N uptake of maize were measured at final harvest of a succeeding maize crop in the 2019/2020 season from on-farm experimental trials across three sites (Arri, Dareda and Riroda) in Babati, northern Tanzania. Lines indicate the linear regressions of dependent against independent variables per site (based on significant legume shoot N yield × site interactions at $P < 0.05$).

4.4 Discussion

Nitrogen fixation, N uptake and residual effects were investigated in various maize-legume intercropping systems, with different fertilizer applications in three agroecological zones. The capacity of the grain legumes to fix atmospheric nitrogen (N_2) differed among the legumes. Long-duration pigeonpea which had the highest shoot DM was consistently among the treatments with the largest amount of N_2-fixed. In most instances, no difference in N_2 fixation of a legume species in pure stand and intercrop was observed. In the 2018/2019 season, the combined N uptake of maize and legume in intercrops was consistently larger than that of pure stands of either maize or the legume. In intercrops, the contribution of maize to total N uptake was in most cases larger than that of the legume. Additionally, sole legumes had consistently larger total N uptake than the intercropped legume. Maize responded to N fertilizer application and produced significantly more grain N and total N uptake in N-fertilized plots than in the control. The grain yield, dry matter production and total N uptake of a succeeding maize crop (2019/2020) were all positively correlated with legume shoot N yield of the previous year.

4.4.1 The $\delta^{15}N$ enrichment of reference weed species

The potential range of $\delta^{15}N$ enrichment of reference plants used in estimation of proportion of N derived from atmosphere (%Ndfa) using the natural abundance method was presented (Table 4.1). The $\delta^{15}N$ signatures of reference plants differed among species over the two growing seasons (Table 4.1). The implication of reference species on the calculations of %Ndfa are most important when the $\delta^{15}N$ of the reference is less than 4‰ (Unkovich et al., 2008; Peoples et al., 2009). Notably, in our study, the values for maize were below 4‰ in 50% of the cases, whereas for weed species were all above 4‰ (Table 4.1). Using the values of $\delta^{15}N$ enrichment of maize in computation of %Ndfa resulted in some negative values (data not shown) and unrealistic estimates of N_2-fixed. We therefore used the $\delta^{15}N$ enrichments of the broad-leaved weeds to estimate N_2-fixation. Indeed, use of the mean $\delta^{15}N$ enrichment of several reference weed species in each site has been shown to give more reliable estimates of N_2-fixed (Nyemba and Dakora, 2005; Ojiem et al., 2007). The variation among reference plants is a possible indication that the $\delta^{15}N$ of the available soil N was not uniform with depth and time (Ojiem et al., 2007; Unkovich et al., 2008). In relation to Peoples et al. (2002), the observed variation in $\delta^{15}N$ signatures of reference plants could further be associated with spatial heterogeneity resulting from non-uniform application of mineral N fertilizers by farmers in the study area, and uneven deposition of manure and urine by livestock which graze freely in the fields after the harvest period.

4.4.2 N_2-fixation by a range of sole and intercropped grain legumes

Biological nitrogen fixation (BNF) in the field is influenced by farm management practices and environmental conditions (Giller, 2001; Peoples et al., 2009). We quantified N_2-fixation under various cropping systems (sole and intercrops) and fertilizer use (control, +P and +NP) across three sites. Clear differences were found across sites, where shoot N yield and N_2-fixed were larger in Riroda than in Arri and Dareda site (Table 4.3). This is consistent with key soil attributes in these study sites, particularly pH and total N. The pH in Riroda (6.38) was higher than in Arri (6.13) and Dareda site (5.83). A negative relationship between N_2 fixation and soil acidity (low pH) is to be expected, since low pH is known to limit the survival and persistence of rhizobia

(Hungria and Vargas, 2000). In addition, smaller values of total soil N were present in Riroda (0.06) than in Arri (0.14) and Dareda site (0.10). High concentrations of available soil N delay the formation of nodules and the onset of N_2 fixation, thus reducing the total amount of N_2 fixed (van Kessel and Hartley, 2000).

Across cropping systems, the percentage N derived from N_2-fixation (%Ndfa) was comparable between sole crops and intercrops of similar legume species (Fig. 4.1). This result contrasts with other studies which have reported larger %Ndfa in intercropped than in sole-crop legumes (Jensen, 1996; Giller, 2001; Corre-Hellou et al., 2006; Cardoso et al., 2007), the explanation being that competition for soil N with maize would stimulate N_2 fixation by legumes (Cardoso et al., 2007; Corre-Hellou et al., 2006; Jensen, 1996). However, other studies reported results similar to ours (Ofori et al., 1987; Van Kessel and Roskoski, 1988; Kermah et al., 2018). In the 2018/2019 season, the mean %Ndfa of long-duration pigeonpea was larger than that of medium-duration pigeonpea and sole lablab (Fig. 4.1). The difference in %Ndfa across legume species are in line with Giller (2001), where %Ndfa was reported to vary enormously between grain legume crops and between different genotypes of the same crop. In the 2018/2019 season, we noted that the shoot %Ndfa for medium duration pigeonpea was larger at final harvest than at mid-pod filling stage. This is partly due to the compensatory growth of the legumes in the dry season after maize has been harvested (Mugi- Ngenga et al., 2022). It is also likely that there is little mineral N available in the soil after maize has taken it up, increasing the dependence of the legume on symbiotic fixation of atmospheric N_2 for its N supply and thus a high %Ndfa (Cardoso et al., 2007; Corre-Hellou et al., 2006; Jensen, 1996).

Similar to %Ndfa, the N_2-fixed was comparable between sole crops and intercrops of similar legume species in the 2017/2018 and 2018/2019 season (Table 4.3). The only exception was long-duration pigeonpea in the 2018/2019 season, for which the amount of N_2-fixed was significantly larger in sole long-duration pigeonpea than in all other systems. Shoot DM and the corresponding shoot N yield were also larger in sole long-duration pigeonpea (Table 4.3). N_2-fixation has often been reported to be strongly associated with shoot DM (Adu-Gyamfi et al., 2007; Peoples et al., 2009; Unkovich et al., 2010; Kermah et al., 2018). In the 2018/2019 season, lablab consistently recorded the smallest shoot-N yield and amount of N_2 fixed (Table 4.3). The larger amount of shoot-N yield and N_2 fixed by pigeonpea as compared to lablab is consistent with the reported greater potential of pigeonpea to fix nitrogen compared to other legume species (Chikowo et al., 2004). In addition, differences in the amount of N_2-fixation have been reported to vary with length of the growing season, whereby genotypes that take longer to mature (e.g., long-duration pigeonpea in our study) have a substantially longer period to nodulate and fix N_2 (Giller, 2001).

In general, no effect of fertilizer was observed in the 2017/2018 season. In the 2018/2019 season, a significant effect of fertilizer was found where intercropped long-duration pigeonpea in control plots fixed up to 32 kg N ha^{-1} more than plots where fertilizer was applied. Elsewhere, application of N-fertilizer was reported to decrease the contribution from N_2-fixation (van Kessel and Hartley, 2000). Indeed, soils low in mineral N favour effective legume-rhizobia symbiosis (Giller and Cadisch, 1995).

4.4.3 Nitrogen uptake in sole and intercropped maize, pigeonpea and lablab

In the 2018/2019 season when N uptake was monitored, the combined N uptake of maize and legume in intercrops was in most cases larger than that by pure stands of either maize or legume as reported by Hauggard-Nielsen et al. (2008) and Kermah et al. (2018). The contribution of maize to total N uptake was in most cases larger than that of the legume (Table 4.4). This is an indication of the 'sparing' of N by legumes (less N removal than by the cereal) (Vanlauwe et al., 2019), as indicated by legumes taking less N from the soil in intercrops than in sole crops (data not shown). Furthermore, sole legumes had consistently larger total N uptake values than the intercropped legumes, but for maize there was no clear difference. This is possibly because the growth of maize was hardly affected by the presence of legumes, whereas the growth and yield of the intercropped legumes was negatively influenced by the presence of maize (Mugi-Ngenga et al., 2022). The larger combined N uptake in intercrops than in sole crops was due to the larger combined grain and biomass production in intercrops (Zhang et al., 2015), which results in more efficient uptake of N in the intercropped systems (Baldé et al., 2011). Maize responded to N fertilizer and produced significantly more grain N (up to 12 kg N ha^{-1}) and had larger total N uptake (up to 40 kg N ha^{-1}) in N-fertilized plots than in the control (Table 4.4).

4.4.4 The N residual effect of two seasons of legumes on the succeeding maize crop

In the third season of experimentation (2019/2020 season), grain N uptake of a succeeding maize crop following two seasons of continuous maize was smallest and in most cases significantly less than in plots where pure-stand legumes or maize intercropped with legumes had been grown. This reflects a carry-over effect of available N by legumes (Kermah et al., 2018). Residual effects of fertilizer were also evident, as plots that had received P and NP fertilizer in the preceding seasons had enhanced maize grain N uptake. Rurangwa et al. (2018) also reported enhanced N uptake of the subsequent maize where legumes had been grown with P and manure in the preceding seasons. Total N uptake of the succeeding maize crop was larger in Arri than in the other two sites (Table 4.5). We attribute this to more fertile soil in Arri that had greater soil organic carbon and total N contents than the other two sites (Mugi-Ngenga et al., 2022). Furthermore, maize following two seasons of sole maize was always among the systems with lowest total N uptake, regardless of fertilizer treatment.

There were clear positive associations between shoot N yield of legume species measured at final harvest in the 2018/2019 season, and grain yield, DM production and total N uptake of a succeeding maize crop grown in the 2019/2020 season (Fig. 4.4). This suggests that legume shoot N yield was the primary cause of the residual effects on the succeeding maize, although we cannot rule out the contribution of non-N effects such as suppression of pests and diseases (Sanginga, 2003; Franke et al., 2018). Notably, there were much poorer responses to N in Riroda compared with the other sites ($P<0.05$) (Fig. 4.4). This was probably due to a period of flooding that occurred in the low-lying Riroda site during the second and third season, which depressed maize growth.

4.5 Conclusions

The amount of N_2 fixed by pigeonpea and lablab was highly variable in pure stands and intercrops. Long-duration pigeonpea had the largest dry matter accumulation and amount of N_2. This is attributed to its longer growing period than the medium-duration pigeonpea and lablab. The contribution of maize to total N uptake in intercrops was in most cases larger than that of the legumes, an indication of the ‘sparing’ of soil N by legumes, as soil N uptake by legumes was less in intercrops than in sole crops. This highlights the suitability of maize-legume intercrops for effective and efficient N use in low input systems. We also observed strong residual benefits of both sole and intercropped legumes on N uptake and associated productivity of a succeeding maize crop. Overall, our results show that intercropping grain legumes with maize is a promising pathway for diversification and intensification of cropping systems, with benefits that carry over into subsequent seasons.

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Chapter 5

The role of inter-specific competition for water in maize-legume intercropping systems in northern Tanzania

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Abstract

Maize-legume intercropping is common in northern-Tanzania. Legumes species choice and relative introduction time are chosen such that negative effects of legumes on maize productivity are minimal. Productivity of the legume is mainly realized after maize harvest, with the legume utilizing the remaining soil moisture reserves. There is limited information on the role of inter-specific competition for water in these maize-legume intercropping systems. For this reason, we analysed experimentally determined shoot dry matter production of maize, long-duration pigeonpea, medium-duration pigeonpea and lablab, in pure stand and intercrop. The experiments were conducted in Arri-site, Babati, northern-Tanzania in two consecutive seasons, which greatly differed in amount of precipitation (2017/2018; 551 mm and 2018/2019; 236 mm). For the analysis, we constructed a transparent, parameter-sparse, crop growth model which was calibrated based on data from sole crops. The model calculates radiation interception × radiation-use efficiency as affected by water balance, by using the tipping bucket principle. When simulated actual soil moisture content fell below a species-specific critical level, the ratio between actual and potential transpiration decreased. Reduction in crop growth rate was set proportional to the reduction in transpiration rate. Generally, there was good agreement between simulated and observed shoot biomass of maize and legumes. With a rooting depth of 6 dm, maize was sensitive to annual precipitation, resulting in a 3.5 t ha^{-1} (34 %) reduction in simulated shoot dry matter production in the second drier season. In contrast, the legumes, with a rooting depth of 20 dm, did not experience water shortage in either of the two seasons, resulting in nearly identical shoot dry matter production in both seasons. Explorative simulations assuming legumes to have shorter rooting depth confirmed the importance of this trait for avoiding water stress, with simulated reductions in dry matter production of 23-34 % for the legumes at an assumed rooting depth of 6 dm. Lablab, which was only introduced 30 days after maize sowing had a reduced shoot dry matter production in the second season due to poor crop establishment. Modelling of inter-specific competition confirmed that maize-legume intercropping is a productive system, resulting in over-yielding, mainly due to temporal (extended light capture) and spatial (rooting depth) niche differentiation. Maize was hardly influenced by the legumes, except in the season with low precipitation, when water shortage for maize was further aggravated. Maize influenced the legumes only through competition for light, as the rooting system of the legume allowed it to utilize the water stored in deeper soil layers. Among the legumes, lablab was characterized by greater radiation capture ability. Delayed introduction of lablab in intercrop with maize was sufficient for avoiding severe light competition of the legume on maize, but this delay also resulted in poor establishment of lablab in the second season. Consequently, simultaneous maize-pigeonpea intercropping seems a more reliable option. Our analysis emphasizes the important role of the deep rooting system of the legume for the success of maize-legume intercropping systems under rain-fed conditions.

Key words: Intercrops, simulation, soil-water balance, rooting depth, radiation interception, radiation-use efficiency

5.1 Introduction

Cereal-legume intercropping is common throughout East and Southern Africa (Giller, 2001), where farmers commonly intercrop to secure food production by averting risks and to maximize utilisation of available resources. Intercropping is defined as the cultivation of two or more crop species simultaneously in the same field (Vandermeer, 1989). Typically, cereal crops such as maize (*Zea mays*), pearl millet (*Pennisetum glaucum*) and sorghum (*Sorghum bicolor*) are the primary plant species, whereas legume crops such as pigeonpea (*Cajanus cajan*), dolichos lablab (*Lablab purpureus*), common bean (*Phaseolus vulgaris*), cowpea (*Vigna unguiculata*), groundnut (*Arachis hypogaea*), and soybean (*Glycine max*) are the secondary species (Kimaro et al., 2009; Mugi-Ngenga et al., 2021; Myaka et al., 2006). In intercrops, inter-specific competition between component crop species will occur, and apart from productivity and nitrogen fixing ability, competitive interactions and potential for complementarity between the component species is key in determining performance of the systems (Lithourgidis et al., 2011). Consequently, to maximize the benefits of a cereal and a legume crop in intercrops, targeting of spatial and temporal complementarity between the two component crops is paramount, such that the species do not fully compete for resources (Vandermeer, 1989). When component crops are complementary in terms of their temporal growth pattern, above-ground canopy structure, rooting patterns and associated dynamics of resource acquisition, intercropping enables a more efficient utilisation of available resources (e.g. sunlight, moisture and soil nutrients) (Willey, 1990). This has been widely shown to result to relatively greater yields than when crops are grown as pure stands (Mucheru-Muna et al., 2010; Li et al., 2020).

Considering the difficulties associated with clearly unravelling how component crop species in intercrops combine and compete for resources such as water and radiation, crop growth simulation modelling provides useful complementary tool to experiments (Corre-Hellou et al., 2009). Simulation modelling of resource competition offers an opportunity to investigate effects of environment on productivity of crops grown as sole or intercrops, as these appear important to determine suitability of component crops to a specific environment (Keatinge et al., 1998; Qi et al., 2000). Several intercrop models exist which simulate competition between two intercropped species (Baumann et al., 2002; Brisson et al., 2004; Tsubo et al., 2005; Gou et al., 2017). However, the models usually require a large number of parameters, and acquiring those is difficult for experiments in smallholder farming conditions with limited experimental facilities.

Recently, experiments on maize-grain legume intercrops typical of northern Tanzania were conducted. Pigeonpea (long and medium-duration) and lablab were intercropped with maize. The aim was to create a situation where growth of maize, as the primary crop, was hardly affected by the legumes, and legumes would be mainly productive after maize harvest. For that reason, the less competitive pigeonpea was sown simultaneously with maize, whereas the more competitive lablab was sown one month after maize as a relay intercrop. Maize was sown at the same density as in the sole crop, and the legume was added within the maize rows (i.e., as an additive intercrop).

Determining the suitability of component crops to a specific environment is important not only during the period when the component crops are growing together, but also after harvest of the early maturing crop, after which the later maturing crop has to make do with the remaining resources. Whereas the competitive relation for radiation between the component crops can be readily observed in the field, it is less evident how below-ground competition for water influences the performance of the intercrop. Does presence of the legume species create or intensify any water shortage that is encountered during the first part of the growing season? Does the legume crop suffer from water consumption by the maize crop in the intercrop or after maize harvest? And how important is a deep rooting system for the legume? To address these questions, a simple radiation interception × radiation-use efficiency model was created and extended with a soil water balance. The simplicity of the model allowed its parameterization based on pure stands of maize and legumes that were simultaneously grown with the intercrops, at the same site. Rather than a predictive tool, this model was designed as a tool for analysis to better appreciate the role of water as an important resource for productivity of the intercrop. Our main objective was to ascertain to what extent the productivity of maize – grain legume systems in northern Tanzania is limited by water availability. The specific objectives were (i) to develop a transparent, parameter-sparse model for analysis of observed productivity of maize, pigeonpea and lablab under rain-fed conditions; (ii) to parameterize the model based on observations of the crops in pure stand; (iii) to determine if maize production in northern Tanzania was restricted by water availability; (iv) to explore whether rooting depth of grain legumes is key to their dry matter production, and; (v) to examine if the combination of maize and legumes in an intercropping system aggravates the dependence of the system on water availability.

5.2 Materials and methods

5.2.1 Field experiments

Data collected during two seasons of field experiments (2017/2018 and 2018/2019) in Arri site, Babati district, northern Tanzania were used to calibrate and test the intercrop model. The site lies in 04^{o} 21’S, 35^{o} 56’E, at an elevation of 1601 m above sea level.

Within the site, three farms were selected to host the experimental trials. In each of the selected farms, fields were ploughed and plots measuring 10 m × 5 m delineated just before planting. Paths measuring 1 m wide were left in between adjacent plots. Test crops used included maize (*Zea mays* L.) Seed Co. 513 hybrid variety, dolichos lablab (*Lablab purpureus* (L.) Sweet) "Selian-Rongai" variety, and pigeonpea (*Cajanus cajan* (L.) Millsp.) long ICEAP 00040 and medium duration ICEAP 00557 varieties. Pure stands of maize, pigeonpea and lablab were planted at a spacing of 0.90 m × 0.50 m inter- and intra-row, respectively. Maize-legume intercrops followed an additive design, with legumes planted in the maize rows, in-between maize hills, maintaining the same plant population for each crop in sole and intercrops (Mugi-Ngenga et al., 2022). Trials were planted with three seeds per hill for both maize and legumes and later thinned to two plants, two weeks after emergence to reduce competition for growth factors. Remaining plant populations of approximately 44,444 plants ha^{-1} per crop were maintained in both pure stands and intercrops. Fertilizer was applied in three treatments: no fertilizer; 40 kg P ha^{-1}; and 90 kg N ha^{-1} + 40 kg P ha^{-1}. Whereas P fertilizer was applied on maize and the legumes, the N fertilizer was spot applied only on maize, thus the NP fertilizer treatment was not applied in the pure legume stands. Further details on experimental design and field management are presented in Mugi-Ngenga et al. (2022). For the current analyses, observations on maize and grain legumes were averaged over the fertilizer treatments.

5.2.2 Above-ground dry matter, plant height and maize leaf area

Above-ground dry matter was assessed through monthly destructive sampling across the two growing seasons. The data were obtained from a 1 m^2 sub-plot, outside the 9 m^2 net plot which was later used to determine yields at physiological maturity. The plants from the 1 m^2 sub-plot were cut at ground level, chopped and both the total and sub-sample fresh weights taken in the field. Sub-samples, 400-500 g in fresh weight, were taken to the laboratory at TARI-Selian, Tanzania for drying to constant weight. During the first season, sub-plots measuring 1 m × 1 m were demarcated in the net plot on all plots containing legumes, and wire-mesh litter traps placed on the ground to capture fallen leaves from the legumes. The litter traps were stolen before the first sampling could be done. Consequently, fallen leaves were not quantified in the first season. In the second season, we installed similar sub-plots in all plots (1 m × 1 m), with no wire mesh. Every two weeks we collected the leaves from the ground to minimize decomposition, weighed and included them in the final determination of biomass yield.

The development of plant height and leaf area index (LAI) of maize was monitored through non-destructive allometric leaf measurements, on a monthly basis throughout the growing seasons from the 9 m^2 net plot. Plant height of four plants, randomly selected within the net plot, was measured, and the average value determined (note that the product of LAI and light extinction coefficient for legumes was monitored indirectly by means of light measurements, (see section "Radiation-use efficiency (RUE) and extinction coefficient (k)"). The plants were marked for subsequent measurements during the season. LAI was estimated using non-destructive methods based on a relationship between parameters that could easily be measured on the canopy, specifically leaf length, leaf width and number of leaves of the 4 plants that were used in determining plant height. Number of leaves was determined by counting the total number from each plant. Leaf length (m) and width (m) were taken from the four sampled plants, by taking measurements of four leaves per plant. LAI for maize in m^2 m^{-2} in pure stands and intercrops was then estimated using an allometric relation for area of a single leaf (LA; m^2/leaf):

$$\mathrm{LA} = 0.78 \times \text{leaf length} \times \text{leaf width}$$

where 0.78 is a crop-specific coefficient for maize (Cunha et al., 2018).

Based on LA, the LAI of a crop was estimated as:

$$\mathrm{LAI} = \frac{\mathrm{LA} \times \mathrm{n}}{\mathrm{GA}}$$

where n is the total number of leaves on the four sampled plants, and GA (m^2) is the ground area available for the four sampled plants, based on a plant population count from a 1 m^2 sub-plot within the 9 m^2 net plot area.

5.2.3 Radiation interception determination and calculations

Radiation interception (RI) was estimated through measurements of photosynthetically active radiation (PAR) in each plot above and below the crop canopy at monthly intervals, up to the time of final harvest. These observations were made at the same date as the destructive samplings. Measurements were taken using an AccuPAR LP-80 Ceptometer (Decagon Devices, Inc.; Northeast Hopkins Court, Pullman, USA). The device allowed for simultaneous PAR measurements above and below the canopy, by wiring to the AccuPAR an external PAR sensor held above the canopy with a tripod stand. The external PAR sensor is a high quality PAR-quantum sensor, so we avoided taking measurements when the sun was strong and near the horizon, and focused on taking measurements within two hours either side of the solar noon. To allow for a good representation of the overall area, measurements of PAR were taken at 14 positions in each plot; eight perpendicular to the rows and six parallel to the rows. At each location, values of PAR below the canopy were measured by placing the AccuPAR at 12.5 cm intervals perpendicular to the rows, and 15 cm interval parallel to the rows. For each sampling date, a comparison of the average PAR readings perpendicular and those parallel to the rows was made by plotting the values measured across the two seasons. Based on the close similarity of both averages, the study used the mean of those two averages as the basis for calculating the fraction of radiation intercepted (fRI):

$$\mathrm{fRI} = 1 - \frac{\mathrm{I_{below}}}{\mathrm{I_0}}$$

where I_{below} is the measured PAR below the canopy and I_o is the incident PAR above the canopy, both expressed in μmols m^{-2} s^{-1}.

Further, daily intercepted amount of radiation (RI; MJ $m^{-2}d^{-1}$) of each species in pure stand and the intercrops was estimated as:

$$\mathrm{RI} = \mathrm{fRI} \times \mathrm{DIR} \times 0.5$$

in which DIR is the daily global incoming radiation in MJ m^{-2} d^{-1} and 0.5 is the factor to convert global radiation into PAR. Daily values of fRI were obtained by linearly interpolating between consecutive measurements. Daily incoming radiation data were sourced from NASA power (https://power.larc.nasa.gov/data-access-viewer/), using GPS coordinates of the site.

5.2.4 Radiation-use efficiency (RUE) and extinction coefficient (*k*)

Radiation-use efficiency (RUE; g/MJ PAR) was obtained as the slope of the linear regression of above-ground dry-matter production on cumulative radiation intercepted by sole crops. For this analysis, the data set used for maize and the legumes covered the duration until the time of maize harvest.

The radiation extinction coefficient (*k*) of maize, which is an indicator of the efficiency at which the canopy absorbs radiation, was derived from LAI and radiation interception measurements in sole maize, by fitting Beer's law (Monsi and Saeki, 2005) as follows;

$$\mathrm{k} = \frac{-\ln\ (\mathrm{I_{below}}/\ \mathrm{I_0}\ )}{\mathrm{LAI}}$$

Since LAI, and consequently also the radiation extinction coefficient (*k*), of the legumes was difficult to determine, an alternative procedure was developed to estimate the contribution of radiation interception of the legumes in the intercrops during the combined growth period of maize and legume. Following the principles of Spitters and Aerts (1983), total radiation interception of the two component species, as well as the distribution of intercepted radiation over the component species was related to the product of LAI and *k*. For maize, LAI was directly estimated, whereas the *k* was indirectly determined based on radiation interception and LAI in pure stands. For the legumes, the fraction of radiation intercepted in pure stands was used to determine the product of LAI and *k*, using Beer's law:

$$\mathrm{fRI} = \left(1.-\mathrm{e}^{-\mathrm{k.LAI}}\right) \rightarrow \mathrm{k.LAI} = \ -\ln(1.-\mathrm{fRI})$$

The product *k*.LAI was then related to the dry weight of the legumes obtained at the corresponding sampling date. Only observations in the first half of the growing season, before leaf fall set in, were used to derive this relationship. Non-linear regression in R, using a quadratic function, was used to describe the relationship between shoot dry weight and *k*.LAI.

5.2.5 Model description

A simple radiation interception x radiation utilization model for crop production, extended with a water balance following the tipping bucket principle, was constructed. The model operates with a time step of one day. The daily amount of intercepted radiation (RI; MJ $m^{-2}d^{-1}$) is obtained by multiplying fRI with daily incoming radiation. The fRI is derived through linear interpolation between the monthly field observations of light interception. Multiplication of RI with the species-specific RUE results in the potential daily shoot growth rate. A species-specific transpiration coefficient of 200 L kg^{-1} biomass for maize (Mudenda et al., 2017) and 300 L kg^{-1} biomass for the legumes (Siddique et al., 2001) is used to obtain the transpiration requirement (potential transpiration rate; mm d^{-1}). A soil water balance was included in the model. The maximum available amount of water in the rooting zone of the soil is calculated based on rooting depth and the volumetric water content at field capacity. Similarly, the volumetric water content at wilting point is used to calculate the minimum amount of soil water at which plants are still able to retrieve water from the profile. The volumetric water content at field capacity and wilting point were set at 0.21 and 0.13 corresponding to the values for a sandy-loam soil, following Ngetich (2012). Based on profile pits dug in the field, rooting depth was set to 6 dm for maize and to 20 dm for the legumes. Rainfall, which was recorded on-site, is used as input to the soil water balance, whereas water is lost through transpiration of the crop and percolation, which occurs if the actual amount of soil water in the rooting zone exceeds the maximum amount. When actual soil moisture content falls below the critical level, the ratio between actual and potential transpiration decreases linearly from 1. at the critical level, to 0. at wilting point (Doorenbos and Kassam, 1979). The soil moisture depletion factor (p) depicts the critical soil water content below which the ratio between actual and potential transpiration rate drops below 1. This factor is positioned between field capacity (corresponding to $p = 0.$) and wilting point (corresponding to $p = 1.$), and was set to 0.8 for maize (Ngetich, 2012) and 0.65 for the legume species (Webber et al., 2006). In the model, the reduction in crop growth rate is set equal to the reduction in transpiration rate (van Keulen, 1975). Actual daily shoot growth rate is thus obtained by multiplying the earlier-obtained potential shoot growth rate with the ratio between actual and potential transpiration. Daily actual crop growth rate is accumulated over time until maturity of the crop, to arrive at the total shoot dry matter production. Maturity of both maize and legumes were based on field observations.

For the simulation of the mixed systems, the model was extended. All crop growth and transpiration algorithms were doubled, with one assigned to the maize and the other to the legume. In an additional routine, the total radiation interception of the mixed canopy is determined and distributed over the two competing species. For both crops, a homogenous leaf area distribution in both the horizontal and the vertical plane, ranging from maximum plant height to zero at the soil surface, is assumed. Plant height of both species as measured in the field is used as input to the model. The canopy is dissected in a top and a bottom layer, with the top layer ranging from the maximum height of the tallest species to the maximum height of the shortest species, and the bottom layer consists of the remaining part of the mixed canopy. Light interception in the top layer of the canopy is calculated using Beer's law, using the product of light extinction coefficient (k) and the LAI of the tallest species in the top layer and by accounting for a canopy reflection of 7%. The radiation transmitted through the top-layer is used as incoming radiation for the bottom layer. Here, a two-step approach for light interception and distribution over the two competing species is used, following Spitters and Aerts (1983). First, total radiation interception of the bottom layer is calculated using Beer's law, using the sum of the product of k and LAI for both species. In a second step, this amount of absorbed radiation is distributed over the two species based on the share of each species in the sum of the product of *k* and LAI. The daily amount of radiation intercepted by the tallest species was then obtained through summation of its radiation interception in the top and bottom layers. For the shortest species, radiation interception comprises only of the amount intercepted in the bottom layer. For maize, both *k* and LAI are introduced as forcing functions, corresponding to field observations (LAI), or as derived based on field observations (*k*). For the legumes the product of *k* and LAI is derived using the earlier determined species-specific relation between *k*.LAI and observed shoot dry weight. Linear interpolation between observed shoot dry weight provides the input variable for this function. In the period after harvest of the maize crop, radiation interception for the legume, as the only remaining species, is directly calculated based on observed fRI following the procedure used in the sole crop models.

Next to a distinction in two canopy layers, the model for simulating intercrop productivity was equipped with two rooting zones. With the upper layer ranging from soil surface to the maximum rooting depth of the maize (6 dm), and the lower layer ranging from thereon to the maximum rooting depth of the deeper rooting legume species (20 dm). If rain is such that soil water in the upper layer exceeds the amount corresponding to that at field capacity, the excess water flows to the deeper layer. If the amount of water in the deeper layer exceeds the storage capacity of the second layer, the amount of water in excess percolates further to deeper layers, out of reach for the crops. For maize, the calculation of the ratio actual/potential transpiration rate follows the same procedure as in the sole crop model. For the legume, the potential transpiration demand is divided over both layers proportional to the depth of each layer. If the actual water content in the top layer is insufficient to meet the potential transpiration demand attributed to that layer, the difference is added to the potential demand accredited to the second layer. Actual transpiration rate of the legumes in both layers is then calculated in a similar way as described above. Actual transpiration rate of the legumes from the first and the second layer are added and compared with the potential transpiration rate. This ratio represents the multiplication factor for obtaining the actual shoot growth rate based on potential shoot growth rate. Since transpiration during the early growth stages is not that large, it is assumed that the legumes have access to the second layer from the start of the simulation.

5.2.6 Simulations

The model analysis started with simulations of pure stands for both growing seasons. At the start of these simulations, the soil was assumed to be at field capacity. The simulated time course of shoot dry matter production was compared with field observations to evaluate the accuracy of the model. Additionally, the time course of the amount of soil water was investigated to check whether, at any point in time, the soil water content fell below the critical level. For each of the simulations, a soil water balance was composed to establish the fate of the water. The initial amount of soil water and precipitation made up the input, whereas the output was comprised of transpiration, percolation, and final amount of soil water. Finally, the simulated shoot dry weight under the prevailing precipitation was compared with the result of a simulation in which the ratio actual/potential transpiration was fixed to one. The difference in shoot dry weight between both simulations provides insight into the degree to which water, as a growth limiting factor, influenced biomass production. A model exploration was made to gain insight into the importance of rooting depth for shoot dry matter production of the legumes. Simulations with reduced rooting depth were made, whereby in consecutive runs rooting depth was reduced by steps of 3.5 dm, from the original setting of 20 dm to a rooting depth of 6 dm, similar to that of maize.

Simulations of maize-grain legume intercrops in the first season did not show a major worsening of water shortage for neither the maize nor the legumes. Focus was therefore put on the second season, when precipitation (236 mm) was considerably less than in the first season (551 mm). The objective was to investigate whether, under conditions of low water supply and compared to pure stands, the combination of maize and legumes in an intercropping system would aggravate the dependence of the system on water availability. The time course of shoot dry matter production for both maize and the accompanying legume were compared with field observations to determine the accuracy of the model. Development of soil water amount in the upper and lower-level soil compartment was inspected to check whether, throughout the growing season, soil water content had dropped below the critical level of maize or the legume. Also, for these simulations, a soil water balance was constructed, with transpiration rate split between maize and legume. Additional explorative simulations were run for the maize in intercrop with all three legume species, with a restricted rooting depth of the legumes of 6 dm. Finally, shoot dry matter production of maize and all three legume species were compared for pure stands in the first season (high amount of precipitation), pure stands in the second season (low amount of precipitation), and intercrops in the second season with legume rooting depths of 20 and 6 dm. The comparisons among these simulation outcomes were used to establish the importance of precipitation for maize and legume shoot dry matter production, and to determine the degree of competition between maize and legume under conditions of scarce water supply.

5.3 Results

5.3.1 Field observations and parameter estimation

5.3.1.1 Radiation interception

For sole crops, maize reached its maximum radiation interception earlier than the legumes. This was at around 90 days after emergence (DAE) (Fig. 5.1a), while for legume species the maximum radiation interception was attained at around 150 DAE across the two seasons (Fig. 5.1b, c, d). For intercrops, the time at which maximum radiation interception was reached depended on which legume species was intercropped with maize. Here, the time of maximum radiation interception ranged from 120-180 DAE (Fig. 5.1e, f, g). Notably, the largest maximum radiation interception was in sole and intercropped lablab in the first season, where more than 90% of the radiation was intercepted (Fig. 5.1d, g). Though the fraction of radiation intercepted (fRI) and its pattern over the growing season was almost identical over the two years of experimentation for sole and intercropped pigeonpea, this was not the case for sole maize, and lablab (sole and intercropped). For those two crops, the intercepted radiation was markedly less in the second season than in the first season.

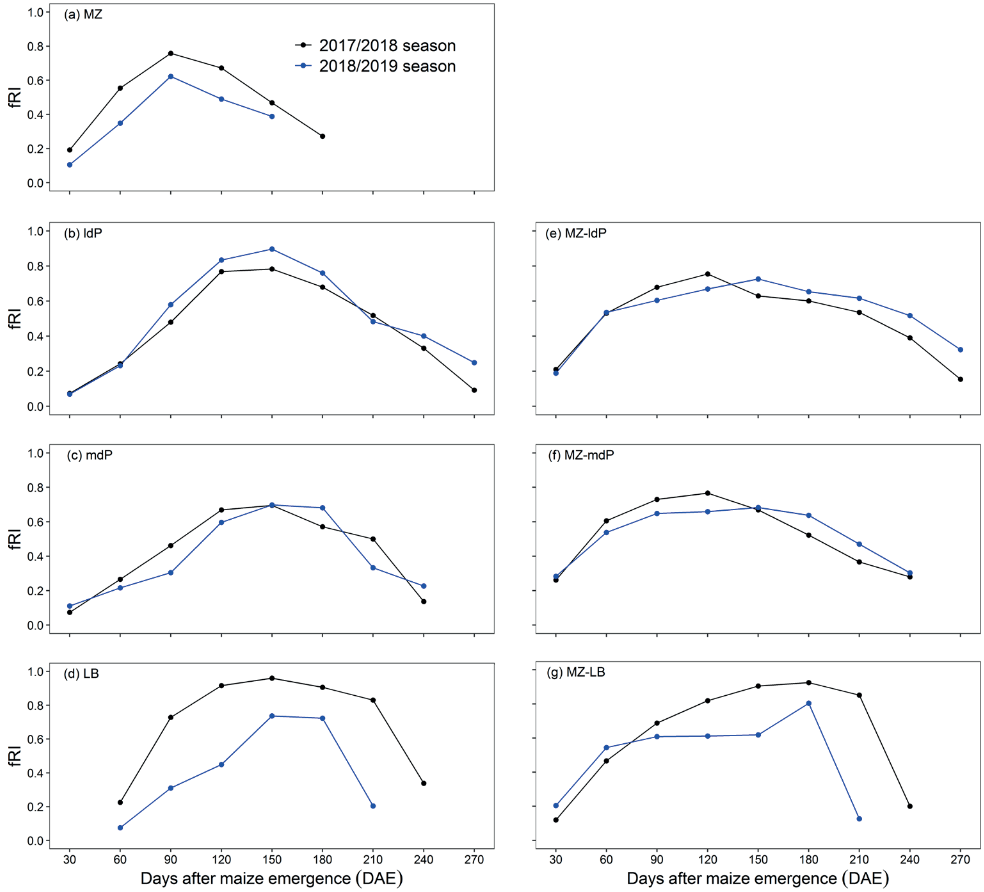

Fig. 5.1: Fraction of radiation intercepted (fRI) in sole crops of (a) maize (MZ), (b) long-duration pigeonpea (ldP), (c) medium-duration pigeonpea (mdP), (d) lablab (LB), and in intercrops of maize with (e) long-duration pigeonpea (MZ-ldP), (f) medium-duration pigeonpea (MZ-mdP), (g) lablab (MZ-LB) in the 2017/2018 and 2018/2019 seasons in Babati, northern Tanzania.

A comparison of radiation interception by crops in pure stand and in intercrop clearly showed the advantage of intercropping over pure stands, as illustrated for the maize-long duration pigeonpea intercrop in the 2017/2018 season (Fig. 5.2). In case of the intercrop, radiation interception in the early growth stages was similar to that of the maize crop, whereas the canopy of long-duration pigeonpea had a slow initial development. The initiation of the reduction in radiation interception in the maize crop, observed somewhere half-way during the maize growing season was markedly postponed in the intercrop. Here, overall radiation interception was still rising due to the presence of the legume. Also, after harvesting of the maize crop, radiation interception continued; initially at a slightly lower level than that of the pure stand of the legume, but at a nearly identical level during the last month of the legume growing season. As a consequence, total radiation interception of the intercrop (1387 MJ m^{-2}) exceeded that of the sole crops of maize (712 MJ m^{-2}) and the legume (874 MJ m^{-2}).

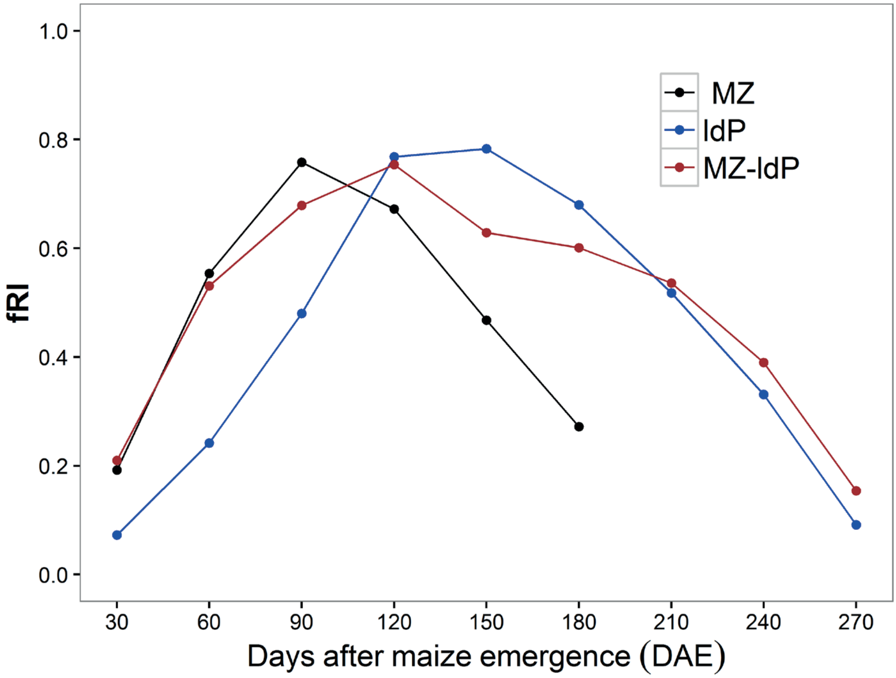

Fig. 5.2: Fraction of radiation intercepted (fRI) in sole crops of maize (MZ), long-duration pigeonpea (ldP), and in intercrop of maize with long-duration pigeonpea (MZ-ldP) in the 2017/2018 season in Babati, northern Tanzania.

5.3.1.2 Relation between biomass and k.LAI

For all of the three legume species, we found a solid relationship between shoot dry weight and the product of *k*.LAI (Fig. 5.3). For long-duration and medium-duration pigeonpea, the relationship was nearly identical, showing that the radiation intercepting ability represented by *k*.LAI as a function of shoot biomass developed in an almost identical manner (Fig. 5.3). Evidently, lablab was more efficient in intercepting radiation at a comparable shoot biomass than pigeonpea. This greater capacity to intercept radiation might also explain the higher competitiveness of lablab, for which reason it was only introduced one month after maize. At the same time, the relation obtained for lablab was marked by a greater level of uncertainty ($R^2 = 0.873$ compared to 0.978 and 0.976 for long and medium-duration pigeonpea, respectively) (Fig. 5.3). This might well be related to differences in development of this crop over the two seasons, where poor establishment of the crop in the second season resulted in delayed canopy growth and reduced radiation interception (Fig. 5.1d, g).

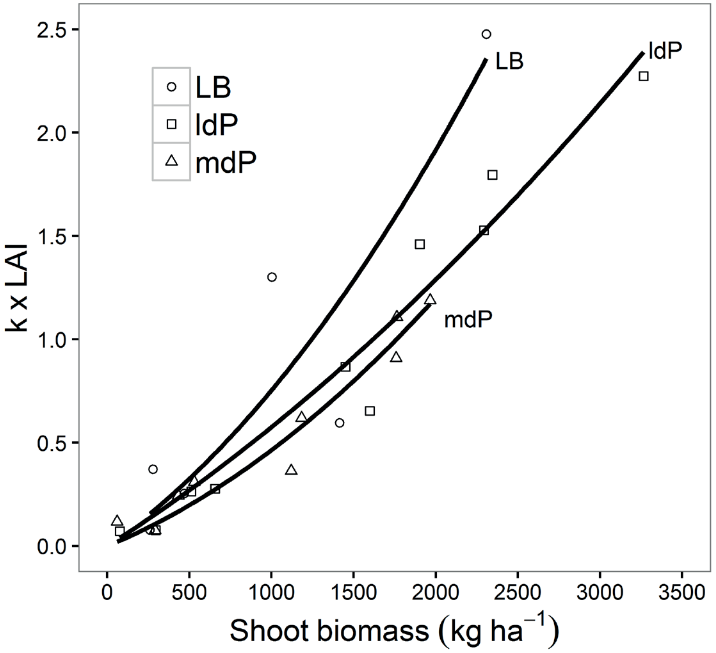

Fig. 5.3: Relationship between shoot biomass in sole crops of lablab (LB), long-duration pigeonpea (ldP), medium-duration pigeonpea (mdP), and the product of radiation extinction coefficient (*k*) and leaf area index (LAI) in Babati, northern Tanzania. (LB: $y = 2.05\times 10^{-7} x^2 + 0.0005x$; $R^2 = 0.873$; ldP: $y = 0.69\times 10^{-7} x^2 + 0.0005x$; $R^2 = 0.978$; mdP: $y = 1.37\times 10^{-7} x^2 + 0.0003x$; $R^2 = 0.976$, where x = shoot biomass in kg ha^{-1}).

5.3.1.3 Radiation-use efficiency (RUE)

Radiation-use efficiency (RUE) calculated based on biomass and cumulative photosynthetic- active-radiation interception was relatively stable across seasons for the two pigeonpea varieties and more variable for maize and lablab. Maize was more efficient in converting intercepted radiation into biomass, with a RUE of 1.435 and

1.067 g MJ^{-1} in the first and second season, respectively (Fig. 5.4a, b). The smaller value was obtained in the second season, when there was less precipitation. For the legumes, RUE ranged between 0.487-0.737 g MJ^{-1} (Fig. 5.4c-h).

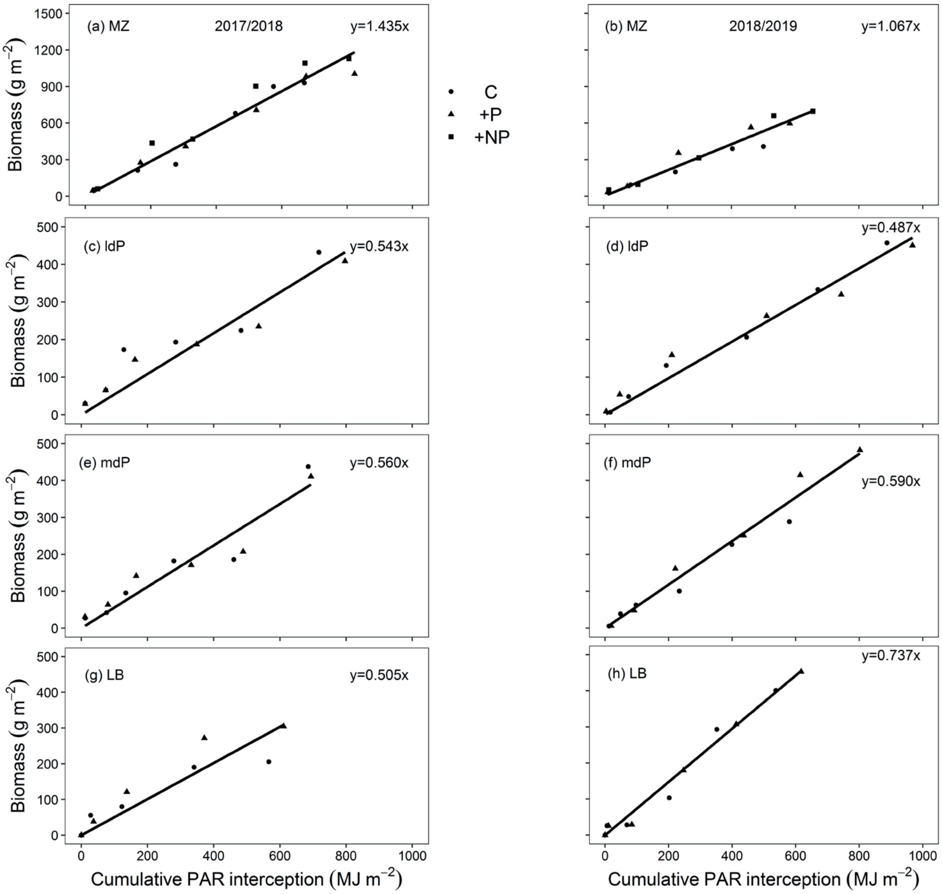

Fig. 5.4: Relationship between above-ground total biomass of pure stands of maize (MZ), long-duration pigeonpea (ldP), medium-duration pigeonpea (mdP), lablab (LB), and cumulative photosynthetic active radiation (PAR) interception in the 2017/2018 (a,c,e,g) and 2018/2019 (b,d,f,h) seasons. The slope of this relationship is radiation-use efficiency (RUE) (g MJ^{-1}).

5.3.1.4 Plant height development

In sole crops, height development across the two seasons was largely identical, with the exception of lablab where height development in the second season was severely delayed, related to the dry conditions around its sowing (lablab was always sown 30 days after the other crops) (Fig. 5.5a- d). Maize and pigeonpea exhibited an upright architecture for which plant height was easy to determine. Lablab on the other hand exhibited a creeping, bushy or twinning growth habit. As such, the height of sole lablab presented in Fig. 5.5d is a result of stretching the stem vertically upwards during measurements. In the intercrop, plant height of lablab (Fig. 5.5g, j) represents the actual height of the canopy, as lablab climbed on the accompanying maize crop. In the intercrops, maize consistently recorded greater or similar height than the accompanying legumes across the two seasons, throughout the co-growth period (Fig. 5.5e-j).

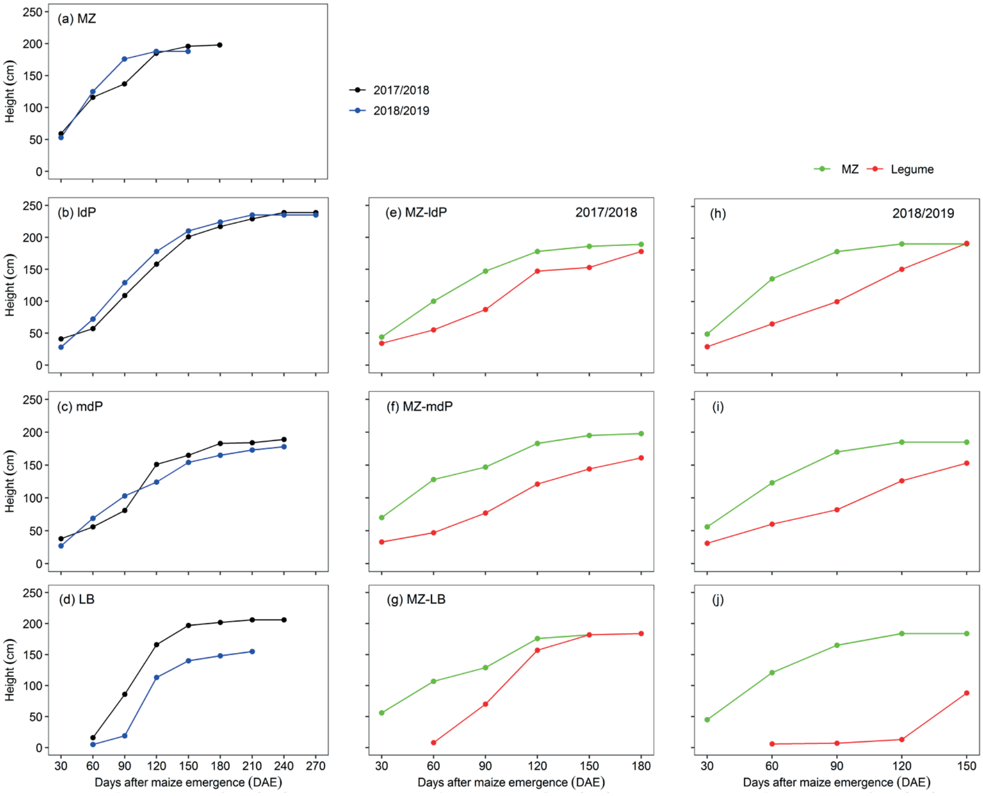

Fig. 5.5: Height development in sole crops of (a) maize (MZ), (b) long-duration pigeonpea (ldP), (c) medium-duration pigeonpea (mdP) and (d) lablab (LB) in the 2017/2018 and 2018/2019 season, and in intercrops of maize with long-duration pigeonpea (MZ-ldP), medium-duration pigeonpea (MZ-mdP) and lablab (MZ-LB) in the 2017/2018 (e-g) and 2018/2019 season (h-j) in Babati, northern Tanzania. In intercrops, height development is presented only for the duration when the two component crops are growing together.

5.3.2 Simulations of sole crops

We used a simulation model to analyse biomass production in sole maize, long-duration pigeonpea, medium-duration pigeonpea and lablab in the 2017/2018 and 2018/2019 season. We included a soil-water balance, to determine if maize production was restricted by water availability. The simulated biomass was then compared with the observed data from sequential harvests (Fig. 5.6). For maize, the RUE of the first season was used, as there were strong indications that the lower RUE in the second season was the result of water shortage. In the model, such a reduction in RUE is included based on the water balance. There was a good agreement between simulated and observed shoot biomass of maize and the legumes, except for the final results of legumes in the 2017/2018 season (Fig. 5.6c, e, g). This is because in the first season, leaf fall was not accounted for, as the litter traps placed to determine leaf fall were stolen. However, it can be noted that the gap for leaf fall in the first season (Fig. 5.6c, e, g) is in line with the gap observed in the second season (Fig. 5.6d, f, h). Here, the open dots indicate observed biomass with exclusion of leaf fall.

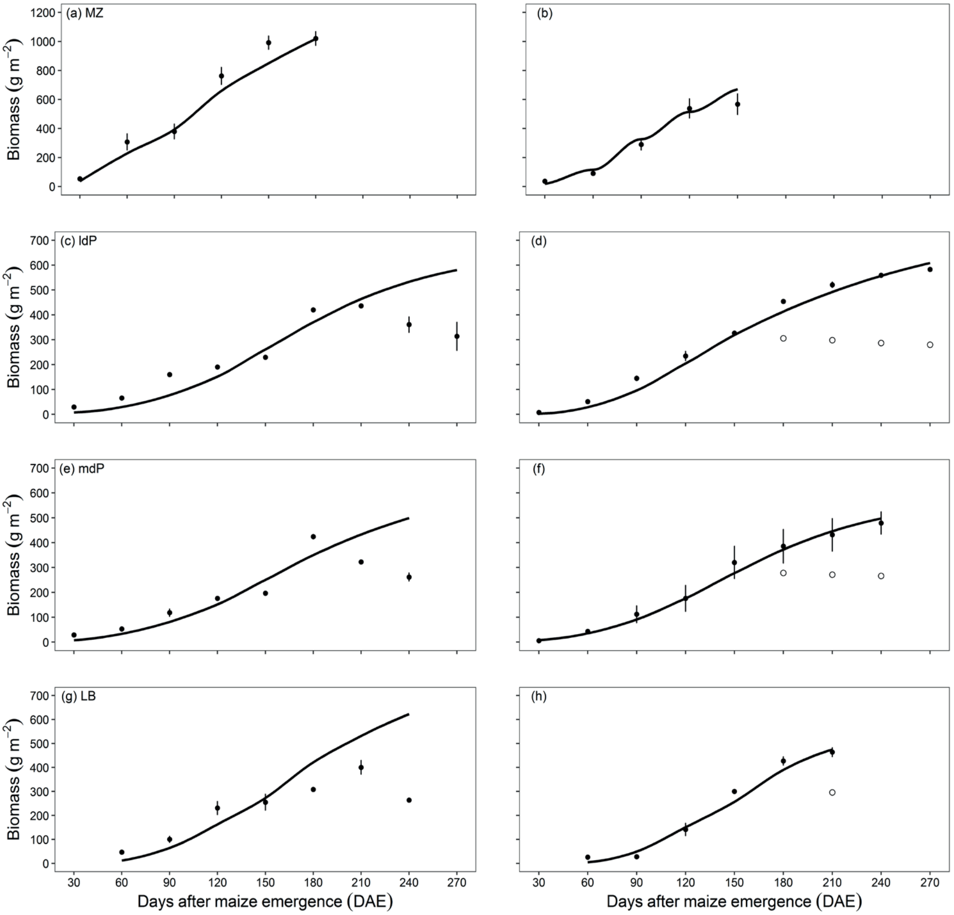

Fig. 5.6: Simulation results for shoot biomass in sole crops of maize (MZ) (a, b), long-duration pigeonpea (ldP) (c, d), medium-duration pigeonpea (mdP) (e, f) and lablab (LB) (g, h) in the 2017/2018 (a,c,e,g) and 2018/2019 season (b,d,f,h) in Babati, northern Tanzania. The closed points are observations. For legumes (c-h), observations in the 2017/2018 season do not include leaf fall, while this is included in the 2018/2019 season. The black lines are simulation results using an effective rooting depth of 6 dm (maize) and 20 dm (legumes). The open points in 2018/2019 season represent observations for shoot biomass of legumes excluding leaf fall.

With a water balance included in the model and considering the amount of water in the soil from soil surface to maximum rooting depth for maize (6 dm) and legume species (20 dm), it was observed that maize encountered water stress in the second season. Simulations showed that the amount of soil water fell below the critical soil moisture level determined using a depletion factor of 0.8 (Fig. 5.7a). With an actual soil moisture level below the critical level, the ratio between actual and potential transpiration rate (RATIOActPot) fell below one (Fig. 5.7b). Water shortage was observed starting 80 days after emergence, and generally lasted for 19 days, after which a rain shower replenished the soil up to an amount above the critical level. During water shortage, the RATIOActPot of transpiration rapidly dropped and reached a minimum value of 0.06. The accompanying reduction in dry matter production amounted to 233 g m^{-2} (Fig. 5.9a).

In contrast, water stress was not encountered by the legumes throughout the growing period in either of the two growing seasons. This is illustrated by the actual amount of soil water which remained above the critical soil moisture level as determined using a depletion factor of 0.65 (Fig. 5.7e). Consequently, the RATIOActPot of transpiration remained one (blue line in Fig. 5.7f). Evidently, the legumes had access to a larger part of the water stored in the soil, as their maximum rooting depth was set to 20 dm. To explore the importance of rooting depth for the legumes, rooting depth of the legumes was systematically shortened in four 3.5 dm steps, up to a minimum of 6 dm. For long-duration pigeonpea, with an assumed rooting depth of 6 dm, the implication for the second season is illustrated in Fig 5.7 (c, d). After the last rainfall event at 144 days after emergence, the soil water steadily decreased, and at 185 days after emergence, the actual soil water content fell below the critical soil moisture level (Fig. 5.7c). From then on, RATIOActPot of transpiration dropped below the value of 1 (Fig. 5.7d). This ratio steadily dropped, until, at the end of the season, the value was nearly zero. With a step-by-step 3.5 dm reduction in rooting depth from an initial 20 dm, the same pattern was observed, but here the reduction started at a later moment in time and ultimately reached a less severe level (Fig. 5.7f).

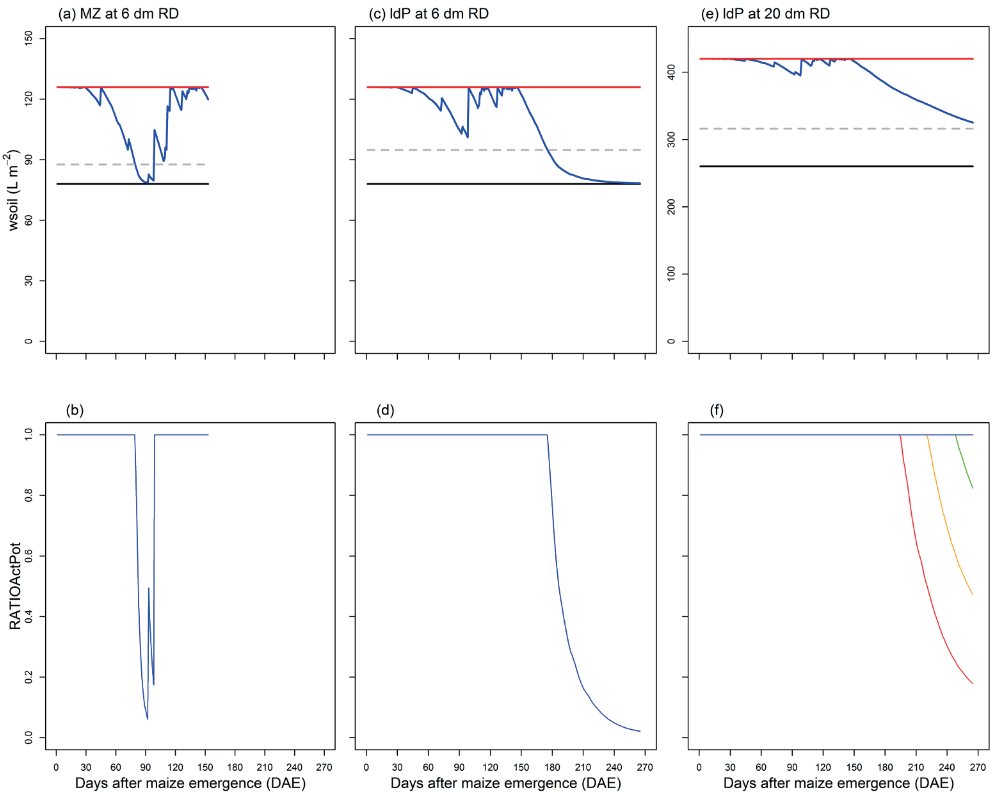

Fig. 5.7: The amount of water in the soil from soil surface to maximum rooting depth (wsoil; Lm^{-2} = mm) (a, c, e), and the ratio between actual and potential transpiration rates (RATIOActPot) (b,d,f) in the 2018/2019 season in Babati, northern Tanzania. Panels a, c, e represent the wsoil for sole crops of (a) maize (MZ) at its actual situation (rooting depth of 6 dm), (c) long-duration pigeonpea (ldP) assuming a rooting depth of 6 dm, and (e) long-duration pigeonpea (ldP) at its actual situation (rooting depth of 20 dm). In Panels a, c, e, the blue, red and black solid lines represent actual amount of soil water and amount of water at field capacity, and wilting point, respectively, while the grey dashed lines represent the critical amount of soil water based on a soil depletion factor of 0.8 for maize and 0.65 for long-duration pigeonpea. Panels b, d, f represent the RATIOActPot of transpiration in sole crops of (b) maize (MZ) (rooting depth of 6 dm), (d) long-duration pigeonpea (ldP) assuming a rooting depth of 6 dm and (f) long-duration pigeonpea (ldP) at rooting depth of 20 dm (blue), 16.5 dm (green), 13 dm (orange) and 9.5 dm (red).

We found that in sole maize, out of the initial amount of soil water and water added to the soil by the rain, about two thirds of it (63.8 %) percolated, while roughly a third (34.9 %) was used for transpiration, with a negligible amount of water left in the system by the end of the first season. In the second season, there was much less percolation which represented about a third (37.5 %) of the available water, while transpiration was nearly a half (47.6 %). Surprisingly, in the second season, more water remained in the soil at the end of the growing season (14.9 %) (Fig. 5.8a). For the legumes, the trend was such that 67 % was percolated under each legume, 21- 27 % was used for transpiration, while 7- 12 % was left in the system at the end of the first season (Fig. 5.8b). Similar to maize, percolation was much less in the second season than in the first season (37-42 %), while transpiration was 36-46 %, and 17-22 % was left in the soil profile at the end of the season (Fig. 5.8b).

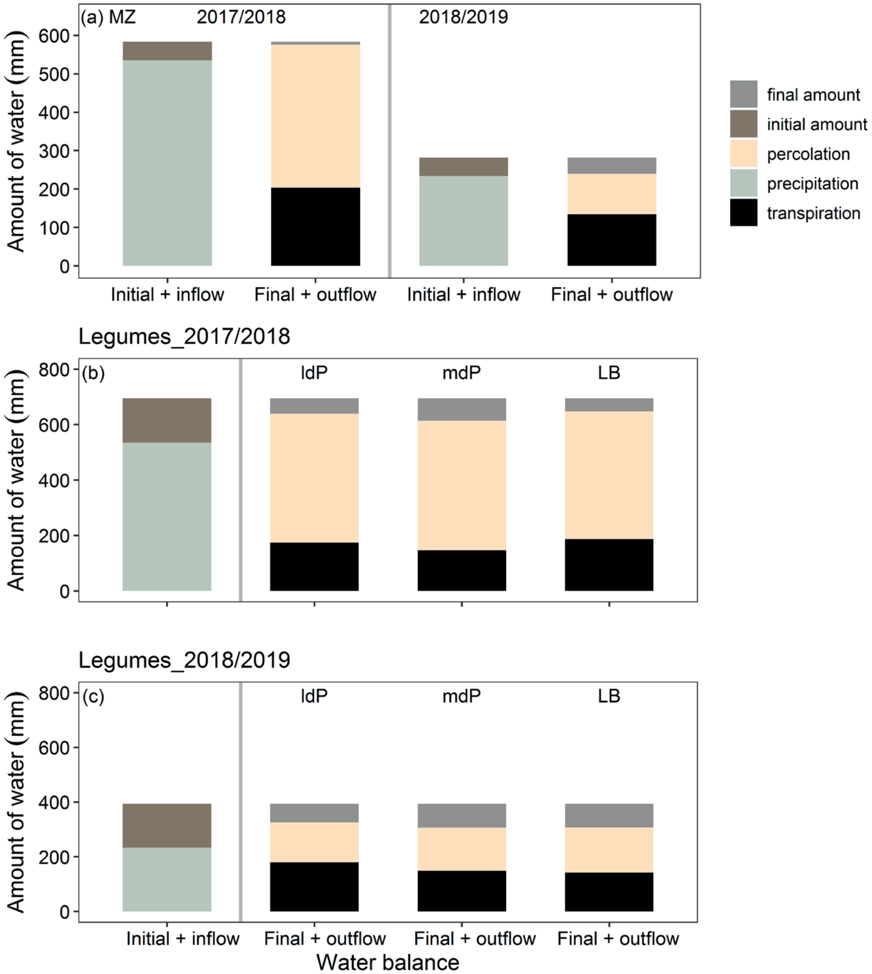

Fig. 5.8: Simulation results for water balance in sole crops of (a) maize (MZ) in the 2017/2018 and 2018/2019 season, (b) long-duration pigeonpea (ldP), medium-duration pigeonpea (mdP) and lablab (LB) in the 2017/2018 season, and (c) the legumes in the 2018/2019 season in Babati, northern Tanzania. The input to the water balance comprises the initial amount of water in the soil (initial amount) and precipitation. The output includes transpiration, percolation, and the final amount of water that is left in the soil (final amount).

The implication of the differences in water supply on the final shoot biomass production of maize and the legumes is depicted in Fig. 5.9. Maize production in the second season was considerably smaller than in the first season. From the gap between simulated production in presence and absence of water shortage, and in line with Fig. 5.7 a, b, it is evident that water shortage played a role. For none of the legumes, neither in the first nor in the second season, was a difference observed between the simulations with the actual water balance and the reference simulations where the ratio between actual and potential transpiration was fixed at one. That means that the pattern for long-duration pigeonpea in Fig 5.7 e, f was representative for the other legumes. Reducing the rooting depth systematically from 20 to 6 dm at intervals of 3.5 dm led to a decrease in shoot biomass production, which was initially negligible or absent. With an assumed rooting depth of just 6 dm, biomass reductions up to 32%, 23% and 34% were recorded for long-duration pigeonpea, medium-duration pigeonpea and lablab, respectively (Fig. 5.9b-g). This illustrates the importance of the deep rooting system for adequate water supply of the legumes.

For long and medium- duration pigeonpea, the ample water supply at a rooting depth of 20 dm also coincided with nearly identical shoot dry matter productions in both seasons. For lablab, this was not the case, as shoot dry matter production in the second season was 149 g m^{-2} less, than in the first season. Again, this is likely related to the poor establishment of lablab in the second season.

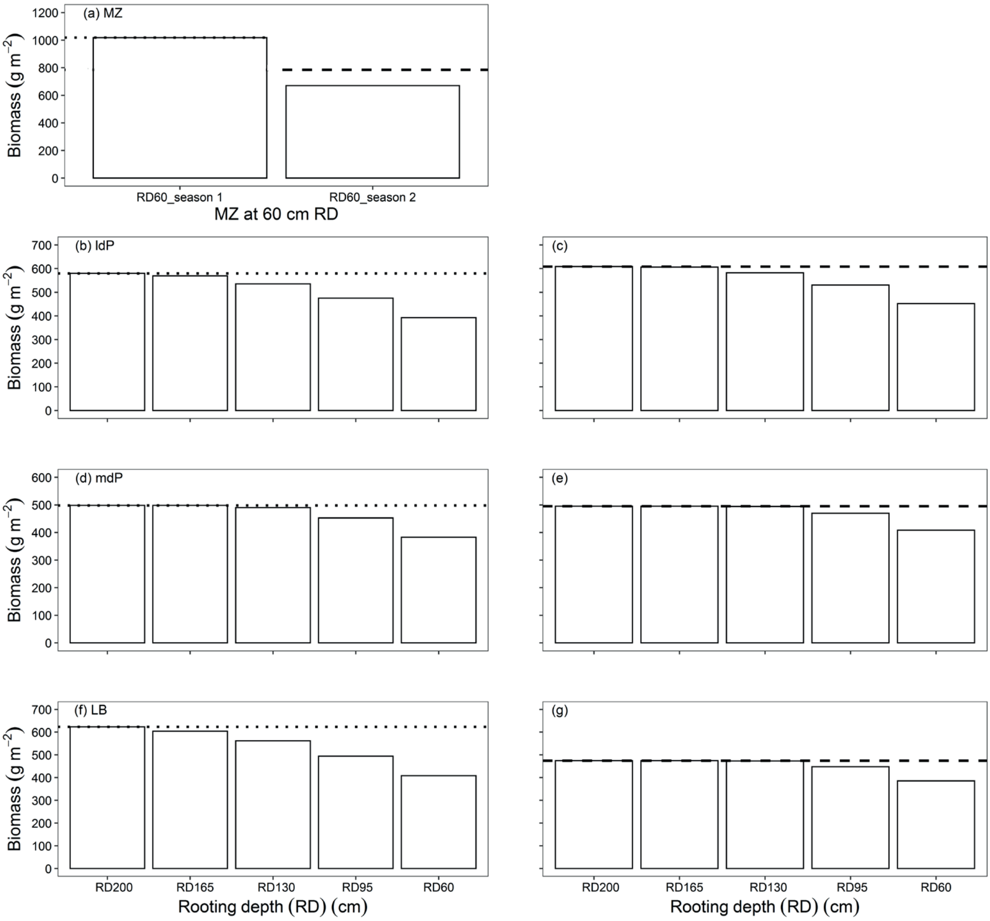

Fig. 5.9: Simulated biomass in sole crops of maize (MZ) in the two seasons (a), long-duration pigeonpea (ldP) (b, c), medium-duration pigeonpea (mdP) (d, e) and lablab (LB) (f, g) in the 2017/2018 (b, d, f) and 2018/2019 season (c, e, g) in Babati, northern Tanzania. Panel (a) illustrates the importance of water for maize crop, while panels (b- g) illustrate the importance of deep rooting depth of legumes. Biomass yields below the dotted and dashed lines are water limited in the first and second season, respectively.

5.3.3 Simulations of intercrops

The simulation model was used to analyse biomass production in intercrops of maize and long-duration pigeonpea, medium-duration pigeonpea and lablab in the 2018/2019 season. Simulated shoot biomass in intercrops was compared with the observed data from periodic harvests (Fig. 5.10). The black dots are observations, while the black lines are the simulation results. For legumes, a species and season-specific RUE across the two seasons determined from sole crops was used. For maize, RUE of sole crop of the first season was used. There was a good agreement between simulated and observed shoot biomass of intercropped maize (Fig. 5.10a, b, c). The legume growth was initially slightly under-estimated during the co-growth period. Whereas this under-estimation remained for long-duration pigeonpea, it turned into an over-estimation in the final part of the growing season for medium-duration pigeonpea and lablab (Fig. 5.10d, e, f).

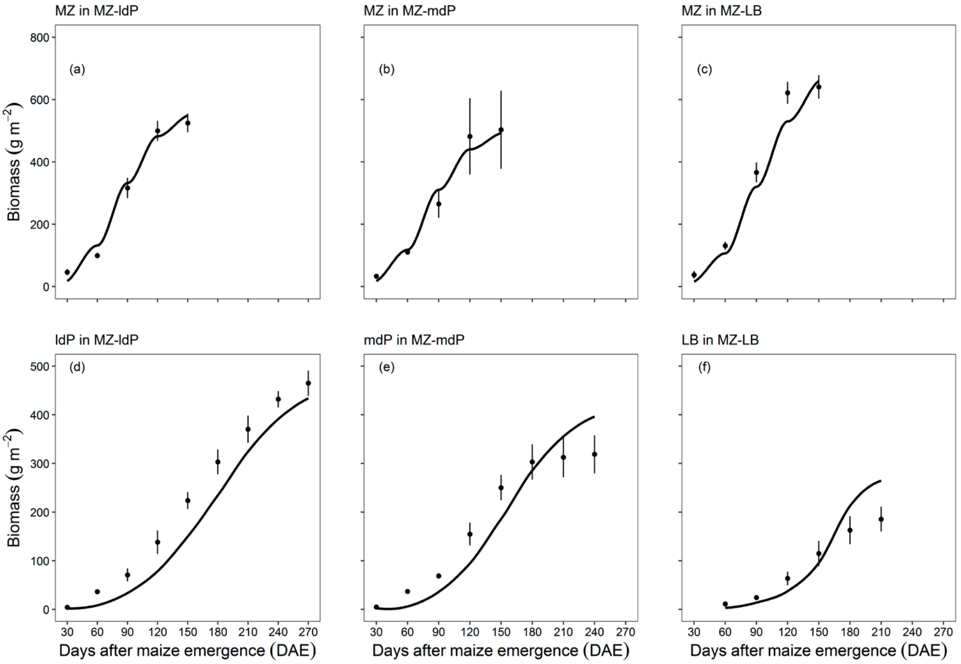

Fig. 5.10: Simulation results for shoot biomass of maize and the accompanying legume in intercrops of maize (MZ) with long-duration pigeonpea (MZ-ldP), medium-duration pigeonpea (MZ-mdP) and lablab (MZ-LB) in the 2018/2019 season in Babati, northern Tanzania. The points are observations. The black lines are simulation results for each crop in intercrop.

Simulations showed that with a rooting depth of 6 dm and 20 dm for intercropped maize and legume, respectively, maize, comparable to its pure stand, encountered water shortage. The amount of soil water in the upper layer dropped below the critical soil moisture level of maize (Fig. 5.11a). This resulted in the ratio between actual and potential transpiration rate (RATIOActPot) dropping below 1 (black line in Fig. 5.11b), and reaching a minimum value of 0.01 (Fig. 5.11b). The intercropped maize experienced water shortage starting 71 days after emergence, which generally lasted for 28 days, after which a rain shower replenished the soil up to an amount above the critical level.

In contrast, throughout the growing period, water stress was not encountered by the legumes. Water shortage in the upper layer, where the legumes (*p*=0.65) would suffer earlier than the maize (p=0.8), was compensated for by a sufficiently high water storage in the lower soil layer. This is illustrated by the actual amount of soil water which remained above the critical soil moisture level in the deeper layer (Fig. 5.11a). Consequently, the RATIOActPot of transpiration remained 1 (blue line in Fig. 5.11b).

By assuming a rooting depth of the legume similar to that of maize (6 dm), the soil water in the deeper layer was no longer available for transpiration. Consequently, both maize and legume suffered from water stress earlier on, as illustrated by the actual soil water content below the critical soil moisture levels (Fig. 5.11c). From that point onwards, parameter RATIOActPot dropped below the value of 1 for both crop species (Fig. 5.11d). Due to its lower soil depletion factor, the legume started to suffer just a few days earlier than maize. The shorter rooting depth of the legume also had implications for water availability after maize harvest. Similar to the simulations with sole legumes, a shorter rooting depth implied a lower amount of stored water, resulting in a situation where available soil water continued to decrease after the last rain and was nearly completely exhausted about one month after maize harvest.

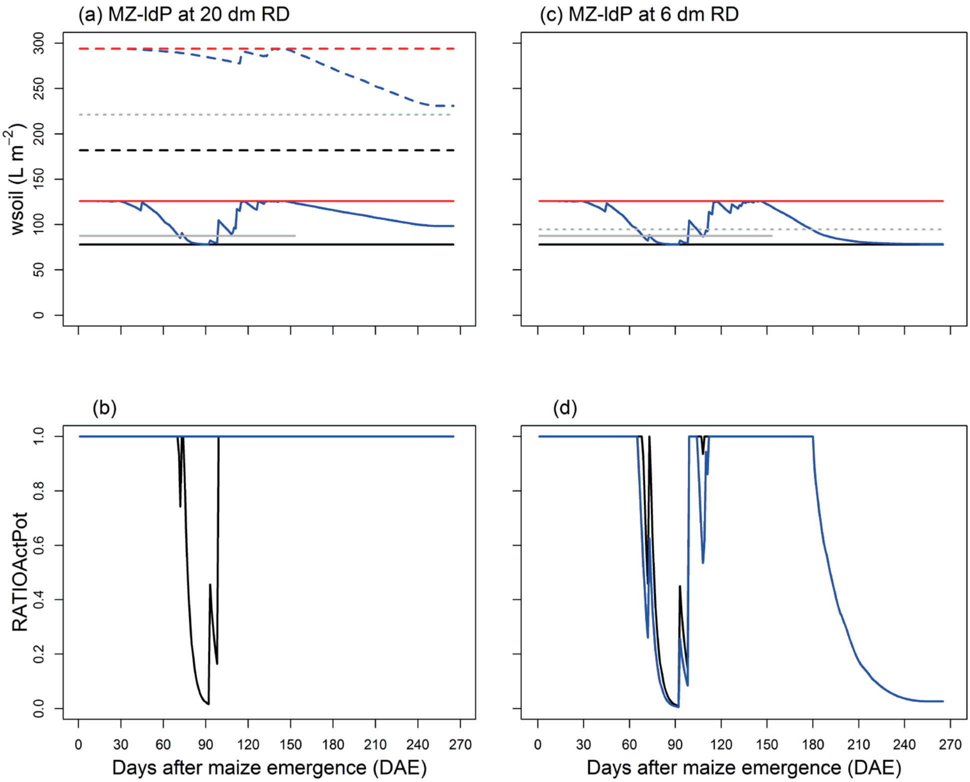

Fig. 5.11: Illustration of the amount of water in the soil from soil surface to maximum rooting depth (wsoil) (a c), and the ratio between actual and potential rates (RATIOActPot) of transpiration (b,d) in the 2018/ 2019 season in Babati, northern Tanzania. Panels a, c represent the wsoil for intercrops of maize and long-duration pigeonpea (MZ-ldP) assuming a rooting depth (RD) of 20 dm (a) and 6 dm (c) for the legume. In Panels a, c, the blue, red and black solid lines represent actual amount of soil water and the amount of water present at field capacity and wilting point, respectively in the upper layer (0-6 dm). The blue, red and black dashed lines represent the same for the deeper soil layer (6-20 dm). The grey solid and dotted lines represent the critical soil water amount for maize and long-duration pigeonpea, respectively. Panels b, d represent the RATIOActPot of transpiration in MZ-ldP intercrop for the maize crop (black lines) and legume (blue lines) assuming a rooting depth of 20 (b) and 6 dm (d), respectively.

In intercrops, assuming a shorter rooting depth for the legume in the second season resulted to an increase in transpiration of maize (25-34 % at 20 dm and 33-44 % at 6 dm), while legumes were hardly affected (20-33 % at 20 dm and 23-31 % at 6 dm). The shorter rooting depth for the legume increased percolation (20-22 % at 20 dm and 32-37 % at 6 dm), but reduced the amount of water left at the end of the season (18-26 % at 20 dm and 1 % at 6 dm) (Fig. 5.12).

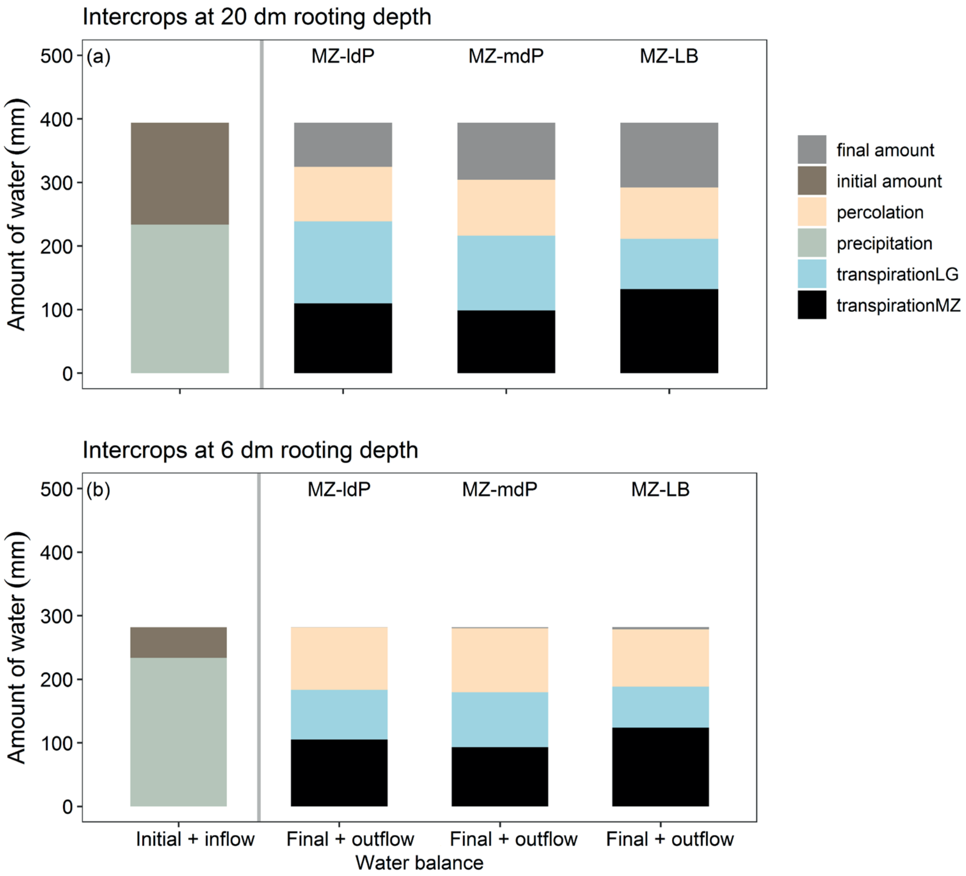

Fig. 5.12: Simulation results for water balance in intercrops of maize (MZ) with long-duration pigeonpea (MZ-ldP), medium-duration pigeonpea (MZ-mdP) and lablab (MZ-LB) at a rooting depth of 20 dm (a) and 6 dm (b) in the 2018/2019 season in Babati, northern Tanzania. The input to the water balance comprises the initial amount of water in the soil (initial amount) and precipitation. The output includes transpiration of maize (transpirationMZ) and legume (transpirationLG), percolation, and the final amount of water that is left in the soil (final amount).

Simulated shoot biomass production for four situations are presented for maize and the three legume species (Fig 5.13). The first two bars represent the sole stands in the first and the second season. The next two bars are the results of the simulations in intercrops, all for the second season, and with an assumed rooting depth of the legumes of 20 and 6 dm. Maize shoot dry matter production depended mainly on the season, most likely related to the amount of rainfall, and was far less affected by presence of the legume (Fig. 5.13a). Particularly, the depth of the rooting system of the legume hardly affected shoot dry matter production of maize. In contrast, legumes, in particular the pigeonpea was barely affected by the season (Fig 5.13b-d). The extended rooting depth created such a water uptake capacity that the dependence on rainfall was minimal. For lablab, a clear difference between both seasons was noted. However, this was not related to a lack of water for transpiration, but due to a dry spell around introduction of this species which delayed establishment of the crop. Furthermore, while maize was not affected by presence of the legume (Fig. 5.13a), this was not the case for the legumes, which appeared to be affected by presence of maize (Fig. 5.13b-d). However, the simulations revealed that this reduction was not due to insufficient water, as soil water content remained above the critical level (Fig. 5.11a, b). With the rooting depth assumed to be similar to that of maize, the shoot dry matter production of the legume dropped even further, and this further reduction could be attributed to water shortage (Fig. 5.11c, d). This underscores the importance of the extended rooting system for the legumes.

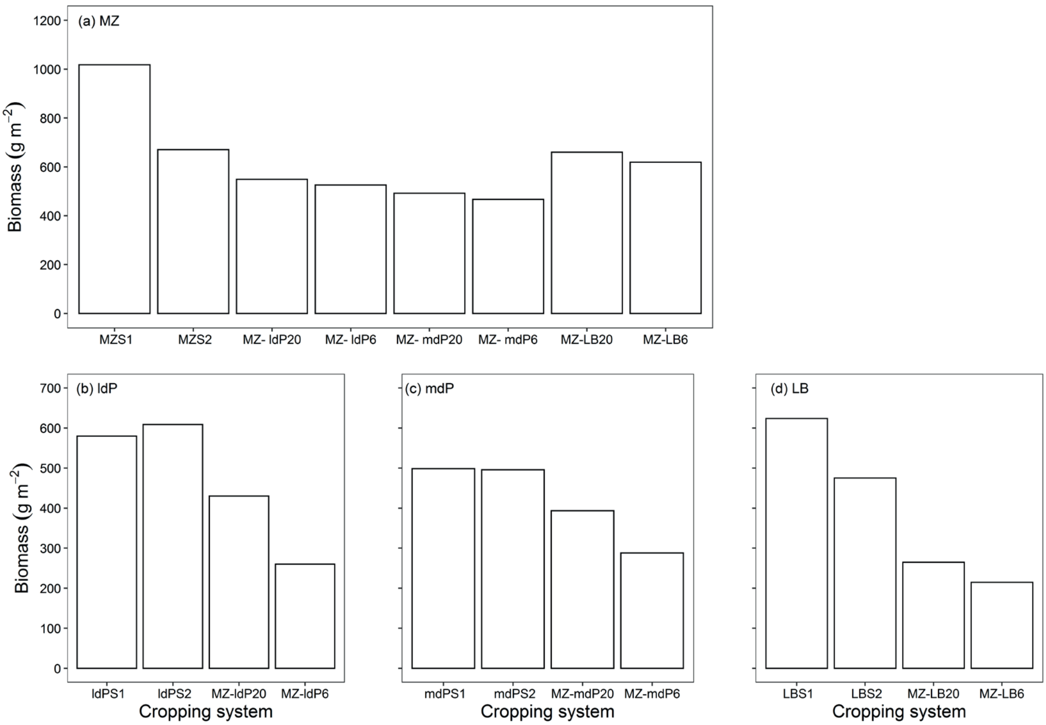

Fig. 5.13: Illustration of simulated biomass of (a) maize (MZ), (b) long-duration pigeonpea (ldP), (c) medium-duration pigeonpea (mdP), and (d) lablab (LB) under different cropping systems in Babati, northern Tanzania. Panel (a) shows maize biomass grown as sole crop in the first season (MZS1), sole crop in the second season (MZS2), maize intercropped in the second season with long-duration pigeonpea assuming a rooting depth of 20 dm (MZ-ldP_20) and assuming a rooting depth of 6 dm (MZ-ldP_6). The further bars in this panel represent maize intercropped with medium-duration pigeonpea and lablab assuming a rooting depth of 20 dm (MZ-mdP_20 and MZ-LB_20) and 6 dm (MZ-mdP_6 and MZ-LB_6). Panels (b, c, d) show biomass of the legumes, either as sole crop in the first season, sole crop in the second season, and intercropped in the second season assuming a rooting depth of 20 and 6 dm.

5.4 Discussion

5.4.1 Importance of water availability and competition for water in sole crops and intercrops of maize and legumes

A transparent, parameter-sparse model was constructed and used to obtain a better quantitative understanding of the influence of water on the productivity of sole maize and grain-legumes, and intercrops comprising of maize and grain-legumes in rain-fed production systems in northern Tanzania. Field observations from on-farm experiments with sole crops and intercrops in two consecutive seasons were used for this analysis, the first being wetter (551 mm seasonal precipitation) than the second (236 mm, seasonal precipitation). Maize was found to be extremely sensitive to this difference in annual precipitation. Dry matter production in the first season was about 3.5 t ha^{-1} (34 %) greater than in the second season (Fig. 5.9a). Simulations showed that in the second season, water shortage occurred and water-limited potential production was not met for 19 days (Fig. 5.7a, b). We relate this to the fact that maize had to meet its transpiration requirements in conjunction with a limited soil-water storage capacity, determined by a relatively short rooting depth of 6 dm, and a narrow gap in volumetric water content between field capacity (0.21) and wilting point (0.13). This corresponds to a storage capacity of 8 mm per dm soil profile and a maximum stock of 48 mm. In the first season, the limited soil-water storage capacity resulted to a high fraction of the water (64%; 372 mm) being percolated and just 35 % (204 mm) being used for transpiration. In the second season, the fraction percolated was much less (37 %), but the absolute amount of water used for transpiration was also considerably reduced (134 mm; 48 %). Surprisingly, in the second season, more water remained in the soil at the end of the growing season (15 %), as compared with the first season (1 %) (Fig. 5.8). This confirms that in addition to the amount of precipitation, its distribution over the growing season is also important. Percolated water is not of use to the crop species grown in that particular season, as only the water transpired by the crop can be considered acquired and used productively in crop growth (Stomph et al., 2020). Our results confirm past research, that one of the major limitations in stabilizing and increasing yields in rain-fed farming systems is crop water stress, caused by inefficient use of total available seasonal rainwater (McHugh et al., 2007). Additionally, the high spatial and temporal intra-seasonal rainfall variability is considered as one of the most important factors affecting agricultural productivity in sub-Saharan Africa (Laux et al., 2010).

In the second season, the presence of a legume caused a further decline in the productivity of maize. Water shortage was resolved by a rain shower at 89 days after emergence (DAE), but started to occur more than one week earlier (at 71 instead of 80 DAE). Implications for maize productivity translated into a simulated reduction ranging from 0.1 (LB; 2 %) until 1.8 t ha^{-1} (mdP; 27%). This influence is substantial, though considerably less than that of the difference between seasons. It contrasts with previous research on maize-legume systems, showing insignificant effects of pigeonpea on maize growth and yield (Myaka et al., 2006; Waddington et al., 2007; Kimaro et al., 2009; Rusinamhodzi et al., 2012). The current analysis suggests that, for seasons with insufficient rainfall, transpiration by grain legumes is able to reduce maize productivity.

The legumes proved to be far less sensitive to differences in annual precipitation. In both seasons, nearly identical production was observed, and water shortage did not occur in either of the two seasons. Despite the higher transpiration coefficient of legumes, the lower transpiration need, following from lower radiation-use efficiency, but in particular the larger rooting depth, were found to be responsible for this. Simulations of legume productivity with reduced rooting depth showed that water stress and a reduced productivity would occur if legumes would not be able to exploit the deeper layers in the soil profile (Figs. 5.7, 5.9). Indeed, increased root proliferation at depths where the water is available has been shown to be a dehydration avoidance mechanism by crops with a deep rooting capacity (Lopes et al., 2011). We further relate the absence of water stress to the fact that legumes are known to lose senesced leaves towards maturity, so as to compensate for an increased transpiration demand in rain-fed conditions and/or decreased water availability without severe yield losses (Sennhenn et al., 2017). Lablab was an exception, with a lower shoot dry matter production in the second year. However, the simulations indicated that this was not a result of insufficient water for transpiration. Water shortage for germination and establishment is more likely the case. Lablab was sown 30 days after maize and pigeonpea, and in the second season this coincided with a dry spell. This shows the risk associated with delayed sowing of a legume, as this might lead to postponed establishment. It further underscores the need for perfect timing of sowing dates, as this is considered as one of the agricultural management strategies, which is known to strongly affect crop production in rain-fed agriculture (Ati et al., 2002). This is even more relevant in many parts of humid, sub-humid and semi-arid Africa, as the rainy season starts with some light showers followed by dry spells, which can cause poor crop emergence or desiccate a newly germinated crop (Makarau, 1995).

In the second season, the presence of maize in legume systems caused a clear reduction in dry matter production of the legume, ranging from 1-2 t ha^{-1} (21- 44%). However, the simulations revealed that this was not caused by competition for water, as also in presence of maize the legumes did not suffer from water stress. Simulations in intercropped legumes again pointed at the importance of the deeper rooting system of the legumes. When the legumes were assumed to have a rooting depth similar to that of maize, the legume would already have suffered from water shortage during the presence of maize, and this would recur later during its growing season, as the rooted soil profile dried out (Fig. 5.11c, d). In such a scenario, the water stress in the upper layer is a result of increased water acquisition in the intercrop, due to increased root density in the upper layers (Stomph et al., 2020). This implies that maize takes its share of water during the co-growth period, thus leading to an earlier depletion of water reserves in the soil (Morison and Gifford, 1984), at the expense of the legume which takes a longer growth period. In relation to this, past research showed that under water limited conditions, water extraction by a crop is limited by root system depth, and by the rate of degree of extraction (Robertson et al., 1993). The reduced transpiration of the legume caused by assuming a rooting depth similar to that of maize (Fig. 5.12) translated into reduced productivity (Fig. 5.13b, c, d), as biomass production is tightly linked to transpiration (Lopes et al., 2011). This approach is thus based on the capacity of the root system to extract stored soil water, whereby the rate of transpiration is likely to be limited by the rate of water extraction (Tsubo et al., 2005).

5.4.2 Parameters derived for the model study

Model-parameterization required a closer look at some system traits, like radiation interception and radiation-use efficiency that are interesting aspects on their own. Compared with sole cropping, intercropping showed to have greater radiation capture potential (Fig. 5.2). We attribute this to the effect of combination of differing spatio-temporal use of radiation among component crops (Willey, 1990). Maize had a greater contribution to ground cover in the initial 90 days after emergence, eventually contributing greatly to radiation interception, while the legume continued intercepting radiation after maize harvest.

For all of the three legume species, we found a solid relation between shoot dry weight and the product of light extinction coefficient and leaf area index (*k*.LAI, Fig. 5.3). The light intercepting ability represented by *k*.LAI as a function of shoot biomass developed in a nearly identical manner for long-duration and medium-duration pigeonpea. Lablab was however more efficient in intercepting radiation at a comparable shoot biomass (Fig. 5.3). This better capacity of lablab to intercept radiation might also explain the higher competitiveness of lablab, for which reason it was only introduced one month after maize, and is possibly due to its inherently dense canopy (Cook et al., 2005). The procedure for distribution of total radiation interception of intercrops over component species, as described by Spitters and Aerts (1983), heavily relies on *k*.LAI. As these characteristics are not used in isolation, the direct determination of this product, which can be easily derived from radiation interception observations, is a valid alternative for situations where determination of LAI and thus *k* is difficult. The absence of proper experimental facilities, as was the case in our study, is one such situation. However, exploration with the current data set showed that the relationship between shoot dry weight and *k*.LAI became far less stable once leaf fall sets in. This suggests the method to be particularly relevant during early stages of crop development.

Maize was more efficient in converting intercepted radiation into biomass, as indicated by greater RUE relative to the legumes. Indeed, cereal crops have been shown to have greater RUE than legumes, with values as low as 0.5 reported for legumes (Muchow et al., 1993; Sinclair and Muchow, 1999). The greater RUE for maize as compared with legumes has been linked to their greater biomass production (Li et al., 2019; Elhakeem et al., 2021). We observed that maize recorded a greater RUE value in the first season than in the second season. The observed greater value for maize RUE in the first season was consistent with observed greater biomass in the first than in the second season, as can be deduced from Fig. 5.4a, b, and as reported in Mugi-Ngenga et al. (2022). Simulations showed that the smaller RUE of maize recorded in the second season was attributable to water shortage. Using the RUE of the first season, where no water shortage was noted, combined with the assimilation routine that accounts for a reduced production following from water shortage, resulted in an adequate simulation of maize shoot dry matter. In relation to this, soil water deficits are said to have a major influence on leaf photosynthesis, and, consequently, RUE is also decreased under drought conditions (Sinclair and Muchow, 1999). The RUE values for legumes were relatively stable, which is in line with the model observations that water shortage was not encountered in either of the two seasons. Lablab was an exception, with greater RUE in the second season. It is unclear whether this result is a reflection of the poor establishment that was obtained in the second season.

5.4.3 Modelling approach

For the current analysis, a simple, transparent and parameter-sparse model was developed. The model provides valuable additional insight in the functioning of maize and legumes, either grown as sole crop or intercrop. The model is largely driven by data directly observed in the field, and was parameterized based on observations in sole crops. As such, the model should be regarded a valuable extension of experimental field observations enabling a better interpretation of collected data. The model is typically well suited for analysis as it is driven by observations, and not for prediction purposes. Although it might seem that our approach violates the rule that parameterization and validation of model performance should be based on independent datasets, we do not have the intention to extend the model for prediction purposes. The strength of the current modelling approach is its transparency and underscores our belief in model simplicity. The model aligns with the level of detail with which observations were made in the field. A few well-described principles and relations for radiation interception, radiation-use efficiency, water use and water storage were included in the model, solely with the intention to increase the understanding of the functioning of maize-legume intercropping systems under rain-fed conditions.

5.5 Conclusion

The current model analysis showed that under rain-fed conditions in northern Tanzania maize production is strongly influenced by water availability through precipitation. Legume productivity proved to be far less sensitive to such differences in annual precipitation, mainly because of the greater rooting depth of the legumes. Maize-legume intercropping is a productive cropping system resulting in over-yielding, partly due to temporal niche differentiation, which gives rise to enhanced light capture. Spatial niche differentiation, through the greater rooting depth of the legumes as compared to the maize greatly enhances the success of the system. In the maize-pigeonpea intercropping system, maize was hardly influenced by the legume, except in the season with low precipitation, when water shortage was further aggravated. Maize influenced pigeonpea merely through competition for light, as the rooting system of the legume allowed it to utilize the water stored in deeper soil layers. Our analysis confirmed the strong radiation capturing ability of lablab. Delayed introduction of lablab in intercrop with maize was sufficient in avoiding competitive stress for radiation of the legume on maize, but also resulted in poor establishment of the legume in the second season. Consequently, simultaneous maize- pigeonpea intercropping seems a more reliable option. Our analysis confirms the important role of the deep rooting system of the legume for the success of maize-legume intercropping systems under rain-fed conditions.

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Chapter 6

General Discussion

6.1. Introduction

Sustainable intensification and diversification of crop production has become essential to manage the socio-economic and biophysical limitations of crop production (Vanlauwe et al., 2014). With regard to socio-economic limitations, with increasing population pressure in sub-Saharan Africa (SSA) under the current crop production practices dominated by smallholder agriculture, sustainable intensification and diversification without further degrading the natural resources of these systems becomes essential (Pretty et al., 2011; Giller et al., 2021). The biophysical limitations include soil fertility depletion, which is a widespread limitation to yield improvement in SSA (Mekuria and Waddington, 2002). Furthermore, the continuous cropping of sole maize without adequate restoration of soil fertility will further exacerbate the problem and threaten the sustainability of production systems across many parts of SSA (Sanchez, 2002; Sanginga, 2003). As is the case in most other SSA countries, Tanzania faces the challenge of declining soil fertility. In many cases, nitrogen is considered the main limiting factor to growth of crops (Bekunda et al., 2002). The most efficient way of adding nitrogen to the soils is through synthetic fertilizers. However, in risk-prone environments typical of smallholder farms in Tanzania, farmers are reluctant to invest in fertilizers (Mwangi, 1996), because they have limited access to cash and are unsure about the returns (Myaka et al., 2006). Grain legumes play an important role in sustainable intensification and diversification, as they increase crop production and eventually food security (Kerr et al., 2007; de Jager et al., 2019). In addition, they contribute to soil fertility by adding nitrogen (N) through biological N_2-fixation (Giller, 2001; Lithourgidis et al., 2011).

Practices that contribute to sustainable intensification and diversification of cropping systems have the capacity to tackle and resolve multiple constraints. In this regard, a diversity of maize-grain legume intercropping systems were explored in this PhD research. Globally, maize-legume intercrops are one of the most common intercropping systems, and they combine a nitrogen demanding crop (maize) with an N fixing crop (legume). Furthermore, a meta-analysis (Li et al. 2020) has shown that intercrops with maize tend to outperform intercrops without maize. The main objective was to explore ways of striking a balance between maximizing the benefits of inclusion of legume species; pigeonpea and lablab in the system, and minimizing potential disadvantages emanating from their competition with maize under on-farm conditions. This chapter synthesizes the main findings and draws conclusions on the potential of the tested maize-grain legume intercropping systems under various fertilizer treatments (control, +P and +NP) across an agro-ecological gradient in northern Tanzania.

6.2. Maize-grain legume intercropping: an important component of climate-smart agriculture

Climate-smart agriculture is an approach to transform agricultural practices with the objective of increasing agricultural productivity, building climate resilience (climate adaptation) and reducing emissions (climate mitigation) (Neufeldt et al., 2013). Projected increases in temperature and rainfall variability either directly or indirectly through pests and pathogens are likely to increase the chances of yield reductions or even crop failures. But intercrops such as inclusion of grain legumes into maize-based systems are believed to reduce such yield risks (Bedoussac et al., 2015). Component crops in an intercrop may complement each other, as they may differ in tolerance to climate-related stress; hence if one crop performs poorly the other may still perform well (Trenbath, 1993). In Chapter 3, we showed a clear difference in maize yield between the 2017/ 2018 and 2018/ 2019 season due to a drastic change in seasonal rainfall. In 2017/ 2018, with up to 551 mm of rainfall, DM (10.3 t ha^{-1}) and grain yield (3.0 t ha^{-1}) were about twice as high as in 2018/ 2019, with up to 236 mm of rainfall (Fig. 6.1). On the other hand, legume productivity was more constant across the two seasons.

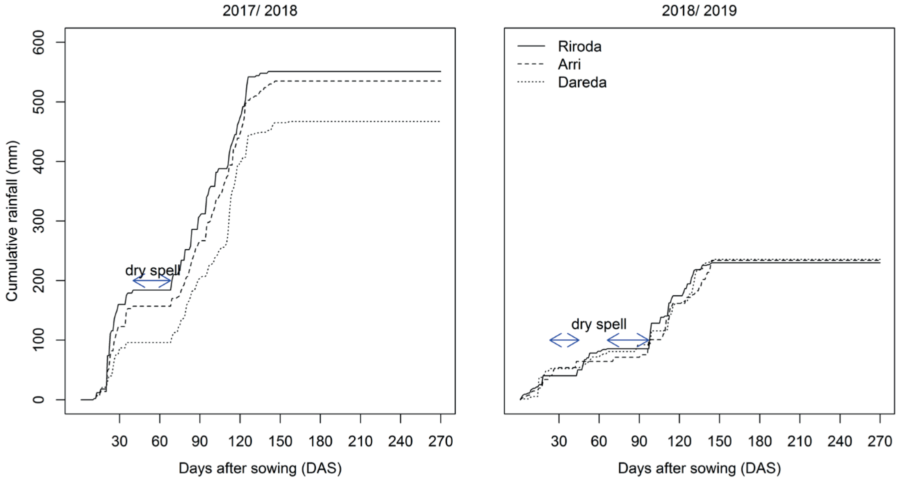

Fig. 6.1: Cumulative rainfall distributions as measured in three sites in Babati, northern Tanzania, during the 2017/ 2018 and 2018/ 2019 seasons. DAS refers to the days after sowing of maize and pigeonpea (lablab was relay planted 30 days after).

We attributed the difference in maize and legumes production across the two seasons to the fact that maize is especially drought-sensitive during the critical reproductive phase (tasselling to grain filling) (Myaka et al., 2006; Daryanto et al., 2016), which in our study occurred at 80-90 days after sowing. This was after the dry spell in 2017/2018 season, but partly coincided with the dry spell in the 2018/2019 season (Fig. 6.1). On the other hand, legumes are more drought tolerant than maize (Rusinamhodzi et al., 2012), presumably due to their deeper rooting systems. Indeed, an inspection of root profiles in our study showed that both pigeonpea and lablab had a deep taproot which extended beyond 2 m depth (e.g., Fig. 6.2). This deep root system enabled the legumes to continue growing and mature on residual soil moisture after maize harvest, and we relate this to their ability to extract water from deeper soil layers (Sekiya and Yano, 2004). Indeed, in Chapter 5, simulations with a crop growth model showed that with the actual rooting depth of maize (6 dm), the crop experienced water stress earlier in the growing period. This is illustrated by the amount of soil water below the critical soil moisture level as determined using a depletion factor of 0.8, and the ratio between actual and potential transpiration rate (RATIOActPot) less than 1. In contrast, with the actual rooting depth of legumes (20 dm), water stress was not encountered throughout the growing period as illustrated by the amount of soil water above the critical soil moisture level as determined using a depletion factor of 0.65, and the RATIOActPot of transpiration at 1 (Fig. 5. 11a and b).

Fig. 6.2: Illustration of the deep taproot of legumes extending beyond 2 m depth as monitored in Babati, northern Tanzania at 150 days after sowing of the crops.

The N_2 fixed by legume crops can also represent an important renewable source of organic nitrogen (N) input for agricultural soils (Peoples et al., 2009). This implies that the inclusion of N_2 fixing legumes helps mitigate climate change by decreasing the fertilizer N requirements of subsequent crops and thereby reducing the net emissions of fossil fuel-derived carbon dioxide (CO_2) needed in the production of synthetic fertilizers (Jensen et al., 2012). In addition, increases in soil organic matter/ soil carbon content from the legumes litter fall are highly beneficial in terms of carbon sequestration as well as from the standpoint of soil health and soil fertility (Paustian et al., 2019). Indeed, in Chapter 3, we observed that both pigeonpea varieties and lablab produced up to 2 t ha^{-1} of senesced leaves on average when grown as a sole crop or intercropped with maize, which was all left in the field after harvest (e.g., Fig. 6.3). This underscores the important role that legumes play in maintaining long-term soil fertility (Fillery, 2001).

Fig. 6.3 Senesced leaf fall of pigeonpea and lablab, which was left in the field after harvest of the legumes in Babati, northern Tanzania.

6.3. Implications of nutrients management in maize-legume intercrops

Smallholder farmers in Tanzania seldomly use fertilizers as shown in Chapter 2, Table 2.1. Previous research has, however, highlighted the benefits of nutrient application in intercrops. For example, the yields of maize and pigeonpea from intercropping in northern Tanzania with an application of 60 kg N and 20 kg P ha^{-1} were greater than those realized without the application of N and P fertilizers (Senkoro et al., 2017). Furthermore, with fertilizer application, maize yield was greater when intercropped with pigeonpea as compared to sole maize in Eastern Tanzania, indicating high complementarity between the two crops when nutrient availability is adequate (Kimaro et al., 2009). Additionally, the application of N fertilizer in cereal-legume intercrops has been reported to increase the competitiveness of the cereals, very likely leading to a competitive imbalance and a failure of legumes in mixtures (Ofori et al., 1987; Pelzer et al., 2012; Yu et al., 2016).

In our study, the effect of 90 kg N and 40 kg P ha^{-1} was evident in Chapter 3 both in the current season (Figs. 3.4, 3.6) and succeeding season (Figs. 3.8, 3.9). In most cases, maize yields increased strongly in response to N fertilizer (Fig. 3.4), while a positive response of legume productivity to P fertilizer was observed (Table 3.7). The improved growth of maize due to fertilizer N application exerted a stronger competitive influence on the legume, resulting in intercrops with N fertilizer recording significantly less pigeonpea and lablab grain yield than where N was omitted (Fig. 3.6). This justifies the recommendation in Chapter 2, to supplement the intercrop systems with mineral fertilizers, and to provide proper training on fertilizer use. Indeed, in our study area where maize stover and pigeonpea/ lablab residues to a large extent are used for livestock feed and a source of fuel wood for the farmers, this is likely to result in partial N mining of the system, unless fertilizer is used. This was evident in Chapter 4, where the total N-uptake amounting to 58-176 kg ha^{-1} mainly ended up being mined from the system. This raises the obvious question: what keeps smallholder farmers from using fertilizer? Reasons for this include low purchasing power of fertilizers, associated with high prices and ease of accessibility (Giller, 2001).

6.4. Residual effects of sole and intercropped grain legumes on a succeeding maize crop

The inclusion of grain legumes is essential for sustaining soil fertility through biological fixation of atmospheric nitrogen (N_2) and N mineralised from legume residues (Giller, 2001). A lot of work has been done on sole legume crops in rotation with maize. However, while within-season effects of intercropping are receiving increasing attention, the rotational performance is rarely investigated across seasons, even though the two are complementary strategies in the sense that they provide spatial (intercropping) and temporal (rotations) crop diversification. Under favourable environmental conditions, pigeonpea can biologically fix up to 200 kg N ha^{-1} but under unfavourable conditions, it might be as little as 6 kg N ha^{-1} (Kumar Rao and Dart, 1987; Adu-Gyamfi et al., 2007). In Chapter 4, when N_2-fixation was quantified from on-farm field measurements using the ^{15}N natural abundance method, up to 22-85 kg N ha^{-1} was recorded (Table 4.3). Notably, the capacity of the grain legumes to fix N_2) differed among the legumes. Long-duration pigeonpea, which had the largest shoot DM, was consistently among the treatments with the largest amount of N_2-fixed. The fixed N_2 can reduce the N fertilizer needed for subsequent cereal crops (Peoples et al., 1995; Myaka et al., 2006). However, the net input of fixed N into the soil depends on amounts of N_2 fixed relative to the amounts of N removed in the harvest products (van Kessel and Hartley, 2000; Salvagiotti et al., 2008). In sole or intercropped legume systems, to obtain a beneficial residual effect after legumes compared to non-legumes, it is expected that the amount of fixed N returned to the soil must be greater than the amount of N in the harvested yield component (Sanginga et al., 2003; Vanlauwe et al., 2019). In our study, the above-ground plant parts of the legumes, except for the fallen leaves, were removed from the field at harvest, as is the common practice of smallholder farmers. This implies that the residual effect must have been due to the decomposition of fallen leaves and senesced roots and nodules (Giller, 2001). Indeed, about one-third of the total N_2 fixed by legumes is assumed to remain underground (Peoples et al., 2009), and may either be used by the succeeding crop or be transformed into soil organic matter (Vanlauwe et al., 2019). This possibly explains the many reports of the increased yield of subsequent crops when legumes are included in cropping sequences than when they are not (Peoples et al., 2009). For example, Rusinamhodzi et al. (2012) reported eight times greater maize yield following pigeonpea, while Adjei-Nsiah et al. (2007) reported up to four times greater maize yield following cowpea than continuous maize. A mean of 0.49 t ha^{-1} increase in yield of cereals rotated with legumes relative to continuous cropping of cereals in SSA has been reported (Franke et al., 2018). In Chapter 3, we evaluated the residual benefits of two seasons of grain legumes (2017/2018-2018/2019 seasons) for the yield of a succeeding sole maize crop grown in the third season (2019/2020), with no fertilizer application. We showed that dry matter (DM) and grain yield following two seasons of continuous maize was smallest and significantly less (1.6- 2.5 t ha^{-1} less DM and 0.8-1.9 t ha^{-1} less grain yield) than in plots that followed pure stand legumes or maize intercropped with legumes (Fig. 3.8, 3.9). We partly attribute the larger DM and grain yield following two seasons of legumes inclusion to N from the legumes grown in the preceding seasons. Indeed, results in Chapter 4 showed positive associations between shoot N yields of legume species measured at the final harvest stage in the 2018/ 2019 season and DM, grain yield and N uptake of a succeeding maize crop grown in the 2019/ 2020 season at final harvest (Fig. 4.5). However, we observed that the associations had R^2 values $\leq$ 50%. This possibly implies that effects, other than the carry-over of N from the previous seasons, could have played a role. Indeed, cereal yield responses are not always wholly attributable to improvements in soil N supply, but both N and non-N factors contribute to the observed improvements in cereal productivity after legumes (Sanginga, 2003). The non-N effects comprise of abiotic factors, such as changes in soil moisture, organic matter, structure, pH, and enhanced P-availability through secretion of enzymes and acids in the legume rhizosphere (Chan and Heenan, 1996; Schlecht et al., 2006; Rusinamhodzi et al., 2012; Franke et al., 2018).

6.5. Complementary and facilitative use of resources in maize-legume intercropping

Productivity of intercrops depends on the balance between intra- and inter-specific competitions. In intercrops, yield reduction is often due to competition for resources such as light, water and soil nutrients (Senaratne et al., 1995; Peoples et al., 2009). For instance, shading of the shorter crop (legumes in the case of this thesis) by the taller crop (maize in this case) in intercrops reduces the photosynthetic rate of the shorter crop, thereby reducing its yield (Namatsheve et al., 2020). On the other hand, when the component crop species have complementary growth patterns (e.g., use different temporal niches by utilizing different periods of the season, or spatial niches through different rooting depths or canopy sizes), inter-specific competition will tend to be weaker than the intra-specific competition, and resources (sunlight, moisture and soil nutrients) will be acquired more efficiently (Lithourgidis et al., 2011). In chapter 5, modelling of inter-specific competition confirmed that maize-legume intercropping is a productive system, resulting in over-yielding, mainly due to temporal (extended light capture) and spatial (rooting depth) niche differentiation. This results in relatively greater yields than in sole crops (Willey, 1979). In Chapter 3, maize-legume intercrops followed an additive design (i.e., plant densities of each crop being the same as in its respective sole crop), with legumes planted in the maize rows, in-between maize hills. We observed that maize growth was hardly affected by the presence of legumes, as the crop in sole and intercrops produced similar dry matter and grain yield (Tables 3.3, 3.4 and Figs. 3.4, 3.5). We attribute this to the complementary growth patterns exhibited by component crops in the intercrops. Pigeonpea has a slow initial growth, limiting early competition with cereals in intercrops (Silim et al., 2005), which was the case in the maize-pigeonpea intercrops in our study. Further, when sown simultaneously with maize, pigeonpea continued to grow for three to four months after maize harvest, which ensured that the greatest demand for water and nutrients occurred after maize had been harvested, similar to the pattern observed by Dalal. (1974), resulting in temporal niche differentiation (TND). For lablab which is more competitive than maize, the delay in sowing time, so-called relay intercropping in our study ensured that the two crops only had a partial overlap, also resulting in a TND. Thus, the timing of the establishment of the intercrop systems in our study helped to minimize the competitive effects of legumes on maize (Fig. 6.4), with legumes benefiting from release of the competition after maize harvest (Fig. 6.5). This resulted in partial land equivalent ratio (LER) values of maize ≥ 1 in almost all cases, whereas partial LER for legumes was in all cases < 1. Since the design in our study was additive, legume yield can be a supplementary benefit to maize yields, making LER of the system > 1 (Fig. 3.7). The LER values partly reflect TND between the companion crops, in that the productivity of intercrops increases with increasing TND (Yu et al., 2015; Li et al., 2020). The positive relationship between LER and TND does not consider that the system requires a larger part of the growing season. In contrast, the area time equivalent ratio (ATER) accounts for the extended growth duration and provides a more meaningful comparison. When accounting for the extended growth duration of pigeonpea and lablab, which was not considered under LER, ATER values > 1 were recorded (Fig. 3.7). This indicates the suitability of investigated cropping systems in our study. It is worth noting that the time accounted for by ATER is only important when additional crops are grown, and that was not the case in our study, given that the legumes extended through the dry season.

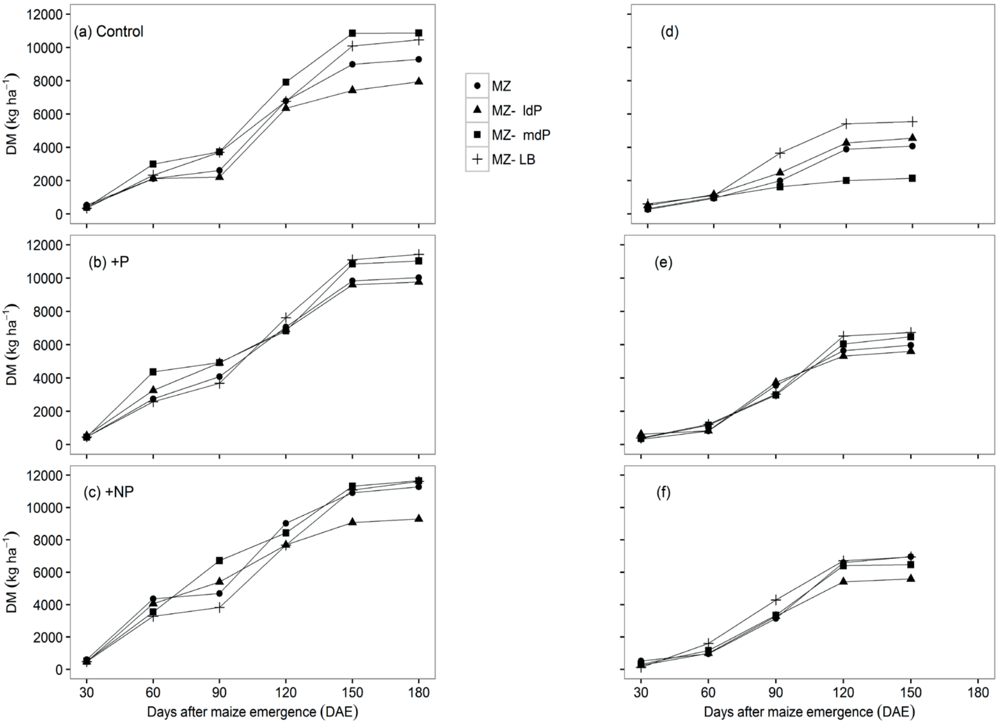

Fig. 6.4: Dry matter (DM) production of maize under different cropping systems and fertilizer as measured from on-farm experimental trials throughout the 2017/2018 (a, b, c) and 2018/2019 (d, e, f) seasons in Babati, northern Tanzania. MZ= maize; ldP= long-duration pigeonpea; mdP= medium-duration pigeonpea; LB= lablab.

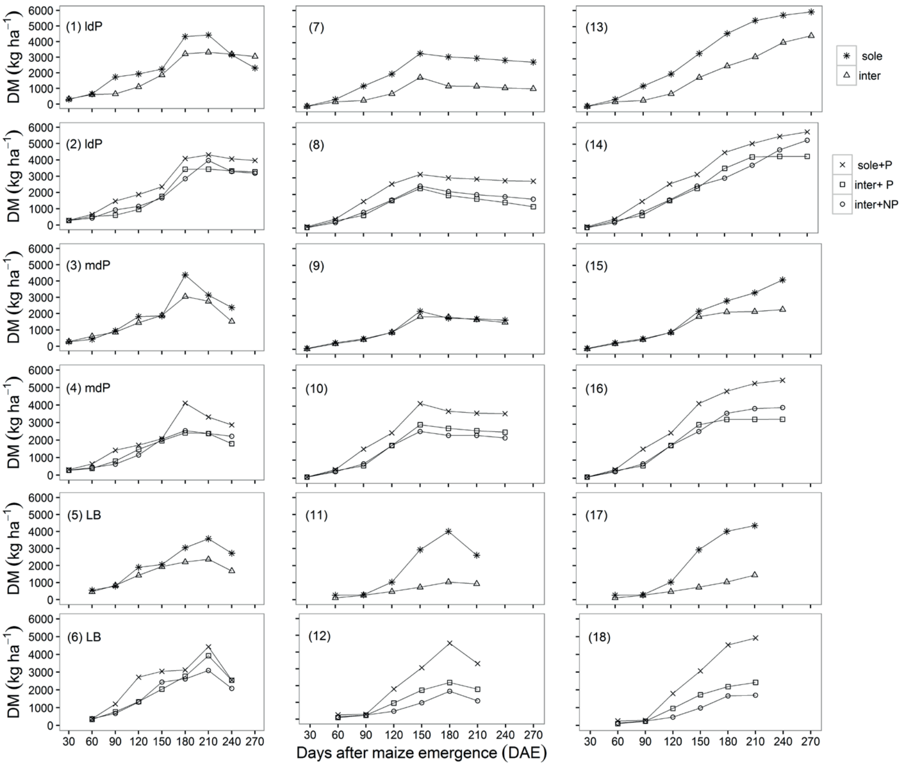

Fig. 6.5: Aboveground dry matter (DM) production of legumes in sole and intercrops as measured from on-farm experimental trials throughout the 2017/2018 (1-6) and 2018/2019 seasons; (7-12 with no leaf-fall quantification and 13-18 with leaf fall quantification) in Babati, northern Tanzania. ldP= long-duration pigeonpea; mdP= medium-duration pigeonpea; LB= lablab; inter= intercropped. Graphs within the same row represent similar treatments.

Managing the spatial arrangement of intercrops is also key to enhancing their productivity, as it determines the balance between intra- and inter-specific interactions. In our study, plant populations of approximately 44,444 plants ha^{-1} for each crop were maintained in both pure stands and intercrops, thus the population in intercrops was double that of sole crops. The additive within-row design of intercropping in our study may have partly contributed to the greater productivity of the intercrops. This is in line with the reported greater productivity of maize-grain legume intercrops when sown within the same row compared with sole crops in the Guinea savanna of northern Ghana (Kermah et al., 2017), Southern Mali (Falconnier et al., 2016) and Central Mozambique (Rusinamhodzi et al., 2012). Furthermore, the deep tap root (e.g., Fig. 6.2) of pigeonpea and lablab could extract water at a soil depth beyond 2 m even after cessation of rainfall. Consequently, this enabled them to grow during the dry period of the year after maize harvest, as reported in Kumar Rao et al. (2001) and Cook et al. (2005), resulting in both spatial and temporal niche differentiation.

Facilitative interactions of intercropping occur when one intercrop component increases the availability of resources to another component resulting in improved growth and survival (Hauggaard-Nielsen and Jensen, 2005). An example is whereby one component crop species can make more phosphorus (P) available to another in an intercrop (Zhang et al., 2004; Hinsinger et al., 2011). For example, phosphorus uptake by maize was significantly larger in a maize-faba bean intercrop than in sole maize, possibly due to organic acids excreted by faba bean, which facilitate P uptake by maize in the intercrop (Li et al., 2003). Furthermore, the use of hydraulic redistribution by a deep-rooted component species to improve water availability to another component of an intercrop has been reported (Caldwell and Richards, 1989; Burgess, 2011). In addition to the N-effects of legumes related to N_2 fixation, we also relate such non-N facilitative interactions of intercropping to the larger dry matter and grain yield of maize following two seasons of sole or intercropped legumes, than in plots with continuous maize as reported in Chapter 3 (Figs. 3.8 and 3.9). In our study, any effect of hydraulic redistribution is unlikely, as maize was harvested at the end of the rainy season, 3-4 months before the legumes.

6.6. Socio-economic implications of maize-legume intercrops

Maize-legume intercropping involves growing more than one crop, leading to crop diversification. Incorporating grain legumes into maize-based systems provides affordable nutritionally-balanced diets by adding proteins and micronutrients to starch-based diets (Kerr, 2007; Jager et al., 2019). This has been highlighted as one pathway for family nutritional gains (Berti et al., 2004), among others. In this sense, it can be viewed to eventually contribute towards Sustainable Development Goal (SDG) 2; zero hunger. For example, in our study, maize was harvested three to four months before pigeonpea. By the time pigeonpea was reaching maturity, some smallholder farmers were likely to have exhausted their maize stocks. In such a case, pigeonpea acts as a bridge through the hunger period, eventually providing food security to the smallholder farmers, where it is consumed as green pods or dry grain. After harvest, pigeonpea stems are used as firewood, a scarce resource in many areas of Tanzania (Myaka et al., 2006; Adu-Gyamfi et al., 2007). Furthermore, seed costs are low, partly because farmers can retain seeds from the previous season (Sakala et al., 2003).

Furthermore, intercropping has often been reported as an effective practice for pests, diseases and weed management (Trenbath, 1993; Stoltz and Nadeau, 2014; Zhang et al., 2019). For instance, the two component crops create complexity in food and habitat of pests, thus decreasing the population of budworm, leaf hopper and maize stalk borer (Maluleke et al., 2005; Kinama et al., 2018). Furthermore, any part of the soil surface that is not occupied by crop species is potentially subject to invasion by weedy species. Thus, a typically more vigorous crop species provides quicker, greater and more extensive soil coverage (Hauggaard-Nielsen et al., 2008). In our study, the ground was covered by pigeonpea and lablab dense canopies at a later stage of growth (Fig. 6.6), which helped to suppress weed growth and minimize the need for manual weeding.

Fig. 6.6: Canopies of pigeonpea and lablab at 120-150 days after sowing, providing a dense ground cover in Babati, northern Tanzania.

In addition to the potential improvement of direct food supply, the sale of legume grain contributes substantially to household income (Giller et al., 2019). There is a good market for the dry grain of pigeonpea and lablab. Pigeonpea has developed into an important cash crop in East and Southern Africa, which is mainly exported to India (Silim et al., 2005). Market surveys from Eastern Africa suggest that there is a high demand (and subsequently a reasonable price) for lablab in Kenya (Ngailo et al., 2003), where it is highly valued by the Kikuyu community for special festivities such as wedding ceremonies. In Chapter 3, maize-legume intercropping systems were superior to sole maize, for the additional grain yield from legumes, among others. A simple economic analysis to demonstrate the potential value of intercrops from the additional legume grain showed that intercrops were more valuable in almost all cases than sole crops, with an average of 44% and 36% greater gross margin in the 2017/2018 and 2018/2019 seasons, respectively (Table 6.1). This can be viewed to eventually contribute towards SDG 1; no poverty.

Table 6.1: A simple economic analysis to demonstrate the potential value of intercrops from the additional legume grain in Babati, northern Tanzania

Cropping system	Mean yield production (kg ha^{-1}) **(A)**		Price of grains (Tsh. kg^{-1}) **(B)**		Gross income from grains (Tsh. ha^{-1}) **(C; (A*B))**		[1]Cost of seeds ha^{-1} (Tsh.) **(D)**	[2]Cost of fertilizer ha^{-1} (Tsh.) **(E)**	Net income from grains (USD ha^{-1}) **(Total C-(D+E))**	
2017/2018	Maize	Legume	Maize	Legume	Maize	Legume			Tsh.	[3]USD
MZ	2888	-	500	-	1444167	-	72000	124200	1247967	555
MZ-ldP	2999	811	500	1300	1499333	1053867	72000	124200	2357000	1048
MZ-mdP	2945	692	500	1300	1472500	899600	72000	124200	2175900	967
MZ-LB	3300	1157	500	800	1650000	925600	72000	124200	2379400	1057
ldP	-	999	-	1300	-	1298700	-	71139	1227561	546
mdP	-	1109	-	1300	-	1441700	-	71139	1370561	609
LB	-	1730	-	800	-	1383600	-	71139	1312461	584
2018/2019										
MZ	1881	-	550	-	1034550	-	72000	123457	839093	366
MZ-ldP	2323	963	550	1200	1277833	1156000	72000	123457	2238377	977
MZ-mdP	2156	628	550	1200	1185800	754000	72000	123457	1744343	762
MZ-LB	1899	554	550	1000	1044633	553667	72000	123457	1402843	613
ldP	-	1365	-	1200	-	1638000	-	64223	1573777	688
mdP	-	1095	-	1200	-	1313400	-	64223	1249177	546
LB	-	1031	-	1000	-	1031000	-	64223	966777	423

[1] Legume seeds were sourced from TARI- Selian at no cost, so seed cost is for maize only. [2] +NP plots had only P- fertilizer applied to legumes, while N- fertilizer was spot applied to maize only. MZ= maize, ldP= long-duration pigeonpea, mdP= medium-duration pigeonpea, LB= lablab. [3] Exchange rate from Tsh. to USD = Tsh. 2250 and 2290 for 2017/2018 and 2018/2019 season respectively. The N was applied in the form of urea at the rate of 90 kg N ha^{-1}; urea fertilizer cost was Tsh. 900 and 1160 kg^{-1} in 2017/2018 and 2018/2019 season respectively. The P was applied in the form of triple superphosphate (TSP) at the rate of 40 kg P ha^{-1}; TSP fertilizer cost was Tsh. 1440 and 1300 kg^{-1} in 2017/2018 and 2018/2019 season respectively. Maize seed cost was Tsh. 6000 kg^{-1} in both seasons; maize seed rate = 12 kg ha^{-1}. Results are averaged over three fertilizer treatments (control, +P and +NP).

6.7. Concluding remarks and future research needs

This study assessed socio-economic factors, field management characteristics, and their association with the productivity of maize-pigeonpea intercrops. The study also explored ways of balancing the benefits of the inclusion of pigeonpea and lablab in the system, and minimizing potential disadvantages emanating from their competition with maize. This included a choice of various cropping systems and fertilizer treatments. We used a combination of farm household surveys, field experiments, and crop growth modelling on smallholder farming systems in northern Tanzania.

Large variability in the data and to some extent a lack of consistent relationships between response and independent variables were observed. We partly attribute the observed variability to the fact that the study was conducted on-farm, with diverse past management history, soil and weather patterns. The results of our study were based on pigeonpea sown simultaneously with maize, and lablab relay-planted one month later. With these timings, the main crop (maize) was hardly affected by the presence of a legume. We however cannot rule out that a slightly shorter or longer delay would have given a similar result, since this was not tested in the current study. We therefore recommend a study to explore the diversity of intercropping with differing sowing dates to provide farmers with additional options of intercrop systems for enhanced productivity. Also, we recommend a more detailed assessment of the occurrence and relevance of non-N effects of grain legumes to the associated or succeeding cereal crop.

Performance of the tested maize-legume intercropping systems was superior to sole maize, not only in terms of the additional grain yield from legumes, but also due to their residual effect in a succeeding cropping season. The benefits were even amplified by fertilizer application, as shown in Chapters 3 and 4. This was made possible mainly by the spatial and temporal niche differentiation exhibited by the intercrop systems as demonstrated in Chapter 5, indicating the suitability of the investigated cropping systems in our study. Thus, following the recommendation in Chapter 2, we reiterate on the importance of fine-tuning maize-legume intercrops through the application of organic and inorganic nutrient sources, as fertilizer application in our on-farm experimental trials resulted in enhanced yields and N uptake (Chapters 3 and 4). Additionally, optimizing the plant density as recommended in Chapter 2 by using an additive design (Chapters 3 and 4) where a similar plant population per crop was maintained in sole and intercrops partly contributed to the comparable productivity of the main crop (maize) when grown as sole or intercropped with a legume.

My results contribute to our understanding of how diversification through cereal-legume intercropping can lead to sustainable intensification of food production in smallholder farming systems.

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Incorporation of grain legumes into cereal-based cropping systems is common in sub-Saharan Africa, where cereals are mainly intercropped with legumes such as pigeonpea, beans, dolichos lablab and cowpeas. Benefits of cereal-legume intercropping include greater ground cover and suppression of diseases and pests, and in subsequent seasons include the increase in supply of N from nitrogen (N_2) fixation, improved soil health, weed (*Striga*) suppression and increased maize yields. In northern Tanzania, smallholder farmers commonly intercrop maize with legumes. This form of agriculture is practiced across a wide range of agro-ecological conditions. These crops form the basis of smallholder family food security and have further been identified as the engines of economic growth. This thesis focused on fine-tuning maize-pigeonpea/ lablab intercropping systems, by working towards striking a balance between maximizing the benefits of inclusion of pigeonpea and lablab in the system and minimizing potential disadvantages emanating from their competition with maize.

In Chapter 2, a farm-scale assessment of maize- pigeonpea productivity in northern Tanzania was done, to assess socio-economic factors, field management characteristics, and their association with productivity of maize-pigeonpea intercrops. Based on farmers' practice, biomass production ranged between 1.0 and 16.6 for maize, and between 0.2 and 11.9 t ha^{-1} for pigeonpea (at maize harvest). The corresponding grain yields ranged between 0.1 and 9.5 for maize, and between 0.1 and 2.1 t ha^{-1} for pigeonpea. From this chapter, we learnt that performance of intercrops can be enhanced through application of organic and inorganic nutrient sources, and agronomic interventions including weeding, implementing soil conservation measures on steep slopes and optimising plant density.

In Chapter 3, on-farm experimental trials comprising treatments with sole crops of maize, pigeonpea and lablab, as well as intercrops of maize with these legumes were conducted, with differing fertilizer application for two consecutive seasons (2017/ 2018 and 2018/ 2019), with a third season (2019/ 2020) where sole maize was grown. An evaluation of the growth and development of maize-pigeonpea and maize-lablab intercropping systems and their interaction with fertilizer showed that maize in intercrops was hardly affected by the presence of legumes, but the growth and yield of the intercropped legumes was negatively influenced by the presence of maize. The productivity of maize was positively influenced by N fertilization, but this was not the case for legumes, which responded positively to P fertilizer. For maize productivity, the difference between seasons was quite pronounced, with dry matter and grain production in the 2017/ 2018 season with up to 551 mm of rainfall being twice as high as in the 2018/ 2019 season, with up to 236 mm of rainfall. Legume productivity on the other hand was reasonably constant across the two seasons. The productivity of a sole maize crop grown in the 2019/ 2020 season following two seasons of legumes or legumes intercropped with maize was larger than in plots on which sole maize had been grown in the preceding seasons. Additionally, plots that had fertilizer applied in the preceding seasons had more productive maize crop, than control plots where fertilizer was not added. Thus, maize-legume intercropping with fertilizer application is effective in enhancing the productivity of smallholder cropping systems, and is superior to maize pure stands, not only for the additional grain yield from legumes but also due to the residual effects in a succeeding cropping season.

Using the same experimental trials as in Chapter 3, Chapter 4 studied the effects of cropping systems and fertilizer use on nitrogen fixation and nitrogen uptake of the component crops in maize-legume intercrops. Sole long-duration pigeonpea fixed more N_2 than all other cropping systems, corresponding to the higher shoot dry matter and N yield of this system. The combined N uptake of maize and legume in intercrops was consistently larger than that of pure stands of either maize or legumes. In the intercrops, the amount of N accumulated by maize was in most cases larger than that of the legume. Furthermore, sole legumes had consistently larger total N uptake than the intercropped legumes, whereas such consistency was lacking for maize. Application of fertilizer resulted in enhanced N uptake both in the current season and in a succeeding maize crop. Furthermore, we observed positive associations between grain yield, dry matter production and total N uptake of a succeeding maize crop, and the N-fixed by legume species in the preceding season. These insights underpin the fact that inclusion of grain legumes either as sole crop or intercropped with maize has a direct positive effect on maize productivity, which is carried over into the subsequent season.

In Chapter 5, a parameter-sparse model was developed using Fortran Simulation Translator (FST) language, and was used to ascertain to what extent the productivity of maize – grain legume systems in northern Tanzania is limited by water availability. We observed that under rain-fed conditions, maize is dependent on the amount of water available, whereby water stress led to reduction in dry matter production amounting to 2330 kg ha^{-2}. Legumes are dependent on their deep rooting system for production, whereby biomass reduction of up to 34% was recorded when their rooting depth was assumed to be similar to that of maize.

Chapter 6 provides a general discussion of the findings generated in the thesis in the light of existing literature. The limitations of the current thesis are also highlighted, including recommendations for further research.

This thesis improves our understanding of maize-legume intercropping systems both within and across seasons and provides valuable information that could help fine-tune these systems for increased productivity. We observed that major benefits of inclusion of pigeonpea and lablab in the system can be achieved, with minimum potential disadvantages emanating from their competition with maize productivity. In the case of maize-pigeonpea, maize productivity is not affected when the two crops are sown simultaneously, likely due to the initial slow growth of pigeonpea. In the maize- lablab intercrops, the latter which has a sprawling habit can be relay-planted one month after maize sowing, to reduce competition with maize.

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About the author

Esther Mugi was born on 1st May 1985 in Mathira East, Kenya, where she grew up and attained her primary and secondary education. In 2005, she joined the University of Nairobi and graduated in 2009 with a BSc (Agricultural Education and Extension). After graduation, she worked as a project assistant in an AGRA-funded project under Kenyatta University, focusing on enhancing productivity and market development of soybeans and climbing beans in the central highlands of Kenya. In 2012, she enrolled for an Msc in Environmental Studies (Agro-forestry and Rural development) at Kenyatta University. Her Msc work was through a project focusing on enhancing crop productivity through soil-water conservation and integrated drought prediction and preparedness techniques in the drier zones of central highlands of Kenya. Esther completed her Msc studies in 2014 and joined the International Plant Nutrition Institute (IPNI), Sub-Saharan Africa program in Nairobi, Kenya (currently APNI). She was in charge of implementation of activities in a project focusing on enhancing capacity for dissemination of site-specific maize production intensification technologies under variable farm, climatic and soil fertility conditions in sub-Saharan Africa, through collaborations with local and regional research institutes and universities. It was while working with IPNI that the idea of pursuing PhD studies was mooted, and she was admitted as a PhD candidate in the Plant Production Systems (PPS) group of Wageningen University under a sub-grant from USAID to Michigan State University. Her PhD focused on diversification and intensification of smallholder farming through intercropping with grain legumes in northern Tanzania.

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List of publications

Peer reviewed scientific publications

Mugi-Ngenga, E., Bastiaans, L., Zingore, S., Anten N. P. R., Giller, K. E. (2022). The role of nitrogen fixation and crop N dynamics on performance and legacy effects of maize-grain legumes intercrops on smallholder farms in Tanzania. Accepted for publication in the European Journal of Agronomy.

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Mugi-Ngenga, E., Zingore, S., Bastiaans, L., Anten N. P. R., Giller, K. E. (2021). Farm-scale assessment of maize-pigeonpea productivity in northern Tanzania. Nutrient Cycling in Agroecosystems, 120: 177-191. https://doi.org/10.1007/s10705-021-10144-7.

Mugi-Ngenga, E., Kiboi, M., Mucheru-Muna, M., Mugwe, J., Mairura, F., Mugendi, D., Ngetich, F. (2021). Indigenous and conventional climate-knowledge for enhanced farmers' adaptation to climate variability in the semi-arid agro-ecologies of Kenya. Environmental Challenges, 100355. https://doi.org/10.1016/j.envc.2021.100355.

Mucheru-Muna, M., Ada, M., Mugwe, J., Mairura, F., **Mugi-Ngenga, E**., Zingore, S., Mutegi, J. (2021). Socio-economic predictors, soil fertility knowledge domains and strategies for sustainable maize intensification in Embu County, Kenya. Heliyon, 7: e06345. https://doi.org/10.1016/j.heliyon.2021.e06345.

Murimi, D., Mucheru-Muna, M., **Mugi-Ngenga, E**., Zingore, S., Mutegi, J. (2020). Nutrient management options for enhancing productivity and profitability of conservation agriculture under on-farm conditions in central highlands of Kenya. AIMS Agriculture and Food, 5: 666-680. https://doi.org/10.3934/agrfood.2020.4.666.

Mugi-Ngenga, E., Mucheru-Muna, M., Mugwe, J., Ngetich, F., Mairura, F., Mugendi, D. (2016). Household's socio-economic factors influencing the level of adaptation to climate variability in the dry zones of Eastern Kenya. Journal of rural studies, 43: 49-60. http://dx.doi.org/10.1016/j.jrurstud.2015.11.004.

Submitted article

Mugi-Ngenga, E., Bastiaans, L., Anten, N. P. R., Zingore, S., Baijukya, F., Giller, K. E. (submitted). The role of inter-specific competition for water in maize- legume intercropping systems in northern Tanzania.

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (6 ECTS)

- A review of small-holder farmers' maize-legume systems in Tanzania

Writing of project proposal (4.5 ECTS)

- Sustainable intensification through optimization of maize- pigeonpea/ lablab based intercropping systems in northern Tanzania

Post-graduate courses (4.7 ECTS)

- Statistical data analysis with R; online; Code academy (2017-2022)
- Farming systems and rural livelihoods; PE&RC (2018)

Laboratory training and working visits (1.5 ECTS)

- Laboratory training and working on samples processing; TARI-Selian, Tanzania (2019)

Invited review of (unpublished) journal manuscript (2 ECTS)

- Journal of Agriculture and Rural Development in the Tropics and Subtropics (JARTS): adoption and utilisation of Zai pits for improved farm productivity in drier upper Eastern Kenya (2019)
- Ecological Applications: Perennial legume intercrops provide multiple belowground ecosystem services in smallholder farming systems (2020)

Deficiency, refresh, brush-up courses (3 ECTS)

- Research methods in crop science; CSA (2016)
- Systems analysis, simulation and systems management; PPS (2016)

- Feeding a hungry planet: agriculture, nutrition and sustainability; SDGacademy (2019-2020)

Competence strengthening / skills courses (2.95 ECTS)

- Information literacy including Endnote introduction (ILP); WUR Library (2016)
- Reviewing scientific paper; WUR Library (2018)
- Research data management; WUR Library (2018)
- Writing scientific research articles: strategy and steps; International Plant Nutrition Institute (IPNI) (2018)
- Ethics in plant and environmental sciences; WGS (2019)

PE&RC Annual meetings, seminars and the PE&RC weekend (2.4 ECTS)

- PE&RC First year weekend (2016)
- PE&RC Midterm weekend (2018)
- PE&RC Last year weekend (2019)
- PE&RC Day (2019)

Discussion groups / local seminars / other scientific meetings (6.3 ECTS)

- Sustainable Intensification of Agricultural Systems (SIAS) discussion group (2016-2019)
- RUsers meeting (2016-2019)
- Lunchtime seminars; PPS & CSA (2016-2019)
- Training workshop for fertilizer stakeholders, Nairobi, Kenya (2017)
- Sustainable Agriculture Matrix (SAM): stakeholder workshop, Nairobi, Kenya (2022)

International symposia, workshops and conferences (7.6 ECTS)

- Cropping systems design modelling workshop; Lilongwe-Malawi (2017)
- 5th ECHO East Africa symposium on sustainable agriculture and appropriate technologies; Arusha-Tanzania (2019)
- 1st African Conference on Precision Agriculture (AFCPA); online (2020)
- Legume science and practice; online (2021)

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