FILLING IN THE GAPS ON SMALLHOLDER MAIZE-LEGUME FARMING SYSTEMS TO ADDRESS FARMER NEEDS IN TANZANIA

By

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ABSTRACT

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Smallholder farming systems in sub-Saharan Africa (SSA) are faced with the major sustainability challenge of increasing production on land with declining fertility. Legume intensification has been proposed as an important pathway for ecologically-sound, sustainably intensified production on smallholder farms, yet numerous challenges stand in the way of enhanced adoption and intensifying production of legumes. Promising legume technologies demonstrated on research stations often fail to be adopted on smallholder farms. Yet, this is where they are needed the most. Legume production is a knowledge intensive enterprise, and as such requires effective extension systems. Addressing challenges in legume production requires understanding the disconnects between research and farmer practice in order for technologies to be developed and disseminated that fit within smallholder farming conditions.

This dissertation consists of three studies focused on maize-legume cropping systems in Tanzania at different scales. An interdisciplinary approach was used to evaluate legume production through integrating field trials, on-farm assessments, and analysis of Tanzania extension systems. In the first study, 14 lablab (*Lablab purpureus*) accessions were evaluated by environment through a multi-site, multi-year field experiment using performance and biological nitrogen fixation measurements. This allowed for determination of suitability in sole and maize intercrop systems to identify appropriate accession types for Tanzanian smallholder farming systems. The second study used survey data from households across Northern and Southern highlands of Tanzania (n=578) with linked soil samples to assess how soil properties and erosion signs are related to farmer perceptions and practices. Additionally, a subset of farms was used to test a new extension approach to quantify site-specific soil degradation, facilitated by the smartphone application LandPKS. In the third study, extension systems and sources of information were evaluated and compared to farmer practices associated with legume production systems to better understand connections and disconnects. Traditional extension and a novel approach involving village-based advisors were explored through mixed methods, including in-depth characterization of farmer legume production systems. Findings from each study highlight how to facilitate the sustainable intensification of legume production at different levels and address the multi-faceted needs of smallholder farmers.

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Chapter 1: Investigating the diverse potential of a multi-purpose legume, *Lablab purpureus* (L.) Sweet, for smallholder production in East Africa

Abstract

Climate change is posing severe challenges in Africa, where resilient crops are urgently needed to withstand drought periods and unreliable rainfall. Multi-purpose legume species, such as lablab (*Lablab purpureus* (L.) Sweet), have been under-utilized yet have the potential to overcome climate challenges. While lablab is native to Africa, there are few characterized varieties and it is under-utilized by smallholder farmers due to a lack of information and access to varieties. Knowledge is especially lacking on the performance of this crop by genotype, management, and environment. We conducted a two-year field study at two sites to evaluate 29 lablab cultivars under sole and maize intercrop management, with 14 cultivars selected for in-depth study. Cultivars were evaluated on vegetative biomass and grain yield production, with N fixation assessed for one site year. Biomass and grain production differed across environments and cultivars, with only biomass affected by intercropping. Average grain yield was substantially reduced to only 37 kg ha^{-1} in environments with maximum temperatures greater than 33°C, but biomass production yielded comparable amounts across high temperatures and in dry (<500 mm rainfall) environments. Tradeoffs were found between biomass and grain yield across high yielding cultivars, with the top three grain accessions averaging 612 kg ha^{-1} of grain and 1.97 Mg ha^{-1} biomass whereas the top three biomass accessions produced 327 kg ha^{-1} grain and 2.52 Mg ha^{-1} biomass across all environments. In a comparison of production and N fixation measurements, cultivars were identified which may have high performance in both. Suitability of lablab for grain and biomass production were visualized across Tanzania in a map comparing max temperature thresholds for grain and biomass against average regional livestock

populations. This provides a way forward for identifying potential areas for lablab cultivation as a novel means to enhance fodder and pulse production with smallholder farmers.

Introduction

As African populations exponentially increase under current food production dominated by smallholder agriculture, intensification without further degrading the natural resources of these systems is greatly needed (Pretty, Toulmin, & Williams, 2011). Legume intensification is one pathway through which smallholder farmer production may be sustainably increased and involves complementing a farmer's current cropping system through incorporating legumes (S.S. Snapp & Silim, 2002). Smallholder farmers have historically grown legumes in ways that have complemented cereal and cash crops, such as maize bean rotations and cereal-legume intercrops (K. Giller, 2001). Increasing this legume presence in maize cropping systems provides many potential benefits such as increased crop diversity, improved soil fertility without the overuse of chemical inputs, increased household dietary diversity, and increased cash income through sale of high market-value legumes (Pretty et al., 2011). Despite these benefits, maize monocrops have continued to be promoted to smallholder farmers, at the expense of legume production. Challenges to increasing legume production, such as limited availability of legume seed, pest problems, lack of markets, and low yields, have held farmers back from adopting more legume intensive systems, and must be addressed for sustainable intensification to occur.

Challenges to legume production have been exacerbated by the limited nature of legume research and minimization of the multi-purpose nature of legumes. Legume studies often prioritize either the grain or forage potential of the study crops, with less focus on the tradeoffs or interactions of these traits (Sinclair & Vadez, 2012; Duc et al., 2015). Studies on farmer objectives in growing legumes however confirm that farmers have multiple production objectives in growing legumes and consider other benefits besides just grain yield in choosing to cultivate legumes, such as improving soil fertility (S.S. Snapp & Silim, 2002; Waldman, Ortega, Richardson, Clay, & Snapp, 2016; Muoni et al., 2019). A legume's ability to improve soil fertility through nitrogen (N) fixation depends on many different factors, including genetics, management and the environment (K. Giller, 2001). N contribution by a legume therefore must be considered across these factors to fully understand the legume's effect within a system. The diverse objectives of farmers must be considered in order for appropriate legumes to be identified that will meet farmer production needs and improve farming systems. As such, studies should evaluate legume potential from multiple angles, such as grain, forage, and N fixation potential, across diverse cultivars and environments for a more robust assessment of these crops.

Typical legume studies, such as those for common bean and cowpea, focus on sole cropping and singular productivity measurements in assessing crop potential and potential across cultivars (Kang, Aggarwal, & Chirwa, 2006; Hendrie, Francisco, Valdenir, & Regina, 2014; Torres et al., 2016; Ochieng, Ojiem, Kamwana, Mutai, & Nyongesa, 2019). There is therefore a lack of quantifying multiple production traits and understanding tradeoffs of these traits within cultivars and in systems that resemble local farmer context, such as in an intercrop with maize. Many cultivar studies have instead focused on finding a few top grain producing types that fit across environments (Chibarabada, Modi, & Mabhaudhi, 2017). However, identifying appropriate legume cultivars that fit within different farming systems requires testing diverse cultivars for multiple production qualities and testing their performance under different environment and management conditions.

Overall there is a need for better understanding of environment and management parameters of legumes, especially those with multipurpose traits. Previous legume studies have been too empirical and fail to look at legume management as a system within which growing parameters may be established (Franke, Van Den Brand, Vanlauwe, & Giller, 2017). This is especially true for understudied multipurpose legumes, and there are few systematic studies that identify ways of introducing novel crops. Lablab (*Lablab purpureus* (L.) Sweet) is one such understudied legume with limited study of its diverse genetic collection and evaluation of its multipurpose qualities (Maass et al., 2010). Our study takes a multi-dimensional approach to assessing lablab amongst different genetic sources, environments, and management, across which these effects are not well understood for lablab. Our overall objective was to identify promising lablab accessions and suitable growing conditions to inform lablab integration into smallholder farming systems. Specifically, we aimed to identify lablab accessions that are high yielding and stable across environments as well as those that perform best in terms of grain yield and biomass in specific environments and sole cropped or intercropped with maize. We further wanted to assess accession performance across vegetative biomass, N fixation, and grain yield to determine whether some accessions have high multipurpose potential or if accessions are more likely to perform well in one trait over another.

Materials and Methods

Study Sites

The study was conducted over the 2016 and 2017 growing seasons at two sites in the Northern Zone of Tanzania, one at the Tanzania Agricultural Research Institute Selian Centre (SARI) located in Arusha and the other at the Tropical Pesticides Research Institute (TPRI) research farm in Miwaleni, Moshi. The SARI site is at an altitude of 1387 MASL with a mean annual rainfall of 1052 mm and mean annual temperature of 19.5 °C. The TPRI site represents lowland areas at 719 MASL with a mean annual rainfall of 600 mm and mean annual temperature of 23.5°C. Both sites are weakly bimodal, with the majority of rainfall occurring in March through May and a short rain period between November and January. Most field crops are planted in the longer rain period of March – May whereas few crops are planted in the unreliable rains that occur November – January.

Experimental Design

The experimental design of the field trials included two factors, accession and cropping system, arranged in a modified split plot with three blocks replicated at each site. The accessions consisted of 29 lablab accessions and 3 cowpea varieties chosen as a reference crop. The lablab accessions included a selection from a core collection identified by Pengelly and Maass (2001) with 5 varieties registered in Kenya and landraces collected throughout East Africa. This study focuses on measurements from 14 lablab accessions chosen as a subset of the 29 total accessions studied with one of the cowpea varieties chosen for reference. Description of the full 29 accessions can be found in Miller et al. (2018) with preliminary performance assessment. The 14-accession subset was chosen based on those that had shown promise from early observations of the full set of accessions, with the goal of selecting cultivars with a range of growth types (Table 1.1). Four of these accessions were subsequently chosen for further study through on-farm trials with the purpose of selecting a final set of accessions for registration. The cropping system factor consisted of each lablab accession sole-cropped or intercropped with maize (Pannar 15). To simplify field operations, cropping system was randomly arranged within blocks in strips of consecutive intercropped or sole-cropped plots. Each strip had either 8 plots (SARI) or 7 (TPRI). One sole maize plot was also included in each block. Individual plots were 4.5 by 5.4 m with 1.5 m unplanted borders between plots within strips. Lablab spacing was 0.9 m between rows and 0.5 m within rows with five rows per plot and two seeds planted per station (4.4 seeds m^{-2}).

Cowpea spacing was half that of lablab, with 0.45 m between rows and 0.5 m within rows. Planting was done in an additive design, where lablab and cowpea spacing was the same intercropped with maize as it was sole cropped. Maize was planted between rows with lablab or cowpea, with six rows per plot at 0.9 m between rows and 0.5 m within rows and two seeds planted per station for a seeding rate of 4.4 seeds m^{-2}. One maize row was planted at the borders of all sole cropped plots to ensure uniform shading regardless of whether sole-cropped plots were adjacent to intercropped plots.

Table 1.1 Lablab accessions and cowpea reference variety used in the study

No.	Accession	Maturity	Seed color	Seed Wt. (g/100 seeds)	Qualities	Origin	Other Properties
1	CIAT 22759	Early-mid	Black	30	Indeterminate	Kenya	Forage type
3	DL1001	Late	Brown	23	Indeterminate	Kenya	Dual purpose
4†	DL1002	Early	Black	26	Semi-determinate	Kenya	Popular landrace
6†	Echo Cream	Mid	White	30	Indeterminate	Tanzania	
8	Highworth	Early	Black	25		India	Forage variety, Popular forage variety
12	ILRI 13700	Very late	Black	38	Vigorous growth	Ethiopia	
14	ILRI 14437	Early-mid	Black	23		Unknown	
16	ILRI 6930	Early-mid	Brown	31	Long pods, high biomass	Unknown	Drought tolerant
17†	Karamoja Red	Mid	Red	36		Uganda	
21	PI 195851	Very late	Dark brown	23	High biomass, low grain	Egypt	Drought tolerant
22†	Q 6880B	Very early	Black	22	Short-season	Brazil	Dual purpose
23	Rongai	Very late	Tan	26	Indeterminate	Kenya	Popular forage variety
25	SARI Nyeupe	Late	White	28		Tanzania	
26	SARI Rongai	Mid	Black	30		Tanzania	
31	Fadhari cowpea	Mid-late	Red	11	Spreading growth	Tanzania	

†Accessions chosen for continuation to on-farm trials

Management

The first trial was established in March of 2016, with field preparation and plantings occurring in early March at the SARI site. Maize was planted first at SARI on 11 March 2016, with lablab seeded 12 days later. The TPRI site was started later, with maize planted on 6 April 2016 and lablab seeded 8 days later. In 2017, maize was planted at the SARI site on 17 March 2017 and lablab seeded 3 days later. Maize planting at TPRI site started earlier on 8 March 2017 and lablab seeded 6 days later. Across all sites and years DAP fertilizer (18-46-0) was applied to maize at planting with a rate of 77 kg ha^{-1}. Urea (46-0-0) was side dressed at 110 kg ha^{-1}. Fields were tilled with a disc plow in 2016 but planted without tillage in 2017. Weed control was achieved using a pre-plant glyphosate application (2.5 L ha^{-1}) at planting, and by hand-hoe throughout the growing season as needed. Insecticide was applied as needed at both sites as significant insect pest damage was observed.

Plant and Soil Measurements

Above-ground biomass was sampled for the lablab subset previously identified to quantify biomass yields and sample tissue for ^{15}N analysis. Destructive sampling of plants was done during the early podding growth stage. In 2016 this occurred at SARI end of June and mid-July and end of July at TPRI. In 2017 biomass was sampled beginning of July at SARI and end of May at TPRI. Plants were sampled within a 0.9 m by 3 m sampling frame in 2016 and a 0.9 m by 2 m sampling frame in 2017. Fresh weight of lablab was measured in the field, and sub samples were taken for dry weight and further sampling. In 2017, root and nodule biomass were recorded from the SARI site from the sole cropped plots of the lablab subset. Roots were sampled from three locations per plot using a soil corer (4,415 cm^3) centered over a lablab plant. All nodules from the root samples were counted with color recorded to determine effectiveness and weighed after drying. Above-ground biomass sub-samples were oven dried at 70°C, ground in a Wiley mill through a 0.5 mm then finely ground in a ball mill in preparation for ^{15}N analysis. Samples were sent to the University of California Davis Stable Isotope Facility, CA, USA for ^{15}N analysis using a PDZ Europa 20-20 isotope ratio mass spectrometer. The resulting ^{15}N natural abundance of the samples was calculated using the following equation: $\delta^{15}N(‰) = 1000\left[\left(\frac{R_{sample}}{R_{standard}}\right) - 1\right]$ where $\delta^{15}N$ is expressed in parts per thousand (‰) and R is the ratio of $^{15}N/^{14}N$ in the sample (Shearer & Kohl, 1986).

Maize grain yield was determined from a sampling frame of 3 m across 2 rows (2016) and 3 rows (2017) within each plot. Grain was air dried then weighed and moisture content of the grain recorded. Due to the range of maturity between lablab accessions, and the indeterminate nature of most accessions, lablab grain harvest began as soon as dried pods were present and continued across several months during which most plots were harvested multiple times. In 2016 this occurred over five harvest dates at SARI and two at TPRI. In 2017 SARI lablab harvest had four harvest dates and TPRI harvest occurred over three dates. Lablab pods were hand-harvested using a 3 m x 4.5 m sampling frame. In addition to weighing dry pod weight at each harvest date, pods from all harvest dates were combined to be threshed and weighed for determination of plot yield.

Soil samples were taken from each site for baseline soil properties at 0 -20 cm and 20 – 40 cm depths, presented in the appendix Table 1.3. A composite soil sample was collected for each block and analyzed for texture, pH, EC, and P. Additional soil samples were taken at the SARI site from the lablab subset plots following the 2016 and 2017 growing seasons to analyze soil nitrate and ammonium using a 2 M KCl extraction.

Meteorological data

Rainfall data was collected at both locations for the 2016 and 2017 growing seasons. SARI rainfall measurements were reported by the Arusha Airport weather station located approximately 1.4 km away and TPRI rainfall measurements were obtained from a rain gauge located on site. Temperature data was retrieved through remote sensing from the Terra MODIS dataset provided by the USGS as day and night temperatures in 8-day increments at a 1 km resolution (Wan, Hook, & Hulley, 2015). These temperatures were averaged per month across 2016 and 2017 and reported for the main growing season (January – September).

Land equivalency ratio

The efficiency of the lablab-maize intercrop compared to sole cropping was evaluated using the land equivalency ratio (LER). LER is defined as $LER = \frac{Y_1}{M_1} + \frac{Y_2}{M_2}$ where Y_1 and Y_2 are the intercrop yields of crop 1 and crop 2 and M_1 and M_2 are the sole cropped yields of crop 1 and crop 2. In this study Y_1 and M_1 were defined as maize grain yield intercropped and sole cropped respectively (Willey, 1985). Given that lablab is often grown both for grain and fodder, two types of LERs were calculated to assess production of grain yield and fodder in intercrop systems with maize. The grain LER defined Y_2 as lablab grain yield intercropped and M_2 as sole cropped grain yield. The fodder LER defined Y_2 as lablab biomass intercropped and M_2 as sole cropped biomass. LER was calculated per accession by block within each environment and results are reported as average LER for each site year.

Data Analysis

Lablab biomass and grain yield were analyzed by a three-way analysis of variance (ANOVA) in SAS 9.7 using PROC MIXED to compare differences across environments (year by site), accession, and management (intercrop vs. sole crop). The model included block nested within environment and management by block as random effects. Maize yield was analyzed by a two-way ANOVA to compare differences across environment and accession. In this model block nested within environment was set as a random effect. While the cowpea variety (#31) yields are presented for comparison, they were not included in statistical analyses with lablab and instead were analyzed separately for differences between environment and management.

A principal component analysis (PCA) was done using PROC PRINCOM in SAS to generate variables representing crop productivity and nitrogen fixation within sole cropped lablab plots at SARI in 2017 and to assess multivariate accession effects. All data points for each of the 14 accessions across three blocks were used in the analysis. Variables included lablab grain yield, biomass, soil nitrate, nodule weight, $\delta^{15}N$, maturity (days to 50% flowering), plant population, and %N of biomass. Principal components with eigenvalues greater than 1 and accounting for more than 15% of the variability in the data were retained. Principal components 1 and 2 were further analyzed by a one-way ANOVA with block set as a random effect to compare accessions across components with the Tukey-Kramer test used to identify accession mean differences (alpha=0.05).

Analysis of multivariate stability statistics was done with the accession main effect plus accession by environment interaction for grain yield and biomass using the GGEBiplotGUI package with RStudio in R statistical software. Two biplot views, “mean vs. stability” and “which-won-where” were used to visually assess accession performance across environments for grain yield and biomass as well as to determine tradeoffs among high performing accessions for both traits. These biplots have been identified as best capturing genotype by environment effects for multi-environment variety trials (Yan, Kang, Ma, Woods, & Cornelius, 2007). Accession measurements were averaged across management practices for each environment to obtain mean performance for each trait which was subjected to the GGE biplot analysis. The data in "Mean vs. Stability" view was not scaled (Scaling = 0), environment-centered (Centering = 2) and based on genotype-focused singular value partitioning (SVP = 1). The "which-won-where" model parameters were also set on un-scaled data (Scaling=0), environment-centered (Centering=2) and environment focused singular value partitioning (SVP=2)(Yan & Tinker, 2006).

Results

Weather

Rainfall across both study years was below average and unevenly distributed across months for both sites. In 2016 the SARI site had 315 mm rainfall between January and September, with the majority of rainfall occurring between January and April (Figure 1.1A). For the same time period the TPRI site had 252 mm of rainfall with the majority of rainfall occurring in April after the field trials were planted (Figure 1.1B). In 2017 the SARI site had 463 mm of rainfall with the majority occurring in April and May, later in the year than 2016. The TPRI site had 311 mm of rainfall in that same time period, with the majority of rainfall also occurring in April and May. Temperatures at SARI were consistent across the two years, with average maximum/minimum temperatures during the lablab growing period (March – September) of 29°C/16°C in 2016 and 28°C/16°C in 2017 (Figure 1.1). Average maximum/minimum temperature for TPRI was higher than SARI. In 2016 the TPRI site was 36°C/20 °C and in 2017 it was 33°C/19 °C. The high temperatures in 2016 mostly occurred between March and May.

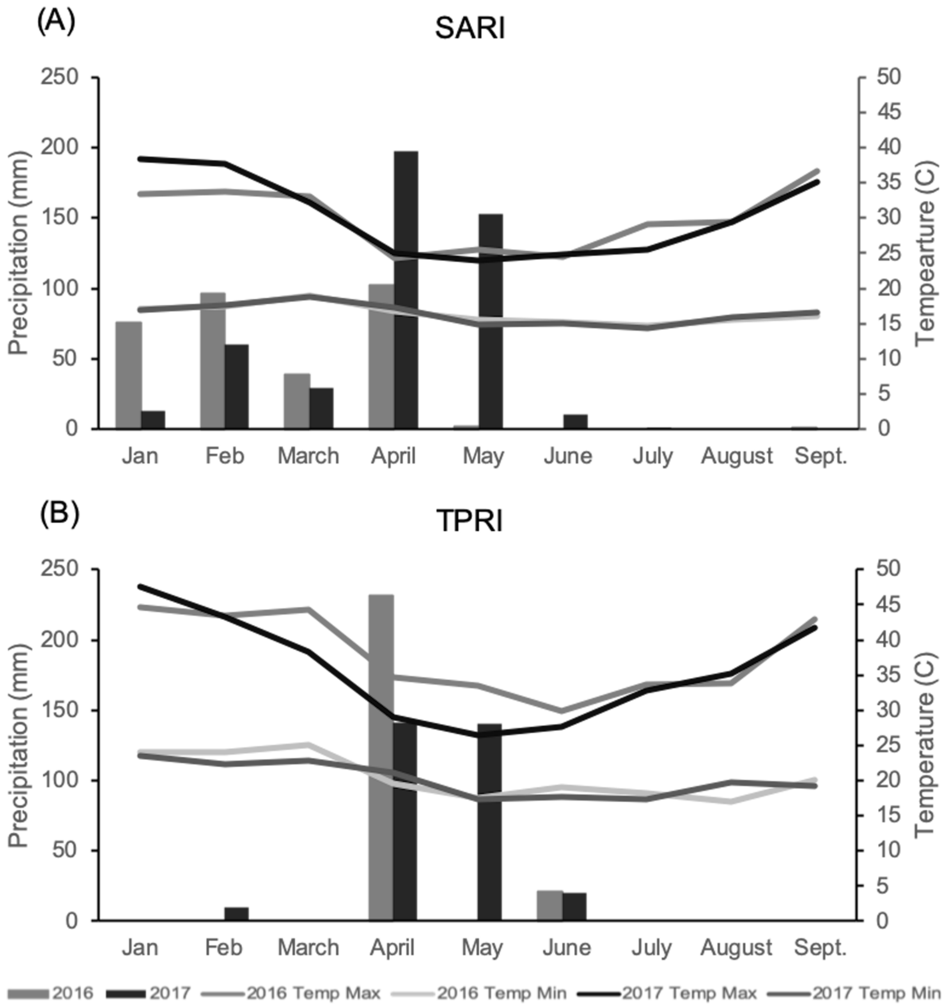

Figure 1.1 Monthly precipitation and temperature for two growing season years across environments. (A) SARI location (B) TPRI location.

Productivity across environments

Overall environment had a strong influence on all measures of productivity, including lablab grain yield, biomass, and maize yield (Figure 1.2, Appendix – Table 1.4). All lablab accessions produced low to nil grain yield at the TPRI site across both years, with averages of 31 kg ha^{-1} in 2016 and 42 kg ha^{-1} in 2017 (Figure 1.2C-D). Many late-flowering accessions did not set seed due to drought stress during reproductive stages. The highest grain yield in 2016 at TPRI was 116 kg ha^{-1} produced by CIAT 22759 (#1) and in 2017 Q 6880B (#22) had the highest yield with 355 kg ha^{-1}. In contrast, the SARI site had medium to high average grain yields of 394 kg ha^{-1} in 2016 and 1067 kg ha^{-1} in 2017 (Figure 1.2A-B). Accession differences in grain yield were seen at the SARI site. In 2016 Karamoja Red (#17) had the highest grain yield at 1001 kg ha^{-1} and in 2017 DL1002 (#4) had the highest grain yield at 2029 kg ha^{-1}. Grain yield did not differ under intercropped vs sole crop management across all environments (Table 1.4). Grain yield of the cowpea reference species (#31) was higher than all lablab accessions at the TPRI site, with 224 kg ha^{-1} in 2016 and 1071 kg ha^{-1} in 2017. At the SARI site, cowpea out yielded all but one lablab accession in 2017, with a yield of 1864 kg ha^{-1} whereas in 2016 it only yielded 395 kg ha^{-1}, which ranked it midway among lablab accessions for that same year. No evidence of cowpea grain yield reduction was found under intercrop vs sole crop management.

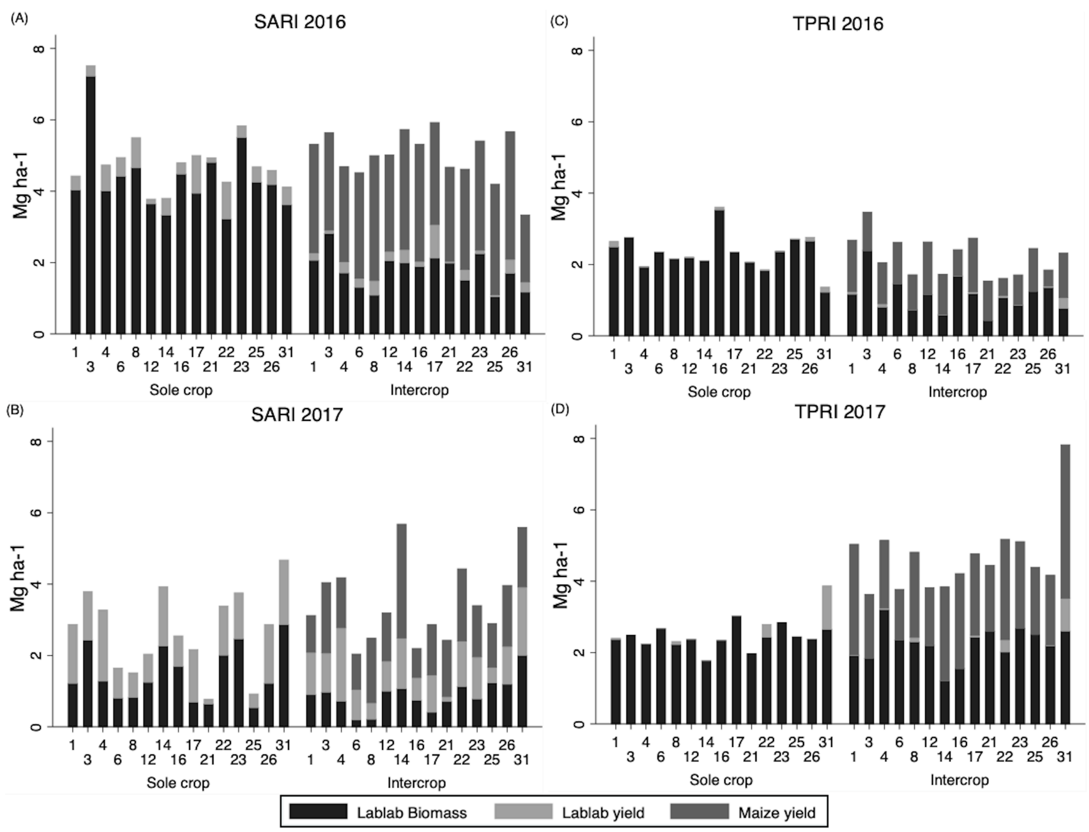

Figure 1.2 Grain and biomass yield across the four environments sole planted and intercropped with maize. (A) SARI 2016 (B) SARI 2017 (C) TPRI 2016 (D) TPRI 2017.

Biomass production differed across environments, accession, and by management (Figure 1.2, Table 1.4). In contrast to grain yield, biomass produced at TPRI was comparable to that produced at SARI. Sole cropped lablab generally produced greater biomass than intercropped lablab, except for TPRI 2017 where the final maize population averaged only 20,200 ha^{-1}. Among sole cropped lablab, SARI 2016 had the highest biomass (4.4 Mg ha^{-1}), whereas SARI 2017 had the lowest (1.4 Mg ha^{-1}). Intercropped lablab produced the greatest biomass at TPRI 2017 (2.2 Mg ha^{-1}) and lowest at SARI 2017 (0.80 Mg ha^{-1}). Within environments, in SARI 2016 DL1001 (#3) had the highest biomass overall (5.02 Mg ha^{-1}) and Q 6880B (#22) the lowest (2.4 Mg ha^{-1}). In SARI 2017 DL1001 was again the highest biomass producer (1.7 Mg ha^{-1}) and Echo Cream (#6) the lowest (0.5 Mg ha^{-1}). DL1001 was also the highest biomass producer at TPRI in 2016 along with ILRI 6930 (2.6 Mg ha^{-1}), whereas the lowest in this environment was PI 195851 (#21) (1.2 Mg ha^{-1}). In 2017 at TPRI the top biomass producers overall (2.8 – 2.7 Mg ha^{-1}) were Rongai (#23), Karamoja Red (#17), and DL1002 (#4) and the lowest (1.5 Mg ha^{-1}) was ILRI 14437 (#14).

Biomass for the cowpea reference crop followed similar trends to lablab biomass, with sole cropped cowpea generally producing greater biomass than intercropped cowpea ($p=0.0053$; Figure 1.2). In SARI 2016 sole cropped cowpea produced 3.6 Mg ha^{-1}, but only 1.1 Mg ha^{-1} intercropped. In 2017 at SARI biomass produced by sole cropped cowpea was 2.9 Mg ha^{-1} and 2.0 Mg ha^{-1} intercropped. Cowpea biomass at TPRI in 2016 was 1.2 Mg ha^{-1} sole cropped and 0.8 Mg ha^{-1} intercropped. In 2017 cowpea biomass at TPRI was twice and three times as high as sole and intercropped 2016 amounts, at 2.6 Mg ha^{-1} under both sole cropped and intercropped management.

Maize yield was also considered in assessing the productivity of intercropped lablab. Maize yield was not affected by accessions and only differed across environments (Table 1.4). Maize yield was highest at SARI in 2016, with 3.0 Mg ha^{-1} and lowest at TPRI in 2016 with 1.1 Mg ha^{-1}. Maize yields in 2017 were within this range, with 2.3 Mg ha^{-1} at TPRI and 1.6 Mg ha^{-1} at SARI.

Intercrop systems were overall more productive than sole cropped plots as shown by LER values greater than 1.7 across environments for both lablab grain LER and lablab biomass LER (Appendix – Table 1.5). An LER greater than 1 is indicative of an intercrop advantage over sole cropped production of the crops. Accessions of lablab performed in a highly similar manner, with no differences detected between accessions in terms of LER for either grain or biomass.

Accession performance, stability, and environmental niches

Lablab accession performance across environments was ranked for grain yield and biomass production through the “Mean vs Stability” view of the GGE biplot (Figure 1.3). This view is based on mean performance and stability across environments within a mega-environment. The single arrowed axis is the average-environment coordination (AEC) abscissa and represents the average environment against which the accession performances are ranked. The arrow indicates the direction of higher mean performance and thus shows the rank of each accession. Stability of each lablab accession is represented by its location along the AEC ordinate (axis perpendicular to AEC abscissa), with the most stable accessions located on the AEC abscissa. The GGE biplots explained 98% of genotypic and genotype by environment variation across locations for grain yield performance and 79% of variation for biomass production (Figure 1.3). Accessions with above average grain yield in order of magnitude are DL1002 (#4), Karamoja Red (#17), Q 6880B (#22), ILRI 14437 (#14), CIAT 22759 (#1) and

SARI Rongai (#26). Of these, DL1002 had the highest grain yield but was the most unstable as its rank was inconsistent across environments. Q 6880B was the most stable of the accessions that had above average grain yield (Figure 1.3A). Accession performance in relation to biomass production shows DL1001 (#3), Rongai (#23), and ILRI 6930 (#16) as having above average biomass yields, with Rongai also being the most stable (Figure 1.3B). In general, those accessions with above average grain yields were among the lowest in biomass production. No accessions had both above average grain yield and biomass. Similarly, no accession had low stability in both grain yield and biomass.

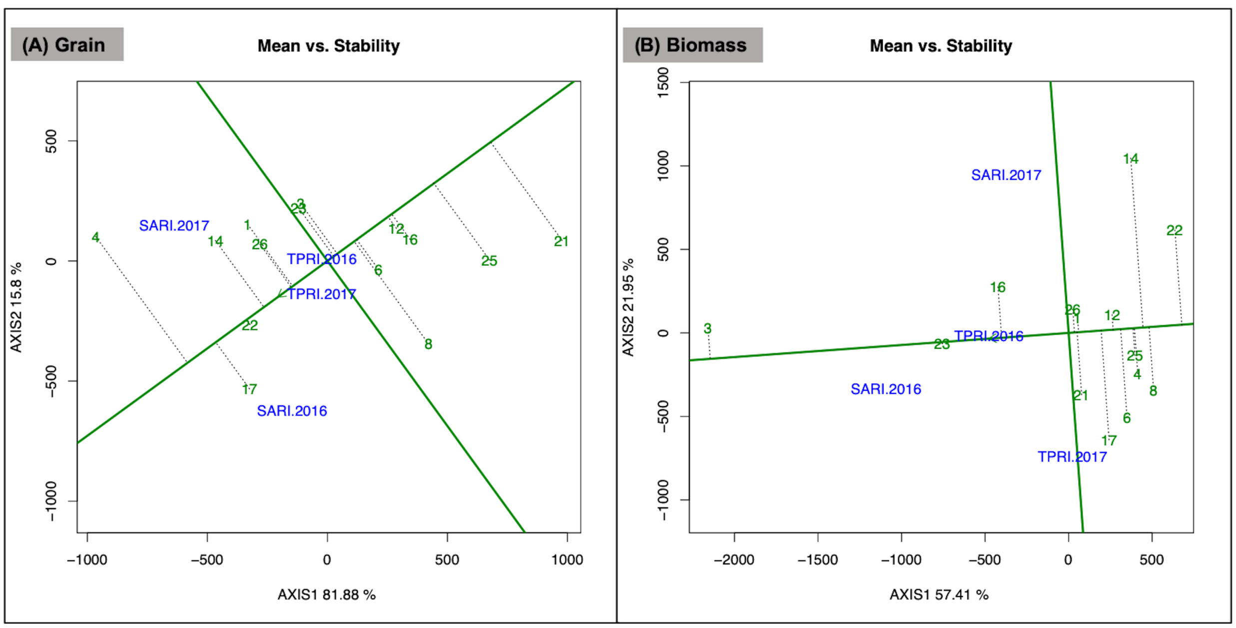

Figure 1.3 Mean vs. stability view of GGE biplot for lablab subset accession grain and biomass performance. (A) Grain yield and (B) biomass across the four test environments SARI 2016, SARI 2017, TPRI 2016, and TPRI 2017. The data were not scaled (“Scaling=0”), environment centered (“Centering=2”), and based on genotype-focused singular value partitioning (“SVP=1”).

The which-won-where view of the GGE biplot identifies the accessions which performed best in different environments as measured by grain yield and biomass (Figure 1.4). In this view, the lines originating from the biplot origin delineate sectors within which accessions and environments are matched as defined by their intersection with the polygon sides. The accession which performed best in each environment is the cultivar represented by the vertex of each sector. If all environments fall within a single sector, this indicates that a single accession did best across all environments. However, if environments fall in different sectors then different accessions performed best in different environments. In the which-won-where view for grain yield, SARI 2016 and SARI 2017 are identified as distinct environments within which different accessions performed well. DL1002 (#4) was the top performer in SARI 2017, with CIAT 22759 (#1), ILRI 14437 (#14), and SARI Rongai (#26) also best adapted to this environment for grain (Figure 1.4A). Karamoja Red (#17) was the best performer in SARI 2016 with Q 6880B (#22) also well adapted to this environment. TPRI 2016 and TPRI 2017 had low grain yields overall and were not clearly identified in a sector, suggesting that these environments are not well suited to lablab grain production. The remaining accessions did not clearly align to a test environment, which indicates that the environments in this study did not necessarily provide ideal conditions for grain production of these accessions.

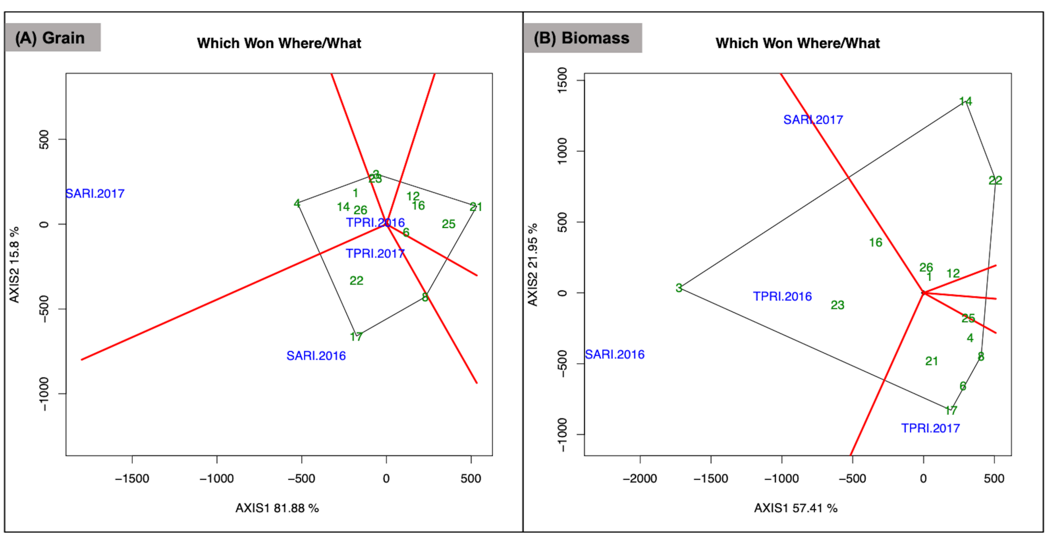

Figure 1.4 Which-won-where view of GGE biplot for lablab subset accession grain and biomass performance. (A) Grain yield and (B) biomass across the four test environments SARI 2016, SARI 2017, TPRI 2016, and TPRI 2017. The data were not scaled ("Scaling=0"), environment centered ("Centering=2"), and based on environment-focused singular value partitioning ("SVP=2").

In the which-won-where view for biomass, SARI 2016 and TPRI 2016 were identified as having similar accession performance, and thus were similar environments for biomass production (Figure 1.4B). Within these two environments DL1001 (#3) was the top biomass producer, with Rongai (#23) and ILRI 6930 (#16) performing well in these environments as well. TPRI 2017 was identified as a unique environment for biomass production within which Karamoja Red (#17) did best. Echo Cream (#6), PI 195851 (#21), Highworth (#8), DL1002 (#4) also did well in this environment. SARI 2017 did not align to a sector, suggesting it was not a suitable environment for maximizing biomass production. The remaining accessions that fell in different sectors without a clear environment signal are consistent with study environments as being not well suited to high biomass production for these accessions.

Principal components analysis of productivity, growth, and nitrogen variables

In order to understand the relationship between grain yield, biomass, and nitrogen components across accessions, a PCA was performed on data from SARI 2017 where detailed nitrogen measurements were taken, including natural abundance assessment of biological N fixation. The variables of interest included lablab grain yield, biomass, soil nitrate, nodule weight, $\delta^{15}N$, maturity (days to 50% flowering), plant population and %N of biomass. Nodule weight and $\delta^{15}N$ values were used as a proxy for N fixation, with larger nodule weight assumed to be associated with increased N fixation and $\delta^{15}N$ values closer to zero associated with higher N fixation given that $\delta^{15}N$ signature of atmospheric N_2 is defined as zero (Shearer & Kohl, 1986; K. E. Giller, 2001).

The correlation matrix showed that grain yield was positively correlated with biomass (r=0.387; $p<0.05$) and %N negatively correlated with grain (r=-0.518; $p<0.001$) and biomass (r=-0.647; $p<0.001$) (S4. Table). The variables were grouped into two components with eigenvalues greater than 1 and which explained 52.3% of the total variability among the variables (Table 1.2). The first component accounted for 33.6% of the variability and represented plant production as it was dominated by large loadings by grain yield, biomass, plant population and negatively with %N. The second component accounted for 18.7% of the variability and was associated with the nitrogen fixation variables nodule weight and $\delta^{15}N$ (negatively correlated) and soil nitrate (Table 1.2).

Table 1.2 Factor loading and percentage of total variability explained for 2 factors in PCA using SARI 2017 data.

	PC1	PC2
Eigenvalue	2.689	1.499
Variability (%)	33.6	18.7
Grain yield	0.434	0.160
Biomass	0.473	-0.160
Soil nitrate	0.104	0.319
Nodule weight	0.127	0.584
$\delta^{15}N$	0.059	-0.534
Maturity	-0.408	0.435
Plant pop	0.417	0.082
% N	-0.466	-0.157

Biplots of the first two components with the variable loadings shows the distribution of accessions and block across productivity/growth (PC1) and N fixation (PC2) (Figure 1.5). Multivariate accession and block effects were found for PC1 but not PC2 (Appendix – Table 1.7). ILRI 14437 (#14) was found to have the highest productivity whereas SARI Nyeupe (#25) had the lowest. This suggests some accessions may be able to maintain high growth (yield, biomass) and N fixation, but for others N fixation may come at a cost to low growth.

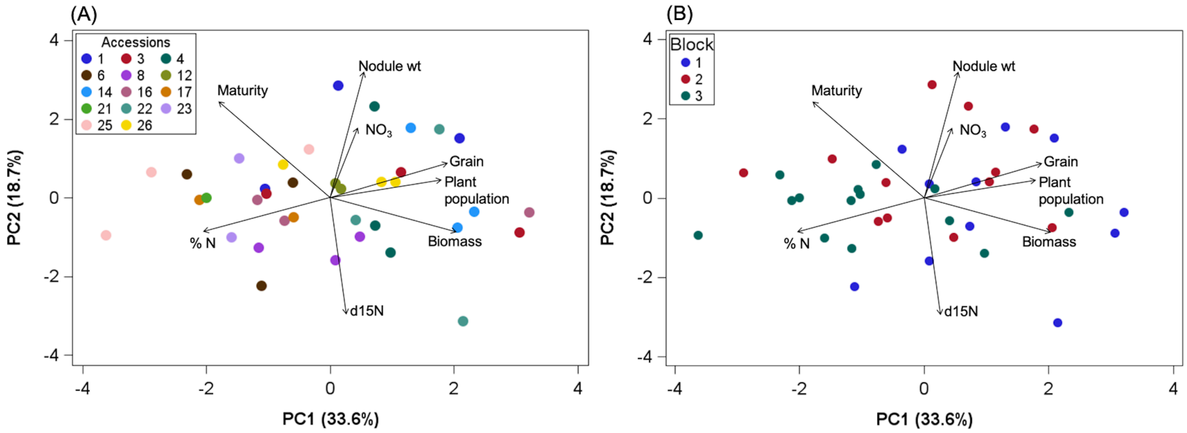

Figure 1.5 Principal components analysis (PCA) biplot of SARI 2017 accession performance plotted against first two components with variable loading vectors (correlations between variables and PCs). (A) PCA grouped by accession. (B) PCA grouped by block. Accumulated variability 52.3%.

Discussion

Lablab grain productivity by environment

Over the range of precipitation observed in the four environments, no clear trends emerged for lablab grain production. Overall, SARI 2017 had the highest average grain yields (1067 kg ha^{-1}) and was the environment with the highest seasonal precipitation (463 mm). This site year also had the highest grain yield of any accession, DL1002 with 2029 kg ha^{-1}, which was more than double the highest grain yield measured in 2016 at this site. SARI 2016 and TPRI 2017 had similar precipitation amounts (310-315 mm), but drastically different grain yields: 93 – 1001 kg ha^{-1} at SARI, and 0 – 355 kg ha^{-1} at TPRI. Previous studies also report a wide range in lablab yields with few consistent responses to precipitation. Whitbread et al. (Whitbread et al., 2011) tested 33 lablab accessions in South Africa and found in one site year at 475 mm of precipitation yields ranged from 1 – 576 kg ha^{-1}. Sennhenn et al. (2017) tested lablab over a moisture gradient and found lablab grain yields as high as 1271 kg ha^{-1} with 190 mm of rainfall.

Our results are generally consistent with these studies as lablab yield ranged widely and was often higher than 500 kg ha^{-1} under low precipitation (<500 mm), suggesting that drought-tolerance is a common trait in lablab.

We further found evidence for an interaction of temperature and precipitation in lablab grain production. The TPRI site in our study had between 252-315 mm of rainfall but was not suitable for grain production. Given that a similar amount of rainfall was seen at SARI in 2016 but with yields upwards of 1000 kg ha^{-1}, hot temperatures at the TPRI site seems to be the limiting factor for grain production. The TPRI site had both higher minimum and maximum temperatures than SARI, with maximum temperatures averaging 36°C in 2016 and 33°C in 2017. This was also hotter than the sites tested in Whitbread et al. (2011) (maximum 32°C), and in Sennhenn et al. (2017) (maximum 31°C). A growth chamber experiment by Sennhenn et al. (2017) testing the effect of temperature on development of lablab found that flowering was delayed at temperatures higher than 28°C. Our results support this finding and suggest that if grain yield is a priority, environments with maximum temperatures >33°C may not be suitable for lablab cultivation.

A third environment effect, intercrop versus sole crop management, was found to not affect grain yield (Figure 1.2, Table 1.4). Previous descriptions of lablab suggest average grain yields around 1500 kg ha^{-1} when sole cropped, but only 450 kg ha^{-1} when intercropped (Adebisi & Bosch, 2004). Interestingly, in the highest grain yield environment, SARI 2017, average intercropped grain yields were higher (980 kg ha^{-1}) than these previous reports. In our study environments grain yields of sole cropping on average were generally modest, and plant densities after emergence were low (<50% emergence in SARI 2017) which may have supported minimal competition with maize in the intercrop and limited yield potential in the sole crop system.

There is a broad literature on grain legume intercropping with maize, and often lower legume grain yields are observed in intercrop vs sole cropped systems (Waddington et al., 2007; Isaacs et al., 2016). This may reflect farmer priorities as legume species are often grown as a secondary crop in an intercrop with maize, with low planting densities used by farmers. In some systems, such as common bean in Rwanda, bean production is the primary crop, and thus is planted at a higher density in the intercrop (Isaacs et al., 2016). In most farmer systems, however, maize is the main crop and planting densities and spacing arrangements within and between rows are such that neither legume grain nor maize yields is diminished (Waddington et al., 2007). Overall our findings are consistent with no differences in yield between sole and intercropped lablab accessions, which supports use of a simplified management system (either sole or intercropped) for future assessments.

Lablab biomass production by environment

Biomass production by rainfall gradient demonstrated unclear trends. While many studies show biomass production increases with increased water availability, Sennhenn et al. (2017) found that the increase in lablab biomass with increased water amounts was gradual in an irrigation gradient. In our study, the highest rainfall environment, SARI 2017 with 463 mm rainfall, had the lowest biomass production overall (1.1 Mg ha^{-1}). In contrast, SARI 2016 (315 mm) had the highest biomass overall (3.1 Mg ha^{-1}) but TPRI 2017 (311 mm), biomass was substantially lower (2.3 Mg ha^{-1}). Disease prevalence amongst legumes is also well known, and increased moisture may increase the severity of disease, thus negatively affecting biomass production (Graham & Vance, 2003).

Biomass production was less affected by high temperatures than grain in our study. The hot TPRI site, with maximum temperatures ranging from 33-36°C, had average biomass yields of 1.8 - 2.3 Mg ha^{-1} across the two years. Previous studies of lablab fodder production in semi-arid environments in East Africa have found similar biomass yields, with Sennhenn et al. (2017) reporting 1.2 – 2.4 Mg ha^{-1} and Macharia et al. (2010) finding 2.5 Mg ha^{-1} in eastern Kenya.

Biomass, in contrast to grain, was affected by intercrop management, with all environments having lower average biomass in intercrop versus sole crop systems, except in TPRI 2017. Across environments, sole cropped biomass ranged from 4.4 Mg ha^{-1} (SARI 2016) to 1.4 Mg ha^{-1} (SARI 2017). Intercropped biomass ranged from 2.2 Mg ha^{-1} (TPRI 2017) to 0.8 Mg ha^{-1} (SARI 2017). Despite the reduced biomass amounts produced in some intercrops, LERs based on lablab biomass ranged from 1.59 to 2.56. This is consistent with a strong production advantage for a forage lablab/maize intercrop system, particularly advantageous to farmers with livestock and limited land. Previous studies of lablab as a forage crop intercropped with maize have focused on lablab's potential as a dairy feed, where lablab was shown to have high potential as a high-quality forage. Maasdorp & Titterton (1997) tested 15 legume crops in Zimbabwe with a range of growth habits for suitability as dairy feed in a maize intercrop system and found lablab's vine growth type to be complementary with maize with no or modest suppression of maize yield. This study found lablab biomass to be reduced in a maize intercrop, relative to sole lablab, but forage biomass produced was still higher than other legumes tested. Overall biomass in the intercrop was substantial, highlighting lablab's high potential in supplementing maize cropping systems (Maasdorp & Titterton, 1997). Armstrong et al. (2008) tested lablab's potential as a maize intercrop produced dairy feed in a cool temperate region and assessed nutritional properties, e.g., crude protein content. Of the legumes tested, lablab was the most acceptable within a dairy system because of the increased nutritional value it added to the system without suppressing maize yield (Armstrong et al., 2008). While lablab may not have the highest production potential compared to other forage crops (Becker & Johnson, 1998), it's multi-purpose qualities enhance its attractiveness to smallholder farmers interested in dual production of grain and forage (Duc et al., 2015). Of note is the similar lablab biomass yields produced under intercrop and sole crop management in the hot environment of TPRI 2017, consistent with this crop as a dual use performer.

Tradeoffs between grain and biomass

One key result from our study is the contrasting trends among accessions for biomass and grain yield as top biomass producers did not have high grain yield. Similarly, Ewansiha et al. (2007) in assessing forty-six lablab accessions across two growing seasons also found an inverse relationship between biomass and seed yield. Amongst another multipurpose legume, cowpea, Kabululu et al. (2014) addressed this tradeoff in biomass and grain yield by testing determinate and indeterminate cultivars in mixtures to assess overall production. The authors found that while not all indeterminate/determinate mixtures outperformed monocultures, some mixtures were able to produce both high leaf and grain amounts. Such an approach has not been taken with lablab accessions, despite lablab and cowpea having comparable production qualities and range of growth habits. Interest in growing accessions in mixtures is further supported by a meta-analysis of cultivar mixtures and yield stability where mixtures often over-yielded relative to monocultures and this increase was more pronounced when mixtures included diverse traits (Reiss & Drinkwater, 2018). This points to the value of identifying dual-purpose accessions in lablab, as growing a mixture of growth habits with complementary traits across cultivars may be necessary to meet farmer's multiple objectives.

Genotype by environment interaction

Results observed for individual accessions indicated high plasticity, with accession performance varying by environment. This is consistent with many test environments being desirable to identify ideal environments for dual-purpose legumes. Generally in cultivar assessment the presence of genotype by environment interactions necessitates multiple test environments to identify suitable varieties for various production areas (Simmonds, 1991). In assessing test environments for common bean across Africa using a GGE Biplot analysis, Kang et al. (2006) identified redundant test environments for bean cultivars with implications for regional breeding centers. While an excessive use of test environments may be possible with a heavily studied crop such as common bean, dual-purpose legumes with a diverse genetic background such as lablab may well require many test environments (Maass, 2016). This is supported by the GGE biplots of lablab accessions included in this study (Figure 1.4), where nine accessions for grain and six for biomass did not clearly align with the test environments, suggesting that further environments are needed to identify suitable growing niches for grain and biomass production, in addition to areas that are suitable for both.

An initial step towards identifying suitable environmental niches for lablab by mapping maximum temperature thresholds across Tanzania shows that the niche for high lablab biomass performance is substantially larger than it is for grain yield (Figure 1.6). Furthermore, these areas have substantial overlap with high livestock production areas. Future lablab performance studies in Tanzania should focus on these areas of overlap between high livestock and hot environments to expand the test environments used for lablab and thus gain additional insight on lablab accessions' environmental parameters.

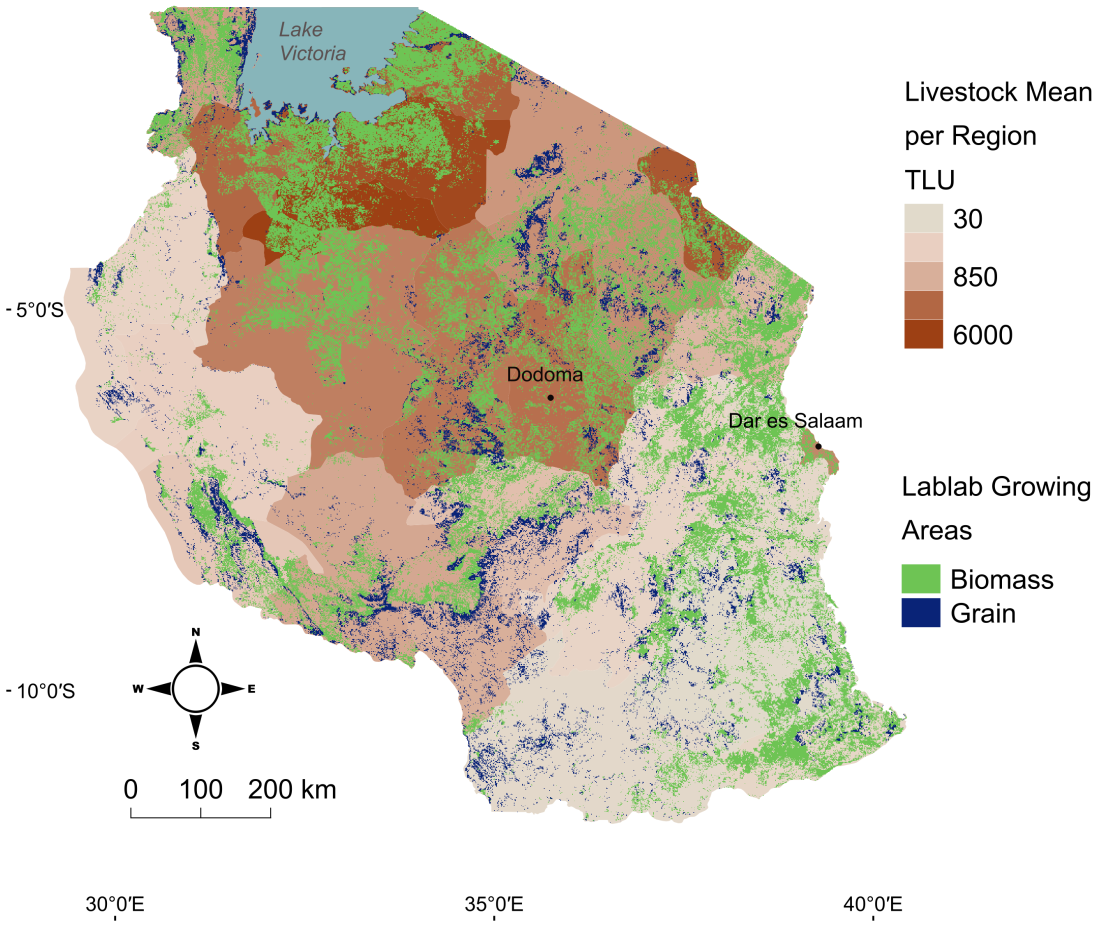

Figure 1.6 Lablab potential growing areas and average regional livestock populations reported in Tropical Livestock Units (TLU) for mainland Tanzania. Lablab potential based on maximum temperature thresholds for optimal grain (28°C) and biomass (40 °C) production from December – August (10-year average) masked to agricultural land. Optimal grain areas are also suitable for biomass, but biomass areas are unsuitable for grain production. Livestock populations calculated as mean pixel TLU per region. Data sources: Wan et al. (2015) 8-day land surface temperature/emissivity; Arino et al. (2012) land cover map (GlobCover); HarvestChoice (2015) livestock prevalence (TLU).

Individual accession performance

Across the four environments studied here, six of the 14 lablab accessions had above average grain yield and four of these accessions (DL1002, ILRI 14437, CIAT 22759, SARI Rongai) performed best under SARI 2017 growing conditions. The other top grain producers, Karamoja Red and Q 6880B, were best in SARI 2016. Of these accessions, three (DL1002, Q 6880B, ILRI 14437) have been identified in other studies as also having high production potential, especially as a short season legume crop (Pengelly & Maass, 2001; Lithourgidis, Dordas, Damalas, & Vlachostergios, 2011; Whitbread et al., 2011; Sennhenn, Njarui, et al., 2017). Q 6880B in particular was found by Sennhenn, Odhiambo, et al. (2017) to be photoperiod insensitive even in higher temperatures, which could explain how Q 6880B was one of the few accessions to produce grain at the hot TPRI site and suggests that this accession may be best suited for promotion as a heat-tolerant grain variety. In our study, only three of the lablab accessions (DL1001, Rongai, ILRI 6930) had above average biomass yields (Figure 1.3B), and these accessions were best suited to both SARI 2016 and TPRI 2016 environments. The Rongai accession is a common lablab variety used for forage production, and previous studies have also noted it's high forage potential (Armstrong et al., 2008; Maass, 2016). Interestingly, another lablab accession often promoted for forage, Highworth, was not found to be a top biomass producer in our study environments (Adebisi & Bosch, 2004).

Of the accessions included in this study, four (DL1002, Echo Cream, Karamoja Red, Q 6880B) were chosen partway through the study for continuation in on-farm trials with the goal of identifying accessions for registration in Tanzania. Of these four, all except for Echo Cream were top grain producers. None of these accessions however were top performers in biomass, reflecting a preference for grain production in promoting lablab in northern Tanzania. Additionally, all accessions chosen for continuation are early-mid maturity types, a common preference in crop breeding programs (Dehaan & Van Tassel, 2014). Snapp et al. (2018) however highlight the risk in a narrow selection of short-statured, early maturity crop types, including perpetuating an unsustainable simplified agricultural production system. Diverse crop growth types with dual purpose traits provide options for crop livestock integration and soil fertility enhancement, suggesting that there are risks associated with reductions in crop diversity through selection for a narrow range of traits. For example, lablab accessions with high biomass production in hot environments may be desirable for farmers in these locations, especially given widespread livestock husbandry. Farmers require expanded crop options, and a wide range of lablab accessions could help address these needs (Maass et al., 2010).

Lablab performance tradeoffs

The SARI 2017 sub-study provided the first systematic assessment in lablab that we know of to quantify variability in accession N fixation traits, biomass, grain yield and soil N status. In this environment, tradeoffs were modest between biomass and grain, with some accessions identified that had high productivity and similar N fixation as those with low productivity. In the only other study of lablab genetic variation in N fixation, Ewansiha et al. (2007), note that late maturing lablab varieties generally were associated with copious growth and large amounts of accumulated biologically fixed N, yet generally had low nodulation compared to earlier accessions. Our study found a similar trend in nodulation as those with higher nodule weight and low d15N (suggesting higher N-fixation) were early-mid maturing accessions. However, previous studies that estimated N fixation rates in lablab report percentages from 35 – 89% (Becker & Johnson, 1998; Sanginga, Lyasse, Diels, & Merckx, 2003; Ojiem, Vanlauwe, De Ridder, & Giller, 2007), suggesting that total N amounts in biomass might not imply greater amounts of N_2, as Ewansiha et al. (2007) indicate especially if N fixation rate differences are due to accession type. Further study is needed to assess lablab N fixation potential across accession types and to understand the relationship between maturity type and N-fixation (Ewansiha et al., 2007), with clear implications for sustainability of multi-purpose legumes in smallholder farming systems.

Lablab potential in smallholder farming systems

Lablab accessions provide unique options that address the multiple needs of farmers who are managing complex cropping systems, with clear potential to expand dual use legume production in hot environments across Tanzania (Figure 1.6). This study provides a methodology for identifying lablab accessions suitable to current farming systems, with the potential to improve overall sustainability. Accessions were identified as high performers in terms of grain or biomass, with particularly strong forage biomass performers identified for hot, dry environments, which could be introduced to support sustainable intensified livestock production in Tanzania (The World Food Programme (WFP) & National Bureau of Statistics (NBS), 2010). At the same time, high environmental plasticity was observed for dual use strong performers, consistent with the need for broader environmental testing of accessions for dual use. Further, the study provided evidence that incorporating lablab into maize cropping systems as an intercrop would allow farmers to achieve sufficient grain and forage yield without having to commit land solely to lablab. The maize-lablab system was also suitable for accession screening, providing consistent results to sole lablab under hot dry environments. A recommendation coming out of our study is that lablab production and accession evaluations be conducted using intercrop rather than sole conditions, as this is most applicable to small-scale farming systems.

Conclusion

While common bean is the most widely grown grain legume in Tanzania, its production area is limited by temperature and precipitation, thus limiting current legume production (Beebe et al., 2011; FAOSTAT, 2015). Expanding the temperature and rainfall range in which legumes are produced would therefore increase Tanzania’s legume production area. Lablab accessions in our study produced substantial amounts of grain and biomass in hot, dry environments that were

6°C above common bean's 25°C max temperature threshold (Beebe et al., 2011). In a review of lablab's genetic diversity and value as a multi-purpose crop, Maass et al. (2010) note lablab's greater drought tolerance over common bean and cowpea. While our study in a low rainfall, high heat environment showed cowpea to have greater grain production than lablab, lablab's high grain market value, particularly in northern Tanzania, and its ability to retain high-quality forage much longer than cowpea makes it a highly desirable drought tolerant crop. Further, farmer demand in hot, dry areas with high livestock dependency may be towards a drought tolerant forage legume such as lablab.

Dual use traits in crops is an under studied area of research and could provide key insights when integrated into methodology to assess novel legume crops for suitability of fit to cropping systems. The approach described here is a systematic means to evaluate lablab accessions by environment, that considers contributions to sustainability, as well as productivity, to expand crop options on African smallholder farms.

APPENDIX

Table A-1 Soil properties of SARI study site. Numbers in parentheses standard errors.

SARI						
	Depth	pH	EC (uS/cm)	P (mg/kg)	Sand %	Clay %
Block 1	0-20 cm	6.79 (0.18)	237.47 (45.3)	9.78 (0.29)	40% (2.35)	40% (2.38)
	20-40 cm	7.00 (0.07)	138.57 (16.7)	15.88 (2.71)	37% (1.07)	42% (2.03)
Block 2	0-20 cm	6.66 (0.06)	167.37 (5.19)	9.38 (0.75)	37% (1.15)	43% (1.33)
	20-40 cm	6.92 (0.03)	135.23 (5.75)	21.42 (0.36)	37% (1.76)	45% (1.20)
Block 3	0-20 cm	6.69 (0.06)	155.57 (5.82)	4.96 (0.75)	39% (1.15)	43% (0.67)
	20-40 cm	6.87 (0.07)	146.23 (8.68)	21.17 (6.87)	38% (0.33)	45% (0.33)

Table A-2 Type 3 ANOVA of lablab grain yield, biomass, and maize yield

Effect		df	F	p
Grain yield	Environment	(3,8)	21	0.0004
(kg ha^{-1})	Accession	(13,207)	9.72	<.0001
	Env x Accession	(39,207)	5.62	<.0001
	Maize Intercrop	(1,8)	3.28	0.1077
	Env x Intercrop	(3,8)	1.15	0.3849
	Intercrop x Accession	(13,207)	0.35	0.9831
	Env x Acc x Int	(39,207)	0.51	0.9926
Biomass	Environment	(3,8)	50.8	<.0001
(Mg ha^{-1})	Accession	(13,207)	3.42	<.0001
	Env x Accession	(39,207)	1.97	0.0013
	Maize Intercrop	(1,8)	92.8	<.0001
	Env x Intercrop	(3,8)	19.5	0.0005
	Intercrop x Accession	(13,207)	1.02	0.4306
	Env x Acc x Int	(39,207)	0.98	0.5125
Maize yield	Environment	(3,8)	10.6	0.0036
(kg ha^{-1})	Accession	(13,98)	1.06	0.3996
	Env x Accession	(39,98)	0.93	0.5918

Table A-3 Land equivalent ratio (LER) for lablab

	Grain LER	Biomass LER
SARI 2016	3.21	2.56
SARI 2017	2.37	2.10
TPRI 2016	2.82	1.76
TPRI 2017	--	1.59

Table A-4 Correlation matrix from PCA of SARI 2017 data. Measurements from sole cropped plots only.

Correlation Matrix								
	Grain Yield	Soil Nitrate	Biomass	Nodule wt	$\delta^{15}N$	Maturity	Plant pop	%N
Grain yield	**1.0000**	0.0330	0.3564	0.3800	0.0182	-.4212	0.2977	-.4633
Soil Nitrate	0.0330	**1.0000**	0.0031	0.0848	-.0518	0.0677	0.2133	-.1937
Biomass	0.3564	0.0031	**1.0000**	0.1382	0.2230	-.4946	0.3939	-.5304
Nodule wt	0.3800	0.0848	0.1382	**1.0000**	-.1802	0.2290	-.0477	-.2146
$\delta^{15}N$	0.0182	-.0518	0.2230	-.1802	**1.0000**	-.2311	-.2572	-.0600
Maturity	-.4212	0.0677	-.4946	0.2290	-.2311	**1.0000**	-.4409	0.2376
Plant pop	0.2977	0.2133	0.3939	-.0477	-.2572	-.4409	**1.0000**	-.4472
% N	-.4633	-.1937	-.5304	-.2146	-.0600	0.2376	-.4472	**1.0000**

Table A-5 Type 3 ANOVA of PC1 and PC2 from PCA of SARI 2017 data.

Effect		df	F	p
PC1	Accession	(13,21)	3.70	0.0038
	Block	(2,21)	8.53	0.0019
PC2	Accession	(13,21)	0.88	0.5833
	Block	(2,21)	2.54	0.1030

Table A-6 Characterization of nodules sampled at SARI 2017 site. Nodules sampled in sole cropped plots only.

Accession Name	Accession Number	Nodules per Plant (#)	Nodule weight per plant (g)	Pink Colored Nodules (%)
CIAT 22759	1	9.6	0.26	88
DL1001	3	4.6	0.15	75
DL1002	4	8.5	0.19	58
Echo Cream	6	8.8	0.16	85
Highworth	8	2.0	0.07	66
ILRI 13700	12	13.0	0.18	79
ILRI 14437	14	9.6	0.20	83
ILRI 6930	16	8.4	0.11	81
Karamoja Red	17	7.1	0.11	84
PI 195851	21	7.6	0.19	84
Q 6880B	22	4.5	0.09	52
Rongai	23	7.3	0.16	77
SARI Nyeupe	25	11.4	0.18	82
SARI Rongai	26	11.6	0.25	74

Table A-7 Soil nitrate from 0-20 cm depth

Accession	SARI 2016 (ug/g)	SARI 2017 (ug/g)
1	0.99	1.35
3	1.12	1.12
4	1.24	0.91
6	1.19	1.03
8	1.05	1.04
12	1.05	1.31
14	1.03	1.00
16	1.00	1.05
17	1.03	1.03
21	1.34	1.00
22	1.00	1.28
23	0.98	1.00
25	1.12	1.05
26	0.98	1.17
Lablab Avg	1.08	1.10
Cowpea Avg	1.33	1.35

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Chapter 2: Documentation of Farmer Perceptions and Site-Specific Properties to Improve Soil Management on Smallholder Farms in Tanzania

Abstract

Identifying sustainable land management practices within smallholder agriculture is a challenge. This is partly driven by the challenge of documenting farmers' perspectives and practices in an integrated manner with site-specific scientific soil assessment. Smartphone applications such as LandPKS provide new approaches to quantify site-specific soil degradation and fertility but are untested with African farm management. We surveyed 578 households in rain-fed maize (*Zea mays*) production areas of Tanzania using a stratified sampling frame to encompass a wide range of soils and agroecologies. A socio-economic survey and simultaneous sampling in focal plots documented farmer characteristics, perspectives and management practices, along with soil properties and crop yields. For a sub-sample of 58 households, we additionally assessed site-specific field status with the LandPKS application. Farmer perceptions of change in soil fertility status were consistent with soil properties, e.g., a field perceived to be declining in fertility was also likely to have low soil organic carbon (1.8% relative to 2.7% for increasing fertility). LandPKS provided additional novel insights on soil limitations such as identifying poor water infiltration areas consistently associated with farmer use of erosion control practices (water infiltration of 4 mm hr^{-1} vs 20 all other plots). This charts a way forward to address soil fertility and land degradation challenges through the use of smartphone applications to capture site-specific conditions and farmer concerns as the basis for land management recommendations that are highly relevant and address local conditions.

Keywords: Farmer practice – Soil fertility – Erosion control – Land management recommendations – Smartphone applications

Introduction

Land degradation and declining soil fertility are major sustainability issues in developing countries of sub-Saharan Africa (SSA) (Tully, Sullivan, Weil, & Sanchez, 2015). A majority of the population in these countries depend on subsistence agriculture. Tanzania in particular depends heavily on agriculture, with 70% of the population employed in this sector (Fraval et al., 2017). Thus, improving the productivity and quality of land is vital to improving food security, and to the development of the agricultural sector to foster general growth.

However, identifying agricultural practices that restore degraded land is challenging, as it requires researchers and practitioners to have a common understanding of the problem in order to identify solutions (Mahon, Crute, Simmons, & Islam, 2017). Studies have shown that farmers and researchers each use their own measures to assess soil quality and farmland conditions, such as farmers focus on observable bio-physical characteristics whereas researchers focus on laboratory soil analyses, creating gaps in perceptions. Additionally, researcher recommendations tend to be general in nature and at a coarse resolution, whereas farmer interest is in site-specific and finely targeted advice (S. S. Snapp, Blackie, & Donovan, 2003). This has led to calls for improved means to incorporate farmer knowledge into research and extension (Oudwater and Martin, 2003; Barrios et al., 2006; Norgrove and Hauser, 2016). Farmers' knowledge often involves detailed descriptions of soil types, and appropriate management practices by soil or land classification (Oudwater & Martin, 2003). Previous studies have primarily focused on linkages or gaps between farmer and researcher knowledge of soil properties (Oudwater & Martin, 2003). Berazneva et al. (2018) compared farmer perceptions and agricultural practices in Tanzania and found that some farmer practices did align with perceptions of soil fertility, but not all. Barrios et al. (2006) identified multiple indicators used by farmers to assess soil quality and erosion, many of which differed from researchers' indicators due to farmers using multiple site-specific and seasonal indicators versus researchers' static measurements. Norgrove and Hauser (2016) expanded the findings of Barrios et al. (2006), and sought to inform extension recommendations. These authors noted however that their recommendations were not site-specific, and had a limited ability to connect local knowledge with extension across farming communities. These studies highlight the limited nature of most indigenous soil knowledge studies, and the need for systematic documentation and integration of farmer knowledge.

One area of potential disconnect relates to researchers frequently using a framework that poses questions on soil fertility as a separate category from soil degradation. For example, in Barrios et al. (2006) and in Assefa and Hans-Rudolf (2016) fertility and degradation were separately used to elicit farmer reflections and indicators, and in other studies soil fertility is considered on its own (Karltun et al., 2011; Berazneva et al., 2018). Indeed, reviews often focus on just one of these topics, and relate this to a set of recommendations, such as soil water conservation practices or integrated soil fertility management (Vanlauwe et al., 2015).

Additionally, agricultural advisors often promote practices based on perceived land degradation and production gaps that do not take into account local perceptions or knowledge, which may differ (Paul & Steinbrecher, 2013). Ramisch (2014) recorded dissonance between scientists and farmers in a community-based project for integrated soil fertility management in western Kenya. He found that addressing differences among groups lead to innovation and improved learning. Bayard and Jolly (2007) provide a theoretical framework that specifically considered farmers perceptions of environmental degradation in connection with their attitudes and behavior toward land restoring practices. They positively connected farmer perception of the severity of land degradation with farmer awareness and attitude of the problem, which in turn affected farmer behavior around using land restoration practices. Therefore, for researchers to provide improved agricultural practices, farmers' current perceptions and practices must first be identified.

To address these gaps the overall objective of this study was to connect local farmer knowledge with research and develop relevant recommendations. Specifically, this study addresses two research questions: How do scientific measurements of land fertility and degradation compare to farmer perceptions and use of land management practices? Furthermore, how do Tanzanian farmers' perceptions of land fertility and soil degradation status influence their practice, e.g. land management, to enhance soil fertility and conserve soil and water?

Materials and Methods

Study Sites

This study encompasses agricultural areas in the northern and southern highlands zones of Tanzania (Figure 2.1). The northern sites (Arusha, Kilimanjaro and Manyara regions) support a wide range of agricultural systems and have highly variable production potential. The Kilimanjaro region in particular has many agro-ecologies based on varying topography and bimodal rainfall pattern (Table 2.1). The southern sites (Iringa, Mbeya, Njombe and Rukwa regions) are generally at a higher altitude than the northern sites, with the exception of Ruvuma, and on average have greater rainfall and cooler temperatures than the north (Table 2.1). Across the study sites there are a wide range of soil types, with areas dominated by Cambisols (Arusha and Manyara), Ferralsols (Kilimanjaro, Mbeya, Njombe, Rukwa, and Ruvuma), Luvisols (Manyara), and Acrisols (Njombe).

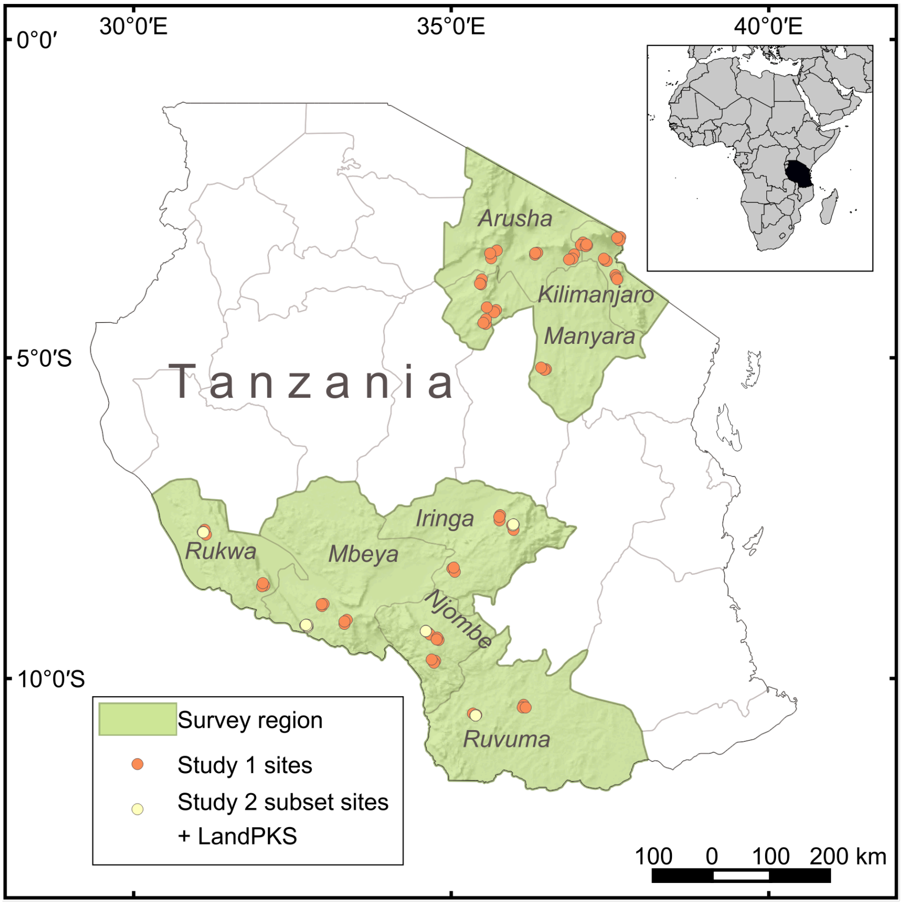

Figure 2.1 Study 1 panel survey and study 2 subset LandPKS survey locations. Location markers clustered across 25 districts, with each marker representing a 1 x 1 km area of eight survey households (N=578). Study 2 sites (n=58) clustered across five districts.

The northern and southern study areas were chosen based on a stratified spatial sampling frame based on pre-identified areas of interest. This included the main maize producing areas in Tanzania with the aim to sample the range of soil types and diverse agro-ecologies within this country (Andrade et al., 2019). While maize is the primary crop grown in all of these areas, a range of cash crops and legumes are also grown, often as an intercrop or in rotation with maize (Mnenwa & Maliti, 2010). Maize yield potentials vary across regions, with maximum maize yields ranging from 11 t ha^-1(Ruvuma and Mbeya) to 6.64 t ha^{-1} (Manyara and Iringa) as indicated by field plot survey measurements collected in this study (Table 2.1).

To examine farmer perceptions of soil fertility and degradation and identify possible connections between perceptions and current farming practices, a mixed methods approach with multiple primary data sources was used. This included a survey carried out in 2017, referred to as Study 1 Survey, and a follow-up survey in 2018 with a subset of Study 1 Survey households, referred to as Study 2 Sub Survey.

Table 2.1 Biophysical characteristics of study sites

	North		
Factors	Arusha (n=69)	Kilimanjaro (n=120)	Manyara (n=89)
Altitude (masl)	1005 - 1523	711-1449	1352-1928
Max Temperature (°C)	32.2 - 36.6	26.7 – 36.0	27.8 - 34.9
Min Temperature (°C)	15.3 - 18.7	15.2 - 20.5	14.0 - 16.9
Annual rainfall (mm)	485 - 762	615 – 1077	598 - 853
Rainfall pattern	Bimodal + Unimodal	Bimodal	Unimodal
Climates	Tropical savannah, Humid subtropical	Tropical savannah	Subtropical highland
Cropping systems	Banana/Coffee/Horticulture; Maize/Legume; Cotton/Maize	Banana/Coffee/Horticulture; Cotton/Maize	Maize/Legume
Maize maximum yield ($t\ ha^{-1}$)†	7.63	9.77	6.64
Households with livestock (%)	88%	87%	92%
Dominant livestock‡	Cattle, Goats, Poultry, Sheep	Poultry, Cattle, Goats, Sheep	Poultry, Cattle, Goats, Sheep

† Maximum maize yield recorded from crop cuts in study 1 survey ‡Listed in order of magnitude
Sources: JAXA ALOS World 3D DSM data set at 30m resolution (elevation); Wan, Hook, & Hulley (2015) 8-day land surface temperature (2007-2017); Funk et al. (2015) monthly precipitation (2007-2017); Mnenwa and Maliti (2010) cropping systems; Census 2012 livestock (http://www.nbs.go.tz/)

Table 2.1 (cont'd)

	Southern Highlands				
Factors	Iringa (n=70)	Mbeya (n=73)	Njombe (n=66)	Rukwa (n=45)	Ruvuma (n=46)
Altitude (masl)	1288-1730	1265-2063	1861-2086	1540-1751	787-1091
Max Temperature (°C)	27.3 - 35.8	27.0 - 33.8	22.7 - 27.9	30.9 - 32.9	29.2 -30.9
Min Temperature (°C)	14.1 – 17.6	12.0 – 17.0	9.9 – 12.9	13.3 – 15.3	15.8 – 17.6
Annual rainfall (mm)	593 - 1042	896 - 1296	1008 - 1354	927 - 1041	1005 - 1053
Rainfall pattern	Unimodal	Unimodal	Unimodal	Unimodal	Unimodal
Climates	Humid subtropical, subtropical highland, semi-arid	Humid subtropical, subtropical highland	Subtropical highland	Subtropical highland	Humid subtropical, Tropical savannah
Cropping systems	Maize/Legume; Tea/Maize/Pyrethrum	Banana/Coffee/Horticulture; Maize/Legume; Cotton/Maize	Tea/Maize/Pyrethrum	Maize/Legume	Maize/Legume
Maize maximum yield (t ha^{-1}) †	6.64	10.9	8.64	10.4	11.0
Households with livestock (%)	85%	82%	87%	83%	85%
Dominant livestock‡	Poultry, Cattle, Goats, Sheep	Poultry, Cattle, Goats, Sheep	Poultry, Goats, Cattle, Sheep	Poultry, Cattle, Goats, Sheep	Poultry, Goats, Cattle, Sheep

† Maximum maize yield recorded from crop cuts in study 1 survey ‡Listed in order of magnitude
Sources: JAXA ALOS World 3D DSM data set at 30m resolution (elevation); Wan, Hook, & Hulley (2015) 8-day land surface temperature (2007-2017); Funk et al. (2015) monthly precipitation (2007-2017); Mnenwa and Maliti (2010) cropping systems; Census 2012 livestock (http://www.nbs.go.tz/)

Study 1. Survey

A survey with a household socio-economic component and focal plot with questions covering farmer practices on the plot, plus soil and plant measurements, was conducted during the main maize harvest season in 2017. This study 1 survey was conducted by SIIL and CIMMYT as part of the Taking Maize to Scale in Africa (TAMASA) project. Detail of the spatial sampling framework was previously reported in Andrade et al. (2019). From this sampling procedure 75 1 x 1 km grid locations were identified as target areas for the survey. Within each of these grids a list of all households actively farming land in the grid area was collected and 8 of these households were randomly selected to be surveyed. This resulted in a target of 600 households. The household member interviewed for the survey identified a focal maize plot from which detailed plot management information, soil, and plant samples were collected as described below. The focal plot was defined as the plot within the study grid that the household identified as being most important to their maize production. If a household grew maize on multiple plots within the study grid the focal plot was identified based on economic importance, often determined based on plot size, location, or intensity of production. The focal plot was identified in the project's first year based on maize production, and the same plot was revisited in 2017 regardless of whether maize was the primary crop that year. If the focal plot was no longer under maize, the plot level questionnaire was carried out and soil samples taken, but no plant samples were taken.

Both the household and focal plot levels of the study 1 survey included structured questionnaires. The household questionnaire covered socio-economic and agricultural topics such as characteristics of the household landholdings, crop production, livestock, assets, income, and household demographics. The focal plot questionnaire consisted of farmer management questions such as crops grown, inputs applied, agronomic practices used and history of applied practices on the focal plot. All data collection was done in Swahili by a team of 12 trained enumerators and supervised by the lead author along with CIMMYT-TAMASA researchers.

Soil and Plant Samples

Plant and soil samples were taken at the focal plots following TAMASA protocols for soil sampling and yield crop cuts. In focal plots where maize was mature, crop cuts were taken from three 5x5m quadrats within the plot and total maize harvest calculated per hectare.

Soil samples were collected using a combination auger (7 cm diameter) at 0-20 cm depth by stratified random sampling through sampling at three random points in each quadrat with the final sample consisting of 9 composited subsamples per depth. Samples were airdried and sieved to 2 mm. All samples were analyzed for soil chemical properties (N, K) and soil organic carbon (SOC) by infrared (IR) spectroscopy (Shepherd & Walsh, 2007). Soil pH was measured in H_2O with a 1:2 soil to water ratio. For the top soil layer (0-20 cm) soil texture was measured in the laboratory from sieved soil using the hydrometer method (Jasrotia, 2008). Active carbon was measured for the 0-20 cm soil layer using the permanganate oxidizable carbon (POXC) method (Weil, Islam, Stine, Gruver, & Samson-liebig, 2003).

Study 2. Sub Survey

A subset of study 1 farmers was revisited in 2018 to collect additional data for the purpose of understanding in-depth farmer perceptions of land quality and site-specific characterization of land potential. This study 2 sub survey consisted of a semi-structured questionnaire and focal plot assessment with the LandPKS app (Herrick et al., 2013). The subset of study 1 farmers was chosen with the goal of capturing a diversity of farmer soil perceptions and management practices. Households were grouped by practices used on the focal plot identified in study 1. The practices of interest were those that either addressed soil and water conservation through physically changing the land, or those used for improving soil fertility as defined by the research team. The sampling grids from study 1 were then used to identify grids containing both households using the practices of interest and those not using practices. This resulted in seven sites in the southern highlands zone totaling 58 households across five districts (Figure 2.1). Information collected on the household's focal plot included management of the plot, information on farmer decision making around farming practices, and farmer perceptions of presence and causes of erosion and soil quality. Training of enumerators for the questionnaire and use of LandPKS app took place over two days and was conducted by the lead author. All data collection was done in Swahili and completed during July 2018.

LandPKS Smartphone Application

The LandPKS (*https://landpotential.org*) smartphone application was used to gather additional land characterization information of focal plots as part of study 2. LandPKS is an open-source project with the goal of improving sustainable land management through providing tools that capture local user input into a cloud database system (Herrick et al., 2013). Information was collected for each focal plot through the LandInfo module of the LandPKS application on Android-based smartphones and tablets. Information collected included the slope, aspect, elevation and soil limitations. Soil erosion signs assessed included presence of rills, gullies and other signs of soil loss based on the Land Degradation Surveillance Framework and recorded on a three-point scale of not present, few, or many (Vågen, Winowiecki, & Tondoh, 2013). Following the LandPKS protocol, the soil profile was assessed to a depth of 70 cm for the 0-10 cm, 10-20 cm, 20-50 cm, and 50-70 cm depth ranges. At each depth soil texture-by-feel and rock fragment category was recorded. Outputs provided by the app included local climate and plant available water holding capacity setting organic matter at a constant 1% for comparison across sites.

Data Analyses

Study 1 Survey

Study 1 survey data was analyzed through data characterization based on principal factor extraction, presented as descriptive means and variation, one-way ANOVAs, and means comparisons by Tukey's test with details provided below. Households missing complete sets of information from the questionnaires and soil analyses were dropped, resulting in 578 studied households. Data from the study 1 questionnaires, study 2 sub survey questionnaire, and LandPKS output were compared to address the main research question of how farmers' perceptions of land fertility and soil type influence land management practices. Land management practices were categorized first from the study 1 survey dataset based on the main practices of interest, specifically those related to soil and water conservation practices and soil fertility. From this total list of practices, minimum/no tillage, grass strips, and drainage ditches were dropped due to low frequencies ($n<10$). This final list included ridging, terracing, contour bunds, manure amendment, slash-burn, fallow, fertilizer input and crop residue incorporation. Fallow practice was defined as any non-cultivation of the plot over the last 10 years for at least one growing season and repeated over multiple years, as recorded in the land use history. Fertilizer input was only considered if it was reported as an input for both the current survey year and the previous year. These eight practices, input as discrete variables consisting of 300 observations, were grouped based on principal factor extraction using an oblique promax rotation (Yong & Pearce, 2013). The analysis identified three factors that explained the majority of variability across the variables and a scree plot confirmed this finding. The first factor was labeled as erosion control as it included terracing and contour bund practices. The second factor was labeled the soil fertility group, as the practices (slash/burn, fallow, and chemical fertilizer application) have been frequently reported as means to improve soil fertility (Vanlauwe et al., 2015; Norgrove and Hauser, 2016). The third factor was labeled the organic amendment group as it included manure application and crop residue incorporation. Ridging was considered as a separate practice group since it was not accounted for in any of the three factors.

To compare the soil fertility of the focal plots across groups, soil variables (SOC, active carbon, pH, and texture) were used as well as maize yield. These variables were identified as being most important in determining soil fertility and are widely used in soil fertility assessments (Li et al., 2017; Berazneva et al., 2018). Yield, SOC, active carbon, and pH variables were winsorized at the 99^{th}, 90^{th}, and 95^{th} percentiles respectively to account for outlier data (Ghosh & Vogt, 2012). Independent samples t-tests were conducted to compare these soil fertility variables against users and non-users of each practice group. One-way ANOVAs were conducted to compare the effect of soil fertility variables across farmer perceptions of soil fertility status and soil fertility change. In this survey respondents were instructed to rank the soil fertility status of their field from 1-Not fertile to 4-Very fertile. Soil fertility change was determined by asking "Since this household first began cultivating this plot, do you think the soil has become more fertile or less fertile", with responses on a three-point scale of 1-Decreasing, 2-Same 3-Increasing. Tukey's test (p=0.05) was used to make multiple pairwise comparisons to identify significant differences in soil fertility variables across farmer perception groups.

Study 2 Sub Survey

Study 2 sub survey data is presented as frequencies, means, and standard deviations for comparison of erosion and soil fertility perceptions across farmer practice groups. Practice groups compared in study 2 are the same practices as used in study 1, with the exception of the erosion control group where reported erosion control practices also included fanya juu/fanya chini, grass strips, and drainage ditches. Respondents were asked to rank the level to which erosion and soil fertility were a problem on their plot along a four-point scale from 1 (no problem) to 4 (large problem). Observed erosion signs were also recorded for each focal plot and frequency of occurrence was compared across practice groups. Output from LandPKS used for analysis included soil texture determined by hand texturing, soil water storage capacity in the surface 20 cm and 1 m of the soil profile and the surface infiltration rate which is the rate at which water moves into the soil. Calculations were provided by LandPKS app and based on Saxton and Rawls (2006). Means and frequencies of LandPKS outputs were compared across farmer practice groups. All data was analyzed using Stata 14 statistical software.

Results

Study 1. Survey

Households surveyed in study 1 ranged in socioeconomic aspects, and corresponding focal plots exhibited a range of biophysical characteristics across regions (Table 2.2). Focal plot size varied across regions, from averages of 0.73 acres (Njombe) to 4 acres (Manyara). Soils sampled in survey focal plots showed large variation in soil fertility status, including soil C, N, and pH. Plots from the northern sites of Arusha and Kilimanjaro tended to have high SOC values (2.1 – 2.4%) compared to southern sites (1.3-1.5%), with the exception of the high SOC average observed at Njombe (3.2%; Table 2.2). Soil pH in the north was generally moderately acid (6.1-6.5), with slightly higher acidity in the South (5.4-6.2), although pH varied within all sites and some focal plots were alkaline.

Table 2.2 Biophysical and socioeconomic characteristics of households and focal plots from study 1 survey (N=578).

	North			Southern Highlands				
	Arusha (n=69)	Kilimanjaro (n=120)	Manyara (n=89)	Iringa (n=70)	Mbeya (n=73)	Njombe (n=66)	Rukwa (n=45)	Ruvuma (n=46)
Maize yield† ($t\ ha^{-1}$)	3.0 (1.8)	3.7 (2.0)	2.5 (1.7)	2.1 (1.8)	3.5 (2.8)	2.5 (2.6)	3.0 (2.5)	3.6 (2.8)
Household size‡	5.6 (2.6)	4.9 (1.8)	6.4 (2.4)	5.2 (2.6)	6.8 (4.2)	4.2 (1.9)	7.4 (6.3)	5.0 (2.5)
Age of household head‡	48 (13)	57 (11)	48 (15)	51 (14)	42 (14)	47 (13)	46 (15)	47 (13)
Plot size (acre) ‡	2.3 (1.5)	1.1 (1.2)	4.0 (5.1)	2.9 (4.0)	1.7 (1.9)	0.73 (0.5)	3.2 (2.7)	1.6 (1.3)
Crops grown on focal plot‡	2.2 (0.9)	1.8 (0.8)	2.2 (0.7)	1.5 (0.6)	1.1 (0.4)	1.2 (0.6)	1.0 (0.4)	1.8 (0.9)
Soil C (%) §	2.1 (0.61)	2.4 (1.0)	1.3 (0.45)	1.3 (0.44)	1.5 (0.73)	3.2 (0.64)	1.4 (0.30)	1.3 (0.45)
Soil N (%) §	0.05 (0.02)	0.05 (0.03)	0.04 (0.02)	0.03 (0.01)	0.06 (0.02)	0.07 (0.03)	0.05 (0.02)	0.03 (0.02)
K ($mg\ kg^{-1}$) §	171 (59)	107 (59)	114 (51)	92 (54)	156 (53)	56 (34)	89 (32)	139 (45)
pH§	6.5 (0.58)	6.1 (0.53)	6.3 (0.38)	6.2 (0.79)	6.2 (0.34)	5.4 (0.30)	6.2 (0.28)	5.8 (0.38)

Figures are averages. Values in parentheses standard deviations from the mean.
†Maize yield determined by crop cut from focal plot of survey
‡Data from household questionnaire in study 1 survey
§ Data from focal plot soil samples

Soil Properties and Farmer Perceptions

No relationship was observed in regard to soil properties and farmer perceived soil status (Table 2.3). For example, SOC values did not vary substantially for soils that farmers perceived as varying from low (1.72%) to high (1.85%) fertility status. No trends were observed in terms of maize yields by soil fertility status, with low fertile plots having 2.39 t ha^{-1} yield and very fertile plots averaging 3.42 t ha^{-1} with large variability within groups. Soil texture was similarly variable with no clear trend in sand and clay by soil fertility status. However, differences among soil properties were found for focal plots when grouped by whether respondents perceived the plot soil fertility as increasing or decreasing over time. Plots categorized as increasing in soil fertility had higher total and active carbon, and lower pH compared to all other plots. Increasing soil fertility plots also had higher clay content than soil fertility plots perceived as decreasing in soil fertility. Farmers also identified which indicators they use in determining soil fertility, with the majority (81%) using previous crop yield as well as soil color (40%) and presence of local plants (40%).

Table 2.3 Famer perceptions from household survey and soil fertility properties from 2017 samples (0-20cm) of focal plots in study 1 survey presented as average and standard deviation (in parenthesis) associated with each farmer perception of soil fertility.

	SOC	**Active Carbon**	**pH**	**Maize yield**	**Sand**	**Clay**
	%	mg kg^{-1}		t ha^{-1}	%	%
Soil fertility status						
Not fertile	1.72 (0.84)	487 (178)	5.95 (0.55)	2.39 (2.10)	54.6 (22.9) a	28.2 (13.9)
Moderate fertility	1.89 (0.95)	506 (199)	6.12 (0.56)	3.18 (2.25)	42.0 (25.7) b	35.4 (16.5)
Fertile	2.00 (1.0)	504 (182)	6.15 (0.60)	2.62 (1.97)	45.2 (23.2) ab	34.2 (14.8)
Very fertile	1.85 (0.89)	521 (183)	6.25 (0.55)	3.42 (1.88)	61.3 (27.5) ab	24.4 (12.8)
Soil fertility change						
Decreasing	1.81 (0.90) a	488 (194) a	6.11 (0.57) a	2.83 (2.13) a	47.7 (24.7) a	32.3 (15.7) a
Same	1.83 (0.90) a	504 (182) a	6.14 (0.55) a	3.18 (2.34) a	40.4 (26.9) ab	35.6 (16.5) ab
Increasing	2.67 (1.2) b	609 (207) b	5.85 (0.53) b	3.79 (1.99) a	31.9 (21.1) b	42.5 (15.3) b

Values with same letters within column not significantly different as determined by one-way ANOVA (p=0.05). Values with no letters not significantly different within column.

Soil Properties and Farmer Practices

Farmer management practices were compared to soil fertility measurements to identify if there were measurable soil fertility differences among users and non-users of practices. Differences were found between users and non-users of some practice groups but not all (Table 2.4). Focal plots with erosion control practices were not associated with altered soil fertility status relative to other plots, although we note the small sample size of this category. Plots amended with organic inputs, under fertility practices or ridged all differed in soil fertility status compared to unamended plots. However, not all differences were in a positive direction. For example, plots with soil fertility practices (fertilizer applied, crop residue burned, or fallowed), had low soil carbon and pH, but at the same time, high maize yields ($p<0.10$), compared to other plots (Table 2.4).

Table 2.4 Soil fertility properties (0-20 cm) and maize yield of focal plots in study 1 survey, presented as average and standard deviation (in parenthesis) associated with each farmer practice.

Management practices	SOC	Active Carbon	pH	Maize yield	Sand	Clay
	%	mg kg^{-1}		t ha^{-1}	%	%
Erosion control† (n=22)						
Yes	1.75 (1.05)	468 (185)	6.08 (0.42)	2.69 (2.12)	46.6 (17.6)	35.5 (9.86)
No	1.88 (0.94)	502 (194)	6.10 (0.57)	2.99 (2.20)	44.4 (25.6)	34.0 (16.2)
t-test	ns	ns	ns	ns	ns	ns
Organic amendment‡ (n=167)						
Yes	2.19 (1.03)	538 (201)	5.99 (0.55)	3.06 (2.15)	41.4 (23.7)	35.0 (13.8)
No	1.74 (0.87)	485 (188)	6.15 (0.57)	2.94 (2.23)	45.6 (26.0)	33.7 (16.9)
t-test	-4.88***	-2.89***	3.19***	ns	ns	ns
Soil fertility practices§ (n=135)						
Yes	1.58 (0.82)	463 (177)	6.03 (0.49)	3.39 (2.70)	57.9 (17.6)	27.1 (12.5)
No	1.96 (0.96)	512 (197)	6.13 (0.58)	2.87 (2.02)	40.9 (26.0)	35.8 (16.4)
t-test	4.46***	2.72***	1.97**	-1.58*	-5.53***	4.13***
Ridging¶ (n=56)						
Yes	1.65 (0.91)	441 (180)	5.97 (0.52)	3.15 (2.34)	60.2 (18.1)	25.9 (13.6)
No	1.90 (0.94)	507 (194)	6.11 (0.57)	2.96 (2.18)	42.7 (25.5)	35.0 (16.1)
t-test	1.90**	2.57***	1.91**	ns	-4.3***	2.66***

*p<0.10. **p<0.05. ***p<0.01 ns=not significant

†Terracing or contour bund practices ‡Application of manure or crop residues §Use of slash-burn, fallow or chemical fertilizer application ¶Includes open and tied ridges (connected by horizontal and vertical ridges)

Study 2. Sub Survey

Soil Fertility Perceptions

Responses from study 2 farmers show an overwhelming concern amongst respondents with the soil fertility of their plot (Table 2.5). Soil fertility was identified as either a problem or a large problem by all respondents. Few trends across practice groups emerged, with one exception being farmers who reported the highest score for soil fertility challenges were likely to be using soil fertility and erosion control practices. Consistent with this, low soil organic C levels (less than 2%) were observed for the majority of farmers, across all categories (Table 2.5). Farmers also noted the indicators they use for assessing soil fertility, with the majority using soil color (64%) as well as previous crop yield (47%) and presence of local plants (22%) in their assessment. Black soil color was overwhelmingly identified as being associated with fertile soil, whereas red and white colors were associated with infertile soil by a few farmers.

Erosion Perceptions

In direct contrast to soil fertility perceptions, most respondents identified their focal plot as having no or small problems with erosion and not one respondent reported the highest score for erosion (Table 2.5). Based on enumerator plot observations only 36% of plots were reported to have signs of erosion present (e.g., rills, gullies or other signs of soil loss detailed in Vågen et al., 2013). Fewer farmers in study 2 (16 out of 58) implemented erosion control measures than soil fertility practices (45 out of 58), which was consistent with farmer perceptions that erosion was not a major problem. At the same time, about one-third of plots had clearly observable signs of erosion, based on study 2 survey assessment (Table 2.5).

Table 2.5 Farmer reported erosion and soil fertility status by farmer practice from Study 2 Sub Survey, July 2018. Farmers reported multiple practices on focal plots resulting in overlap across categories (N=57).

	Ridging (n=31)	Erosion control (n=16)	Organic Amendments (n=17)	Soil fertility practices (n=45)	All respondents (n=57)
Erosion score†					
No problem	75% (24)	44% (7)	61% (11)	70% (32)	64% (37)
Small problem	19% (6)	38% (6)	33% (6)	24% (11)	28% (16)
Problem	6% (2)	19% (3)	6% (1)	7% (3)	9% (5)
Large problem	0%	0%	0%	0%	0%
Plots with erosion present†	28% (9)	50% (8)	39% (7)	30% (14)	36% (21)
Slope‡§	1.12 ± 0.49	1.10 ± 0.46	1.11 ± 0.61	1.12 ± 0.42	1.09 ± 0.46
Soil fertility score†					
No problem	0%	0%	0%	0%	0%
Small problem	0%	0%	0%	0%	0%
Problem	91% (29)	81% (13)	94% (17)	80% (37)	83% (48)
Large problem	9% (3)	19% (3)	6% (1)	20% (9)	17% (10)
Total Carbon (%) ‡¶	1.42 ± 0.73	1.57 ± 0.74	1.59 ± 0.81	1.43 ± 0.66	1.41 ± 0.63

†Values in parentheses are counts.
‡Values are means followed by standard deviations.
§Source JAXA ALOS World 3D DSM data set at 30m resolution
¶ From soil samples
Erosion control = Fanya juu/fanya chini, grass strips, drainage ditches, or contour bunds practices
Organic amendments = Application of manure or crop residues
Soil fertility practices = Use of slash-burn, fallow or chemical fertilizer application

Farmer Perspectives on Management Practices

Farmers in study 2 subset were asked open-ended questions concerning their reasons for using reported practices. For soil fertility management practices, reasons commonly centered around themes of resource conservation and desire to improve soil fertility, although a broad range of reasons were reported (Table 2.6). Responses showed farmers had multiple objectives when managing their fields, with themes of land management to prevent losses of soil and water, as well as reduce labor and protect crop health and seedling establishment (e.g., prevent bird damage). Reasons for using soil fertility practices were broad and showed an awareness of interactions such as soil water dynamics and managing for soil moisture retention (Table 2.6).

Table 2.6 Farmer reported reasons for use or non-use of erosion control and soil fertility practices. Parentheses indicate frequency of responses of those reporting using practice (or not using practices) from farmers surveyed in Study 2 Sub Survey. Respondents reported multiple reasons and frequency of reason does not directly relate to frequency of practice used.

Practices	**Reasons**
Erosion Control	
Contour bunds	Reduce soil erosion (7)
Fanya Juu/Fanya Chini	Water conservation (1), Prevent runoff (1)
Grass strips	Reduce soil erosion (3), Improve soil fertility (2), Water conservation (1)
Drainage ditches	Control water flow (4), Reduce soil erosion (1)
No erosion control practice	Flat plot (12), No erosion signs (1), fallow plot (1), Unaware of practices (1)
Ridges (open and closed)	Soil moisture conservation (13), Reduce soil erosion (10), Support plant structure (6), Avoid bird damage (4), Ease of planting (1)
Soil fertility	
Manure/Compost application	Increase soil fertility (14), Increase crop yield (2), Improve soil water holding capacity (1)
Slash-burn	Clean plot (14), Reduce labor (4), Improve soil fertility (3)
Fallow	Low fertility (1)
Incorporate residue	Improve soil fertility (2), Improve soil water holding capacity (1)
Apply chemical fertilizer	Increase yield (24), Improve soil fertility (7), Provide crop nutrients (2)
No soil fertility practice	Used crop residue (2), Couldn’t afford (2), Prevented by weather (1), No reason (1)

LandPKS Assessment

Output from the LandPKS application were used to compare land characteristics of the subset focal plots across management practice groups (Table 2.7). The LandPKS app used user input of slope, soil texture by depth, rock fragmentation, and soil limitations to produce estimates of plant available water capacity (AWC) to 20 cm and 1 m as well as surface infiltration rates. LandPKS output identified erosion control sites as having poor soil infiltration properties and steep slopes (Table 2.7). LandPKS identified plots with steeper slopes (categorically recorded) than had previously been identified for the same subset plots in study 1 with slope from remote sensing. 13 out of the 58 plots recorded with LandPKS had slopes categorized as moderate to hilly (associated with 6-30% slope). Of the 16 plots with erosion control measures in study 2, 7 had slopes recorded as moderate to hilly slope. This is in contrast to study 1 findings, where slope values were no greater than 2.47% and no differences were found by site slope or other properties for users and non-users of erosion control practices (Table 2.4). Additionally, LandPKS results indicated that fields with erosion control practices had much lower surface infiltration rates (4.06 mm hr^{-1}) than other fields (24.7 mm hr^{-1}). These low infiltration numbers appear to be due to high frequency of clay layers throughout the 0-70 cm soil profile on these plots (Table 2.7).

Table 2.7 LandPKS assessment at focal plots from study 2 sub survey grouped by farmer practices presented as average and standard deviation (in parenthesis). More than one practice was allowed to be reported by farmers on focal plot (N=57).

	Ridging (n=31)	Erosion control (n=16)	Organic Amendments (n=17)	Soil fertility practices (n=45)	All respondents (n=57)
AWC to 20cm (mm)	2.21 (0.49)	2.30 (0.39)	2.15 (0.51)	2.23 (0.51)	2.19 (0.47)
AWC to 1m (mm)	10.1 (1.94)	10.9 (2.43)	9.94 (2.03)	10.1 (2.24)	10.3 (2.17)
Surface infiltration rate (mm hr^{-1})	23.1 (18.9)	4.06 (4.12)	23.6 (21.9)	17.5 (19.0)	18.9 (18.6)
% Moderate – Hilly Slope	25%	38%	28%	28%	24%
Soil texture†					
0-10 cm	Sandy Loam 45% Loam 23%	Sandy Clay Loam 31% Clay Loam/Sandy Clay 19%	Sandy Loam 47% Loam 18%	Sandy Loam 29% Sandy Clay Loam/Loam 18%	Sandy Loam 37% Sandy Clay Loam 18%
10-20 cm	Sandy Loam 36% Loam 16%	Sandy Clay 38% Silty Clay 31%	Sandy Loam 29% Sandy Clay Loam/Clay 18%	Sandy Loam 24% Sandy Clay 20%	Sandy Loam 28% Sandy Clay 19%
20-50 cm	Sandy Clay Loam 32% Clay 19%	Clay 38% Sandy Clay 31%	Clay/Sandy Clay Loam 24% Sandy Clay/Sandy Loam 18%	Clay 29% Sandy Clay Loam 20%	Clay 26% Sandy Clay 19%
50-70 cm	Clay 32% Sandy Clay Loam 26%	Clay/Sandy Clay 38% Silty Clay 19%	Clay 29% Sandy Clay 24%	Clay 40% Sandy Clay 22%	Clay 39% Sandy Clay 21%

†Reported soil texture top two most commonly recorded soil textures per depth. Soil textures in equal frequency denoted by / with percentage of each texture respectively.

Discussion

Farmer perceptions of agricultural land

Farmer perceptions documented in this study align well with many soil fertility and land degradation measures, but not with all. Majority of farmers reported perceptions of low soil fertility, which is reflected in overall low regional averages in SOC levels and other fertility properties (Table 2.2). This was observed in both the initial study 1 plots, and in the follow up study 2 plots. SOC ranged from 1.0 to 2.2%, which is similar to previously reported values found across Tanzania (Bhargava, Vagen, & Gassner, 2018), and is on the low end of SOC content needed for effective fertilizer use based on the literature. Some studies have found fertilizer response from soils as low as 1 – 1.5% SOC while other studies suggest a higher threshold of 2.7% SOC is needed for effective fertilizer use (Marenya and Barrett, 2009; Kihara et al., 2016; Ichami et al., 2019). Soil nitrogen was similarly low across regions, with a range of 0.03 – 0.07%, well below the 0.2% threshold used in Berazneva et al. (2018) which also measured soil fertility of agricultural land in Tanzania. Average pH values across sites were not highly acidic (>5.0) suggesting soil acidity did not appear to be a factor exacerbating low soil fertility in the study sites, which has been a limiting factor in other Tanzanian regions (Kimaro, Timmer, Chamshama, Ngaga, & Kimaro, 2009).

A key finding here is the importance of soil fertility change perceptions. In contrast, farmer perception of current soil fertility status is not related to soil fertility variables in this study. This suggests farmers ability to detect soil fertility change over time may be a reliable indicator. Previous studies assessing farmer perceptions of soil fertility in East Africa were unable to find differences between soil fertility status groups (Kelly and Anderson, 2016; Berazneva et al. 2018). In an in-depth study in Southeast Asia focused on a smaller geographical area, Bruun et al. (2017) compared multiple soil quality measurements to farmer perceptions of soil fertility status and found pH and active carbon to have the greatest differences between groups whereas SOC did not differ. In large household surveys such as the World Bank Living Standards Measurement Study (LSMS) soil fertility is documented based on questions about current status but we know of no large-scale surveys that considers farmer perceptions of trends in soil fertility status over time. Karltun et al. (2011) asked farmers in Ethiopia about soil fertility change over time with a modest sample size, and most farmers (92%) reported declining soil fertility. In our study a range of perceptions was found, where the majority of respondents (65%) reported decreasing soil fertility, and a small but substantial group (7%) reported increasing fertility. Soil properties from fields perceived as increasing in fertility were associated with high SOC and active carbon relative to fields perceived as decreasing in fertility (Table 2.3; $p<0.05$). The sampling frame in our study purposefully included a wide variability in land types, allowing the capture of farmer perceptions for different soils and environmental contexts. This contributed to the successful differentiation observed in this study.

A range of farmer perceptions were documented along with LandPKS characterization of highly local information by site. This provides unique fine resolution data, compared to the coarse soil property data from world databases which is often at a 250 m scale resolution, followed by down-scaling to a specific site (Hengl et al., 2015). Through this protocol Kelly and Anderson (2016) compared farmer perceptions of field soil fertility status to predicted soil fertility properties, and found the two to not be related. Extraction of soil parameters at a coarse scale is a common approach used by researchers (Nijbroek and Andelman, 2015; Berazneva et al. 2018; Bhargava et al., 2018). However, our use of direct soil measurements at field sites and corresponding farmer perception information contributed to identifying a connection between scientific measurements and farmer perceptions. This expands upon a previous framework connecting farmer perceptions to behavior addressing land degradation (Bayard & Jolly, 2007).

Farmer management and soil status

Farmers in our study often had multiple objectives for using practices. This was seen with users of organic amendment practices who had elevated soil carbon, but not high maize yields, which corresponded with farmers reporting prioritizing increasing soil fertility levels over maximizing yield. Bhargava et al. (2018) evaluated fields in Tanzania for SOC across various farmer practices and did not find a relationship between use of organic amendments and SOC. The authors attribute this to the low frequency of organic amendment use. Berazneva et al. (2018) which compared Tanzanian and Kenyan farmer perceptions of soil fertility to farming practices also found that application of organic amendments did not vary with soil quality perceptions. In contrast, study 1 findings reported here showed that most farmers who perceived their plot as increasing in soil fertility applied organic amendments. Berazneva et al. (2018) and Bharagava et al. (2018) both used a general household survey, the LSMS, to identify farmer practices, whereas our detailed survey included focal plot monitoring and was able to pick up practices that were not widely reported in the LSMS, and thus find significant relationships between soil quality and practices.

Fields with soil fertility practices had low levels of soil carbon, relative to fields with organic amendments (Table 2.4, $p<0.01$). However, a trend towards high maize yields was observed with this soil fertility group which was not found with other practices ($p<0.10$). It should be noted that soil fertility practices in this Tanzania-based study involved mostly slash and burn, or fallow, with limited use of chemical fertilizer. Previous studies on the effects of burning on soil organic carbon support the observation that these fields had low SOC levels, although the magnitude of this effect can vary with soil texture (Bird, Veenendaal, Moyo, Lloyd, & Frost, 2000). Fallow practices may be associated with high crop yields, but studies measuring effects on soil carbon show minimal change, with changes relative to the inherent soil fertility level (Mertz, 2002; Bruun et al., 2006; Hepp, de Neergaard, & Bruun, 2018). Additionally, farmers' reasons for conducting soil fertility practices in study 2 included concern about crop yields, and interest in conserving labor (Table 2.6).

Land Management and LandPKS

An important observation from this study is a disconnect between farmer perceptions of site characteristics and the need for land husbandry and extension recommendations for soil conserving practices. Extension advice often considers the slope of the site, yet farmers did not implement erosion control measures preferentially to sloped land in our study, nor in a previous study by Tenge, Graaff, & Hella (2004). Based on remote sensing data, the slope at the focal plot site was not different for plots with or without erosion control measures as both were around 1%. This is well within favorable land conditions for cultivation (Li et al., 2017). Slope recorded through LandPKS indicated slightly steeper land, with 7 out of the 16 plots with erosion control categorized as moderate to hilly slope (associated with 6-30% slope).

There was no evidence to support that farmers preferentially practice erosion control on steep slope sites. There was evidence for farmer consideration of other site characteristics, such as the site property of water infiltration rates (Table 2.7). Erosion control measures were often implemented at sites with reduced infiltration rates, often due to the presence of a clay layer at specific soil depths. Indeed, surface infiltration rate as predicted by LandPKS appeared to be a good indicator of farmer utilization of erosion control practices. In Ethiopia, Assefa and Hans-rudolf (2016) surveyed farmers on indicators they use to assess soil erosion. Farmers noted indicators of soil erosion such as low soil depth and soil workability, which could relate to compaction layers and high clay content. Results from LandPKS in our study show how local knowledge of erosion control practices can be systematically documented to empirically assess soil erosion and relate local observations, such as soil texture and slope, with scientific assessments (eg. AWC, surface infiltration rate) to identify site specific practices. While the concept of assessing soil conditions at different depths on farmer fields isn't new, most notably described in Dalgliesh et al. (2009) with farmers in Australia, the execution of this process in the form of a free, open access smartphone application is novel. Our study provides the first evidence of an accessible way forward that links local and scientific knowledge on smallholder farms, and documents site-specific information for enhanced relevance.

Farmer objectives concerning land management and soil fertility

Whereas in the literature soil fertility and land management practices are often considered in isolation (Ellis-Jones and Tengberg, 2000; Barrios et al. 2006; Assefa and Hans-Rudolf, 2016), farmers often considered these practices as part of a continuum of overlapping categories. This has implications for extension recommendations, as advice will be ineffective if it disregards farmer strategies that involve multiple practices and cumulative effects on soil. Further, our study highlights that farmers often consider soil fertility and degradation issues together and use practices that are able to address both simultaneously (Table 2.6). Previous research has found that researchers often focus on the biophysical benefits of practices, whereas farmers report multiple objectives covering biophysical and socioeconomic considerations (Ramisch, 2014). Assefa and Hans-rudolf (2016) recorded local knowledge and also found that soil erosion and fertility loss were considered by farmers as connected. Similarly, we found that farmer concerns about soil fertility were interrelated with concerns about soil water dynamics and erosion.

The findings in this study are consistent with the need to identify sustainable agriculture practices that consider both physical soil and fertility management. Current extension services in Tanzania may be ineffective in this regard, and could be strengthened through recognization of the interaction between these issues. Nijbroek and Andelman (2015) evaluated extension services in Tanzania and found that only 5% of farmers considered extension services they received as above average, but when farmers did receive good agricultural services there was a measurable increase in maize yield. This is suggestive that increasing access to good agricultural extension, such as through mobile platforms, can positively impact livelihoods. Our results show that to be effective, a smartphone based approach may need to incorporate farmers' multiple objectives and address soil fertility and land degradation issues together.

Conclusion

This study provides evidence that characterization of sites and farmer perceptions through a smartphone application can improve understanding of soil status, at both the surface and deeper depths. This provides a scientific basis for unique, and highly local, insights into soil water drainage and water holding properties. This study shows the value in identifying underlying land conditions, and farmer goals and perceptions, as a basis for locally-appropriate advice such as how to target scarce inorganic and organic amendments. This approach utilizes the LandPKS app not as a substitute for an advisor but as a resource that can catalyze engagement between extension agents and farmers for improved soil management advice.

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Chapter 3: The complex and often disconnected relationship between agricultural extension knowledge systems and farmer practice in Tanzania

Introduction

Extension of sustainable agricultural practices is a key component to achieving sustainable intensification (SI) of smallholder cropping systems, but there are many barriers to achieving this (Pretty et al., 2011). Identifying and disseminating effective sustainable agricultural practices involves understanding local farming systems and conditions. Especially in sub-Saharan Africa where most agricultural production is undertaken by smallholder farmers under heterogenous conditions, contextualizing practices and understanding local conditions is essential (Aune, Coulibaly, & Giller, 2017).

Agricultural research and extension has historically focused in many instances on maximizing production potential and agronomic inputs over incorporating local farmer knowledge (Biggs, 1990). Yet smallholder farmers have a broad range of agricultural objectives and low use of inputs often due to limited access or risk-aversion (Muzari, Gatsi, & Muvhunzi, 2012). While attempts to account for smallholder conditions and priorities have been promoted through initiatives such as farming systems research, these approaches have often fallen short. Reviews of farming systems research and extension show that local farming context and farmer practice remain overlooked (Biggs, 1995). Dissemination of input-oriented solutions and technologies developed on research stations has until recently been the dominant agricultural extension mode (Leeuwis, 2004). However, while participatory research approaches have been receiving more attention, current extension literature still focuses on linear technology transfer. Studies frame ineffectiveness of extension as insufficient knowledge transfer from extension to farmer (Lukuyu, Place, Franzel, Kiptot, & Taylor, 2012; Sekiya, Tomitaka, Oizumi, Assenga, &

Jacob, 2015; Niu & Ragasa, 2018). This approach assumes that the technology being promoted would be effective if all information and resources were received by the farmer. While value in local farming knowledge has been promoted in participatory research methods literature, there have been limited attempts to incorporate this knowledge source into research and extension systems (Schindler, Graef, & König, 2016). Emerging interest in local farmer agricultural knowledge therefore is vital for actualizing more effective farming systems research and extension.

Strengthening the system by which agricultural knowledge is transferred between researchers and farmers is an important linkage to creating sustainable agricultural systems for smallholder farmers. These extension systems are a key factor in connecting agricultural knowledge generated by researchers to farmers and support farmers to overcome production challenges (Agbamu, 2000). Extension systems consist of many different actors, ranging from government, research, NGOs, to industry. In Tanzania, the government extension system in place operates under a hierarchical structure whereby research generated by institutes under the Ministry of Agriculture is reported to regional level government officials responsible for disseminating the information down to extension workers who operate at the village level (Mattee, 1994). In addition to the government, NGOs and private companies are also involved in the generation and dissemination of agricultural knowledge, partly as a response to insufficient reach by poorly resourced government extension. NGO and agro-industry extension services however are not formally integrated into the public sector, and it is unclear how they are influencing local extension and farming practices (Rutatora & Mattee, 2001). In a review of agricultural extension research, characterizing advisory services has been identified as an area of further research (Faure, Desjeux, & Gasselin, 2012). Therefore, assessing the current status of extension and elucidating how extension agents source information are important information gaps that need to be filled for enhancing extension effectiveness.

Limited knowledge exists on extension knowledge systems that address the complexity of smallholder farming systems, particularly as this relates to SI. Addition of legumes within cereal based rainfed production is one of the pillars of sustainable intensification, as a means to enhance biological nutrient cycling, resilient production, and family nutrition (Pretty et al., 2011; Snapp et al., 2018). A recent country-wide survey in Tanzania highlighted SI benefits including child nutrition gains associated specifically with maize-legume cropping systems (Kim, Mason, Snapp, & Wu, 2019). Legume crop production has been shown to be a knowledge-intensive and complex aspect of smallholder farming systems, often influenced by gender and resource constraints (Ferguson, 1994; Waldman, Ortega, Richardson, Clay, & Snapp, 2016). Despite the importance of grain legumes to smallholder farmers, extension support that acknowledges the complex cropping systems within which legumes are produced has been limited (Muoni et al., 2019). There is a need therefore for extension systems that acknowledge and support smallholder grain legume intensification, thus achieving SI on smallholder farms.

To understand disconnects and connections across research, extension and farmer practices, there is a need to identify extension information sources and recommendations at different levels. To accomplish this our study examines the extension system in Tanzania and focuses on the farming practices and extension recommendations around maize-legume cropping systems, specifically highlighting the two main legumes grown in these systems, common bean (*Phaseolus vulgaris*) and pigeonpea (*Cajanus cajan*). The objectives of this study were first to understand the complexity of smallholder agricultural systems in Tanzania through identifying seasonal cropping patterns and practices on maize-legume plots. Second, to assess the current state of extension in Tanzania we documented extension knowledge systems and information sources specifically in the Southern Highlands. Our third objective was to elucidate extension recommendations and farmer practices to better understand connections and disconnects focusing on maize-legume production systems as a case study.

Materials and Methods

Data collection and research areas

This mixed methods study conducted in Tanzania involves primary and secondary data sources to capture farmer cropping systems, management practices, extension information sources, and extension recommendations. Administratively, Tanzania is divided into regions which are further divided into districts made up of wards which represent several villages (Figure 3.1). Agricultural extension is divided by seven zones in the country, each of which includes many regions. The main areas of research in this study focus on agricultural activities in the Northern and Southern Highlands zones. Data collection on farmer management included a survey carried out in 2017 encompassing the Northern and Southern Highlands zones of Tanzania and farmer focus groups in two of the same Southern Highlands districts as the 2017 survey. Extension recommendations were acquired through interviews with extension officers in both the North and Southern Highlands, a survey in 2019 in the Southern Highlands with village-based agricultural advisors (VBAAs), and printed material supplied by the Ministry of Agriculture (Table 3.1). Printed material included a book published by the Department of Research and Training under the Ministry of Agriculture which provides detailed extension recommendations for all major agricultural crops grown in Tanzania (Kanyeka, Kamala, & Kasuga, 2007).

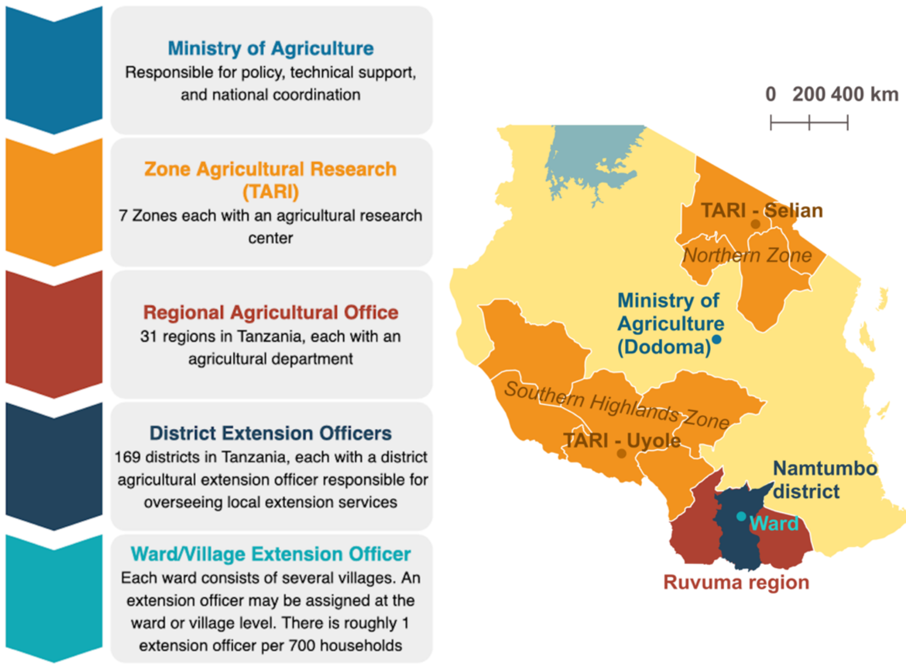

Figure 3.1 Extension diagram demonstrating different levels of public extension organization in Tanzania. Order of oversight starts with the Ministry of Agriculture, which oversees the Department of Research and Training under which are Zone Agricultural Research institutes (TARI). Regions (e.g. Ruvuma) are administrative units which comprise of several districts (e.g. Namtumbo) within which are wards made up of several villages.

Table 3.1 Information sources for bean and pigeonpea management and recommendations

	Farmer Practice	VBAA Recommendation	Extension Recommendation	Ministry of Agriculture Recommendation
Source	TAMASA Survey 2017 Focus groups	VBAA survey 2019	Interviews	Printed material
Regions Covered	North – Arusha, Kilimanjaro, Manyara Southern Highlands – Rukwa, Mbeya/Songwe, Iringa, Njombe, Ruvuma	Southern Highlands – Iringa, Songea, Ruvuma, Njombe, Mbeya, Songwe	North – Babati Southern Highlands – Mbozi, Mbeya	Whole Country
Number of entries	230 Focal plots 106 bean fields, 124 pigeonpea fields 5 Focus groups 8-11 participants each	Baseline – 182 VBAA bean responses Endline – 161 VBAA bean responses; 5 pigeonpea responses	Northern Zone – 7 extension officers (2 District level, 5 ward/village level) Southern Highlands – 5 interview groups with 2-3 extension officers per group	1 Published Book (Kanyeka, Kamala, & Kasuga, 2007)

TAMASA Survey (Farmer practice)

A survey encompassing household socio-economic factors and questions covering focal plot management was conducted by the International Maize and Wheat Improvement Center (CIMMYT) under the Taking Maize to Scale in Africa (TAMASA) project with support from the Sustainable Intensification Innovation Lab (SIIL). The survey targeted the main maize producing areas in Tanzania with the goal of identifying detailed management practices on smallholder maize production. A stratified spatial sampling frame was used to identify the survey areas selecting major maize production areas across a range of soil types and diverse agro-ecologies. A detailed description of this sampling frame has been previously described in Andrade et al. (2019). From this sampling frame 75 1 x 1 km grid locations, with 3 grids per district, were randomly chosen for identifying survey households. Within each grid a list of all households actively farming land was collected, and 8 households randomly selected to be surveyed. The household member interviewed for the survey identified a focal plot in the first year of the project, defined as the maize plot most important to a household's maize production, from which detailed plot management information and plant samples were collected. The same focal plots were revisited in 2017 with the same management questions covered regardless of whether maize was the primary crop that year. This allowed for capturing detailed management practices around legume production, with pigeonpea and common bean the two most common legumes grown on the focal plots. The survey was conducted in May – July 2017 during the main maize harvesting period, a time when pigeonpea is still present in the plot. As such pigeonpea plant measurements were also taken on the focal plots where pigeonpea was presented, allowing for measurements to be recorded on plant spacing and density. Survey responses with complete focal plot information was 578, of which 21 plots were fallow that growing season resulting in 557 focal plots with crop management information. Of these 557, 46% of the focal plots had legumes with 220 plots including either common bean or pigeonpea. From these 220 plots, management practices were summarized by the cropping system in which the legumes were grown divided by region. Pigeonpea was always grown as an intercrop with maize, and so the pigeonpea system refers to intercropping of pigeonpea with maize. Common bean was found to be grown as both a sole crop and intercropped with maize, and plots were delineated as such for descriptive analysis.

Focus Groups – Southern Highlands Bean Production (Farmer practice)

To capture detailed legume management information, focusing on common bean in particular, and expand upon information collected through the TAMASA survey, farmer focus groups were conducted in 2016 in the Southern Highlands area specifically in five wards that were visited in the TAMASA survey and known to be major bean producing areas. These five wards covered two different districts representing two regions in the Southern Highlands. They included Magamba and Itumpi ward in Mbozi district, Songwe region and Mapinduzi, Itawa, and Mshewe wards in Mbeya Rural district, Mbeya region. Focus groups consisted of 10-12 farmers representing multiple villages within the ward. The ward agricultural officer selected farmers who primarily grew beans to be participants, including both men and women farmers in each group. Focus group questions focused on bean management practices within the ward, including questions concerning the utilization of bean harvests, family food sources, and food security. Given that beans are planted multiple times throughout the growing season in each ward, bean management questions included identifying the timing of the main bean management practices such as land preparation, planting, weeding, and harvest for each of the bean plantings.

Government Extension Interviews (Recommendations)

Extension recommendation information was collected through interviews with government extension officers at the ward and district levels in the Southern Highlands for bean recommendations and in the Northern zone for pigeonpea recommendations as well as from a researcher at TARI-Uyole. Interviews were conducted with groups of extension officers using a semi-structured approach. In the Southern Highlands zone five wards were visited and interviews were conducted with groups of 2-3 ward and village level agricultural extension officers. In the Northern zone five ward level extension officers were interviewed individually. Respondents were asked to detail the recommendations for beans or pigeonpea with a focus on varieties, spacing, fertilizer type and amount, method and timing of fertilizer application. Questions also included how the legumes are typically grown by farmers, if farmers follow the recommendations mentioned, source of information for extension recommendations and whether farmers ever provide feedback on recommendations. Interviews with district level extension included extension officers in Mbeya district in the Southern Highlands and Babati district in the Northern zone. The interview with Mbeya district extension included three agricultural officers and Babati district extension included two agricultural officers. These district level respondents were asked similar questions as the other extension officers around legume recommendations and sources of information for extension, as well as additional questions concerning how recommendations are compiled.

Village-based agricultural advisors (VBAA) Survey (Recommendations)

In addition to government extension officers, legume management recommendations were collected from village-based agricultural advisors (VBAAs) for the non-profit organization Farm Input Promotions-Africa (FIPS-Africa). The VBAA extension approach is a model being promoted as a scalable support system that supplements government extension by providing training to farmers to act as local extension advisors. In addition, this model seeks to enhance public-private linkages by supporting VBAAs to become village-based agricultural input providers. VBAAs are selected by their communities and trained by FIPS-Africa in good agricultural practices and entrepreneurship with the goal of becoming certified small agro-dealers and informal extension advisors. FIPS VBAAs' primary activities involve setting up maize and bean "mother demos" and distributing free small packs of improved seed varieties or inputs (e.g. fertilizer or seed treatments) to farmers in their communities. The mother demos include demonstration plots that highlight improved varieties, inputs and management practices being promoted. Distributing small packs allows for farmers to experiment with the inputs being promoted on the mother trials on their own farms with the assumption that this will improve farmer learning and engagement around improved management practices. In 2017 216 active VBAAs from six regions in the Southern Highlands area received additional bean agronomy training highlighting improved bean varieties and the use of the fungicide-insecticide seed treatment Apron Star. In 2019 193 of these VBAAs were reached for a follow-up survey to assess their activities as VBAAs and the recommendations that they provided to farmers in the previous growing season. From these responses, VBAA recommendations on bean (and pigeonpea where grown) were summarized and compared to recommendations from government extension and farmer practice (Table 3.1).

Results

Farmer practice in cropping systems

The TAMASA survey recorded maize-legume cropping systems in focal study plots where a wide range of systems were observed, with marked differences between the Northern and Southern Highlands (Table 3.2). Bean and pigeonpea were the most common legumes present, with pigeonpea plots always grown as an intercrop with maize and common bean grown either as an intercrop or in rotation with maize. Household members involved in the decision making of plot management did not differ across cropping system or area, as plots in each cropping system appeared mostly split between either the head with sole decision making or head and spouse. Few female headed households were recorded for these plots (9% of plots), similar to the female headed household ratio for the entire survey (13%; 74 out of 558).

Pigeonpea plots were found in both the North and Southern Highlands, with the majority (87 out of 114) grown in the Northern sites (Table 3.2). Pigeonpea plots in the North had the highest average plot size (1 ha average) compared to both pigeonpea plots in the Southern Highlands (0.69 ha) and all other bean plots (0.49 – 0.65 ha). Planting characteristics also differed in pigeonpea plots in the North versus Southern Highlands, with pigeonpea in the North planted in higher density (18,800 plants ha^{-1}) than in the Southern Highlands (8,400 plants ha^{-1}). Pigeonpea was broadcast planted around maize in both the North (53% of 87) and the Southern Highlands (48% of 27). The remainder were planted in rows, where the majority of Northern plots had pigeonpea planted between maize rows (33 out of 46) whereas Southern Highlands row-planted plots all occurred within maize rows (14 out of 14). Seed types in both the North and Southern Highlands were majority local seed varieties, with only five plots in the North and one in the Southern Highlands reporting use of improved pigeonpea seeds. For both improved and local seeds, majority were recycled seeds with only 13 out of the 87 plots reporting seed type indicating that seeds planted were purchased. Fertilizer use in pigeonpea plots was found in both the Northern and Southern Highlands plots, with Southern Highlands plots having a higher percentage of fertilizer use (74%) and higher application rates (141 kg ha^{-1}) than Northern plots

(18% use, 111 kg ha^{-1} average urea application). In both areas majority of inorganic fertilizer applied was urea, suggesting fertilizer use was targeted to maize. The main overall fertility amendment applied in Northern pigeonpea plots was manure, reflective of high manure use in Northern sites in general.

Bean plots were characterized as either maize-bean intercrop or sole bean (Table 3.2). Sole bean plots were mostly found in the Southern Highlands area (n=38), and all of the plots in the Southern Highlands were continually rotated with maize based on responses to the five-year land use history of the plot. Northern sole bean plots were few (n=4) and were less consistently rotated with maize and more commonly included other crops in the previous growing seasons. Instead, bean plots in the North were more often intercropped with maize (n=51) more so than in the Southern Highlands where maize-bean plots were 13 compared to 38 sole bean plots. Plot size did not differ greatly across bean cropping system type or area, with average plot size smallest for maize-bean intercrops in the Southern Highlands (0.49 ha) and largest in sole bean plots in the North (0.65 ha). Similar to pigeonpea, bean seed varieties used were mostly local and recycled. Sole bean plots in the Southern Highlands had the highest use of improved varieties (n=7), but even these were mostly recycled (4 out of 7). Fertilizer use differed between maize-bean plots and sole bean plots, with 31% of maize-bean plots having fertilizer applied of which most was urea. In contrast, 55% of sole bean plots (not including the 4 Northern plots) had fertilizer applied, most of which was diammonium phosphate (DAP) (20 out of 21). Fertilizer rates had large ranges, with the largest range amongst urea use on maize-bean plots in the North (54-558 kg ha^{-1}) resulting in an average rate of 180 kg ha^{-1} per plot. Maize-bean plots in the Southern Highlands in contrast only had an average rate of 32 kg ha^{-1} with a range of 15 – 69 kg ha^{-1}. DAP application on sole bean plots in the Southern Highlands had the second highest application rate with 161 kg ha^{-1} average per plot and range of 37 – 417 kg ha^{-1}. Pesticide use, including herbicides and insecticides, was overall low (0-16%) with the highest occurrence in sole bean plots in the Southern Highlands. The only other plots with pesticide use were two pigeonpea plots and one maize-bean plot in the North.

Table 3.2. Farmer practice of pigeonpea and bean cropping systems collected from TAMASA survey focal plots.

		North			Southern Highlands	
	Maize-bean intercrop	Sole bean	Pigeonpea	Maize-bean intercrop	Sole bean	Pigeonpea
$n_{focal\ plots}$	51	4	87	13	38	27
Focal plot size (ha)	0.57	0.65	1.0	0.49	0.61	0.69
Decision making of field						
Head only	26 (7 Female)	4 (0 Female)	42 (6 Female)	8 (3 Female)	16 (2 Female)	13 (1 Female)
Male Head + Spouse	23	0	40	4	21	9
Seed types† % Local	39 (95%)	4 (100%)	62 (93%)	10 (100%)	31 (82%)	19 (95%)
% Improved	2 (5%)	0	5 (7%)	0	7 (18%)	1 (5%)
Legume plant spacing	-----	------	78 cm x 57 cm	------	-----	103 cm x 106 cm
Plant density (plants ha^{-1})	-----	-----	18,800	------		8,400
Fertilizer Use (Organic/Inorganic)	17 (33%)	0	16 (18%)	5 (38%)	21 (55%)	20 (74%)
Type	Urea (14); Manure (4); DAP (2)	N/A	Manure (7); Urea (6); Compost (2); SA(1)	Urea (4); DAP (2); CAN (2)	DAP (20); Yara (2); Urea (1)	Urea (16); SA (13); CAN (2); Yara (1)
Inorganic Fertilizer Rate ‡	Urea		Urea	Urea	DAP	Urea
Average (kg ha^{-1})	180		111	32	161	141
Range (kg ha^{-1})	54 – 558	N/A	4.9 – 195	15 – 69	37 – 417	20 – 333
Pesticide (Insecticide, Herbicide, etc.)	1 (2%)	0	2 (2%)	0	6 (16%)	0

†Of reported seed types – not all respondents reported source of seed, therefore number of responses do not sum to number of plots in each cropping system

‡Of most reported inorganic fertilizer

Bean systems in Southern Highlands

Within bean cropping systems, in depth farmer practice was collected through focus groups in five wards in the Southern Highlands area to gain detailed information about bean management in these areas. From these discussions, a crop calendar was constructed displaying the different management practices across the year for each bean planting that commonly occurred in a ward. Many areas within the Southern Highlands have multiple plantings of beans, and responses from the study wards show number of plantings and timing of plantings varies widely across wards and amongst farmers. While not all respondents in each focus group reported having multiple plantings of beans, four out of five wards reported multiple bean plantings. Within a ward with multiple bean plantings, reasons a farmer may not plant beans multiple times included factors such as the food needs of a family and late planting. For some families one bean harvest may be enough to support family food needs and therefore they do not see the need to plant again in a season. For others, if the first bean planting is delayed the harvest will not occur early enough to plant the second bean crop before the rains end. Across wards with different bean plantings, respondents reported climate and local soil moisture as major factors determining if the area was suitable for multiple bean plantings. Low soil moisture was a main reason cited for not supporting multiple bean plantings, even in areas with large rainfall amounts local soil conditions may not retain a sufficient level of moisture to support a bean crop. In other areas local rainfall amounts may not be high enough to support multiple bean cropping.

In each of the five wards the type and timing of agricultural activities associated with bean production were recorded, including land preparation, planting, weeding, and harvest (Figure 3.2). Overall there were four bean planting patterns noted. The first pattern, commonly seen in Mbozi district, involved planting beans at the start of the rainy season followed by a second bean planting around the time of the first planting harvest, which corresponded with the last two months of seasonal rainfall. Another pattern included delaying the first bean planting until the middle of the rainy season, followed by a second planting during the dry season that depended on sufficient residual soil moisture. This pattern occurred in areas (e.g., Mapinduzi ward) where rainfall in the beginning of the season was of high intensity and prevented a successful bean crop. A third pattern, observed in Mshewe ward, included three bean planting times, with the first starting at the beginning of the rainy season. The second bean crop was planted around the time of the harvest of the first, and this pattern continued throughout the year with the third planting carrying over into the first planting of the following rainy season. The fourth pattern, observed in Itawa ward, included just one bean planting in the year which occurred in the middle of the rainy season. Interestingly, the area with just one bean planting during a growing season is located in the same region as the ward with three bean plantings demonstrating the highly local nature of bean cropping patterns.

Bean crop activities sometimes differed by planting period, with less labor and inputs commonly given to the second bean planting. Most often respondents noted that the second bean planting was weeded less or not at all and land preparation was often not done in comparison to the first. Herbicides were used by at least some farmers at all locations. When used in areas where farmers planted multiple bean plantings, herbicides were generally applied during the first bean planting, and not necessarily at the second planting. One ward noted that the first bean planting was expected to produce higher yields than the second. Insecticides were commonly noted as being applied around the time of weeding.

In addition to bean production activities, respondents identified the months when people often struggle with food security and the coping strategies used. While periods of food insufficiency and bean cropping varied between wards, within each area hunger periods commonly occurred before bean harvests and sometimes after (Figure 3.2). The alignment of food insecure periods with bean harvests highlight the potential contribution of gains in bean production to directly address household food insecurity. Coping strategies mentioned by respondents also included borrowing food to be repaid with future harvests and selling cash crops such as common bean. Generally, utilization of bean harvests from all planting periods was reported to be for both home consumption and market. Similarly, for bean varieties grown, generally there was no preference for planting certain varieties during one planting time versus another. Some bean varieties were seen as desirable based on early maturity, which allowed for planting multiple times. The first bean harvest was often used as seed for the second.

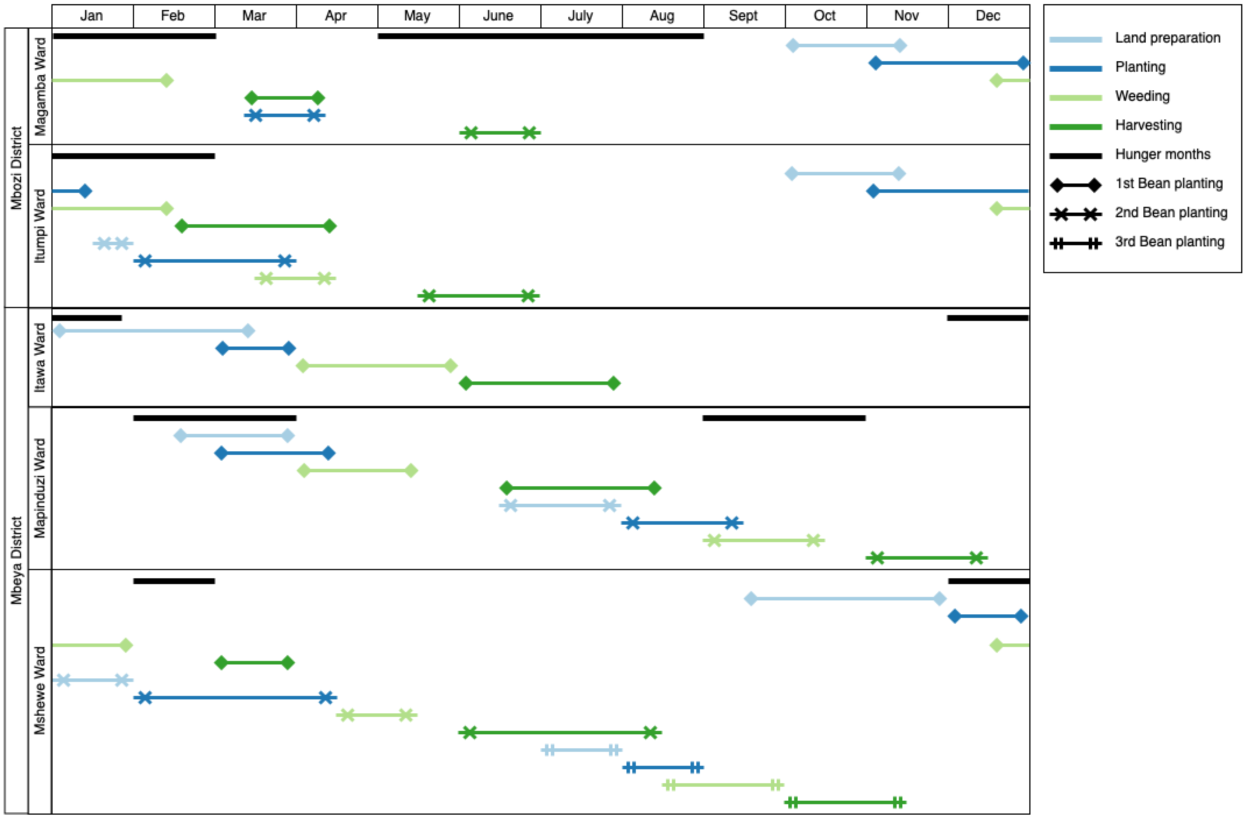

Figure 3.2 Calendar detailing bean crop activities across five wards in the southern highlands zone comprised from interviews with farmers in these wards.

Village based agricultural advisor (VBAA) extension recommendations

Extension advice by VBAAs to farmers in the Southern Highlands is reported based on the VBAA survey (Table 3.3). The recommendations primarily focused on bean production, with a few VBAAs (n=5) additionally making recommendations on pigeonpea (Table 3.3). Advice included recommendations on spacing, fertilizer use, seed varieties, and other inputs, with some VBAAs providing recommendations in all areas and others in just a few. Of the VBAAs providing spacing recommendations, all recommended planting beans in rows but row spacing distance varied. Majority (54%) of VBAAs recommended a spacing of 50 cm between rows and 10 cm within row, while 16% of respondents recommended 30 cm between rows instead (Table 3.3). The remaining 30% of respondents recommended another spacing combination beyond 30 or 50 cm by 10 cm. The majority of VBAAs (81%) recommended fertilizer application for beans. The most recommended fertilizer was DAP, with 74% of recommendations including this fertilizer type and 63% of all recommendations were just for DAP. The second most recommended was the Yara fertilizer brand, included in 28% of fertilizer recommendations, with 13% of recommendations just for Yara Cereal fertilizer type. Fertilizer rates were most commonly recommended in kg per acre, and specifically in the amount of 50 kg/acre (66% of recommendations). A few respondents reported rates in grams per hole instead, with 12% of recommendations recommending 5 grams/hole. Bean varieties recommended were tabulated using responses from an initial (baseline) survey of the same VBAAs several years prior to the main survey as part of the VBAA study included an intervention on distribution of improved bean varieties. Before the study, four common bean varieties were identified as most recommended by VBAAs and included the varieties Uyole 96 (recommended by 82% of VBAAs), Njano Uyole (79% of VBAAs), Calima (26% of VBAAs) and Wanja (21% of

VBAAs). Many VBAAs also recommended other inputs such as seed treatments (76%) and insecticide/fungicides (77%).

While pigeonpea recommendations were few, those recorded provided key insight into local recommendations being provided. All five of the VBAAs providing recommendations on pigeonpea recommended that it be sole cropped instead of intercropped with maize. Four out of five of the VBAAs recommended spacing, although each noted a different spacing arrangement. This ranged from 75 – 80 cm between rows and 30 – 60 cm within row. Only two VBAAs recommended fertilizer application to pigeonpea, with both respondents recommending DAP. Seed varieties were also only recommended by two VBAAs and these where for a local variety.

Table 3.3 Village-based agricultural advisors (VBAA) recommendations from VBAA survey. Total N_{VBAAs}= 193.

Pigeonpea	n_{VBAAs} providing recommendations	5
	Sole cropped / Intercropped	5/0
	Spacing	75 cm x 30 cm (1) 75 cm x 60 cm (1) 80 cm x 30 cm (1) 80 cm x 40 cm (1)
	Fertilizer	DAP (2)
	Seed	Local, white variety (2)
Common Bean	Provided spacing recommendations Recommended planting in rows	161 100%
	Bean spacing	50 cm x 10 cm (86) 54% 30 cm x 10 cm (26) 16% Others (49) 30%
	Bean fertilizer – Recommend (Y/N)	Y - 156 (81%)
	Types[†]	DAP - 115 (74%) Yara - 44 (28%) Others - 19 (12%)
	Rate	50 kg/acre - 103 (66%) 5 gm/hole - 19 (12%)
	Bean varieties (baseline – 183 respondents)	Uyole 96 – 150 (82%) Njano Uyole – 145 (79%) Calima – 47 (26%) Wanja – 39 (21%)
	Bean seed treatment (Y/N)	Y - 147 (76%)
	Bean insecticide/ fungicide (Y/N)	Y - 149 (77%)

[†]Respondents reported recommending multiple fertilizer types, therefore numbers do not add to total VBAAs providing recommendations.

Extension legume recommendations vs. farmer practice

Farmer practice of common bean and pigeonpea management was compared to extension recommendations across three different levels, from village level VBAAs, district and ward level public extension officers, and Tanzania Ministry of Agriculture official publications. A Venn diagram listing practices versus recommendations demonstrates areas of overlap and disconnect between the different sources (Figures 3.3 and 3.4).

For bean management, few of the farmer practices overlapped with recommendations (Figure 3.3). All sources of recommendations (VBAAs, extension, and Ministry of Agriculture) recommended a spacing of 50 cm x 10 cm. Additionally, all sources recommended applying insecticide to beans but there was limited evidence of farmers using insecticides, with a few applying this input on sole bean plots. Herbicides were recommended by both extension and the Ministry but were minimally used by farmers. The one area of synchrony observed was that of fertilizer rates for bean production. A wide range of farmer fertilizer application rates was observed, and VBAA recommendations for fertilizer rates varied as well; however, there was overlap. For example, DAP fertilizer for bean recommendation rates ranged from 50-100 kg/acre (124 – 247 kg/ha). Farmer practice in the Southern Highlands for DAP applied to sole bean cropping systems varied, but an average rate (161 kg/ha) was within the recommended range. Yara fertilizer brand was recommended by both VBAAs and extension staff at a rate of 50 kg/acre, but this fertilizer brand was not an observed farmer practice. Fertilizer rates in general were reported in hectares by the Ministry, which also listed recommendations by nutrient (e.g. amount N), whereas extension reported rates as kg per acre and by fertilizer type (not the nutrient content of the fertilizer).

Interestingly, farmer practice differed by bean cropping system (intercropped vs sole cropped), whereas variation in bean production system was rarely acknowledged by recommendation sources and not accounted for in any recommendation. The Ministry of Agriculture publication divided some recommendations by extension zone (e.g. Northern vs Southern Highlands), which is a coarse delineation of regions across the country. Other materials published by the Ministry of Agriculture have delineated multiple agroecologies with tremendous diversity of systems and farmer practices, within Northern and Southern Highland zones (De Pauw, 1984).

Farmers mostly used local recycled seeds, with sole bean systems in the Southern Highlands having the highest use of improved varieties at 18%. In contrast, the Ministry recommended 14 improved varieties that have been developed in various agricultural research institutes across the country. Extension officers listed ten improved varieties that were common in the Southern Highlands, of which only two overlapped with the Ministry list. There were only four common varieties promoted by VBAAs, of which two were also mentioned by extension and one was listed in the Ministry booklet.

Pigeonpea management generally had few recommendations despite the prevalence of this crop in study focal plots. One extension officer interviewed in the North noted that pigeonpea production recommendations are not a priority and instead their focus was on maize recommendations. This is seen in the substantial disconnects for pigeonpea production between farmer practice and recommendations. While farmers almost exclusively grew pigeonpea in an intercrop with maize, both VBAAs and the Ministry of Agriculture recommended sole cropping pigeonpea. The Ministry recommendations specified that sole cropping should be used for short duration varieties whereas medium to long term duration varieties may be intercropped. No other recommendation source differentiated variety types, with VBAAs and extension recommending local varieties which are longer duration. There were also planting differences between the North and Southern Highlands, suggesting local adaptation to cropping practices. Recommendations however do not provide site specific management practices. Instead recommendations focused on intensive spacing and chemical inputs such as insecticide and fertilizers. Inorganic fertilizer application by farmers occurred in only 26% of pigeonpea plots and the types of fertilizer applied were high in nitrogen content (urea, SA) which suggests the target was maize production, as maize is a nitrogen responsive cereal.

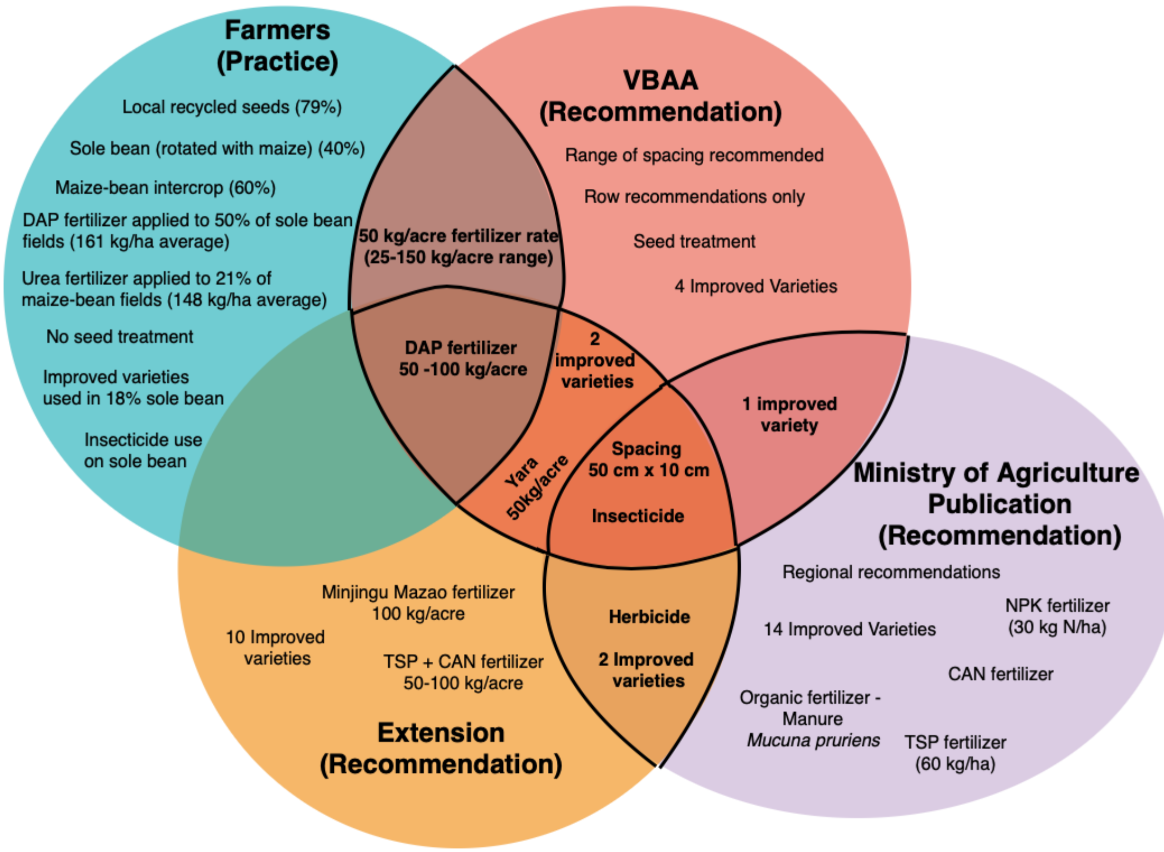

Figure 3.3 Venn diagram of farmer practice and extension recommendations for common bean management. Farmer practice determined by survey 1 focal plot responses (n=106). Extension recommendations compared across three different levels, with VBAA recommendations (n=193), government extension officers (n=5), and an official Ministry of Agriculture publication (Kanyeka, Kamala, & Kasuga, 2007).

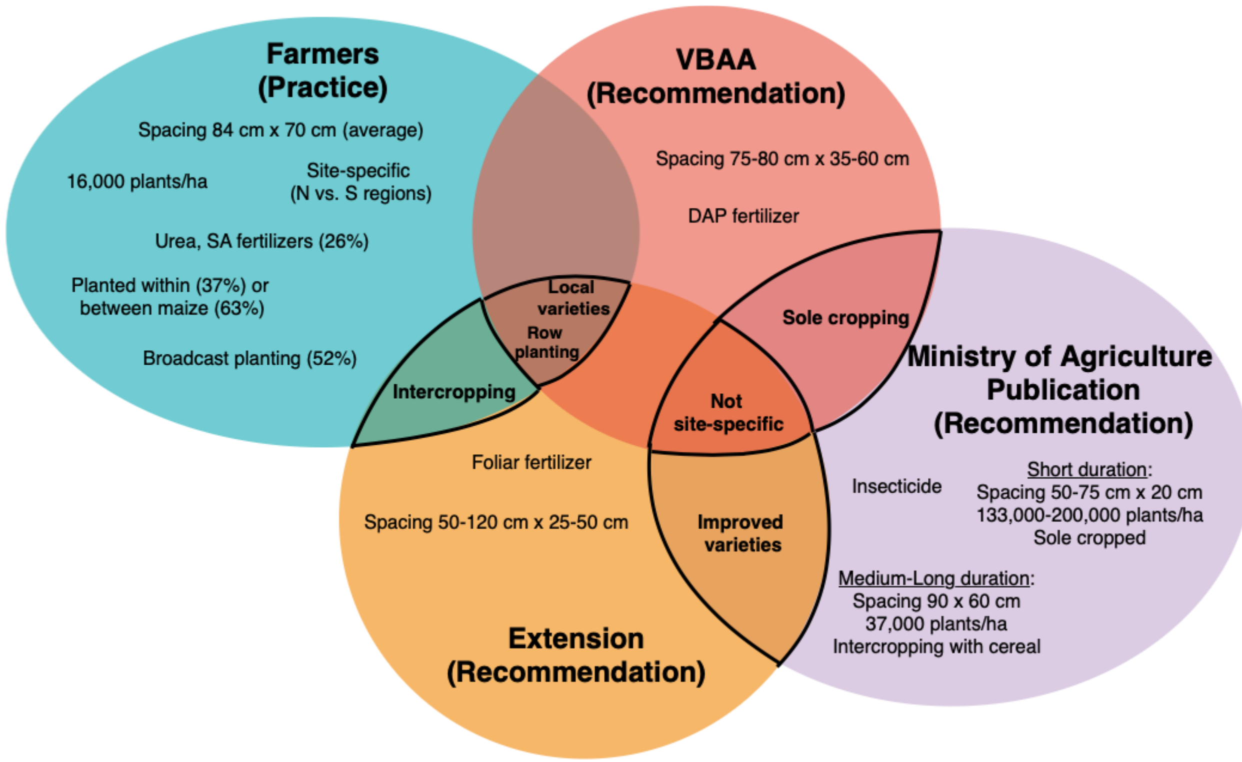

Figure 3.4 Venn diagram of farmer practice and extension recommendations for pigeonpea management. Farmer practice determined by survey 1 focal plot responses (n=114). Extension recommendations compared across three different levels, with VBAA recommendations (n=5), government extension officers (n=5), and an official Ministry of Agriculture publication (Kanyeka, Kamala, & Kasuga, 2007).

Extension sources of information

An information flow diagram was constructed to provide an overview of sources of agricultural recommendations and information as it is received by extension officers at the ward/village level (Figure 3.5). While this diagram is not an exhaustive list of all sources and flows of information to farmers and extension, it provides a summary of information sources from key informants interviewed to gain an understanding of agricultural recommendations. Five extension officers in the Southern Highlands area were interviewed, with those located in Mbeya district shown in Figure 3.5 to illustrate the flow of information. The diagram illustrates where information most frequently comes from (solid arrows of three different widths representing frequency of information source), where feedback is delivered (dashed arrow), and the discrepancies in access to information across different areas. The most common sources of information that extension officers cited for their recommendations were Uyole research, NGOs, and their formal (certificate or higher degree program) education from training institutes. Extension officers at the ward level reported that both Uyole researchers and NGOs regularly set up demo plots in their area and held other activities such as farmer field schools, ward level trials, and trainings for both farmers and extension. District level extension officers also noted the role of Uyole researchers and NGOs in providing recommendations, as well as the Ministry of Agriculture as a source of information at the district level. The district level officers noted that many NGOs were focused on fertilizer and seed inputs and contributed to recommendations this way in addition to fertilizer and seed companies which also had a large presence in the area, with companies regularly having demo plots to promote their products. While no ward level extension officer directly mentioned private companies as a source of their recommendations, one extension officer reported regularly bringing farmer feedback to these companies but noted that providing negative farmer feedback to companies resulted in threats to extension officers. Extension officers in some areas reported only receiving information from a few sources (Uyole or NGOs) but reported more frequent delivery of information. Others mentioned their formal education training as a major source of information for recommendations and as such this information would only be recent for those extension officers at the beginning of their careers but extension officers with various career lengths still mentioned this information as the majority of their recommendation knowledge.

The main flows of feedback from extension officers to other areas of government extension was mostly from ward extension officers to the district and district feedback to Uyole and Ministry of Agriculture (Figure 3.5). District level extension noted that they received feedback from extension officers at the ward level in the form of a written report. Ward extension officers are instructed to report their activities and challenges that they've encountered on a monthly, quarterly, and yearly basis. The district address challenges either directly through their agricultural department or they bring the challenges to researchers, NGOs, or the Ministry.

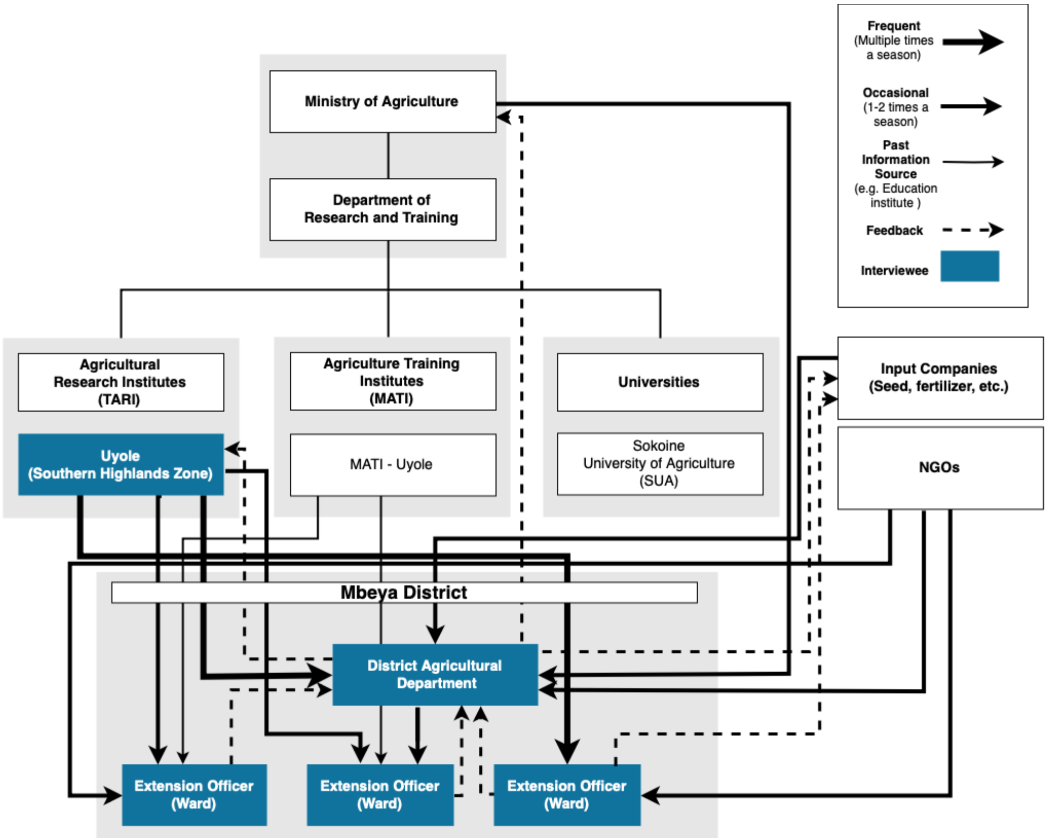

Figure 3.5 Diagram illustrating flow of information to ward level government extension officers as reported by three ward extension officers, district agricultural extension officers (n=3), and a researcher at TARI-Uyole.

Discussion

Smallholder field management

The focus of our study is on legume management within maize-legume systems in Tanzania given the complexity that legumes add to the system and the high frequency within which they are cultivated alongside maize, an important staple crop. As such this is the only study we know of detailing legumes on maize-based fields, which is an important characterization considering the potential impacts to both legume and maize production. Farmer practice differed across the Northern and Southern Highlands regions and cropping systems, such as intercropping, sole cropping, and planting periods, reflecting farmer adaptation to local conditions. Pigeonpea was always grown with maize, whereas common bean was sole cropped and intercropped with maize with sole cropped plots including multiple sequential plantings of common bean within a season.

While pigeonpea was always intercropped with maize, management differences were found between Northern and Southern Highlands sites. Literature on pigeonpea production in Tanzania often focuses on the main production areas in the North where it is grown primarily as a cash crop and sold for export (Amare, Asfaw, & Shiferaw, 2012). This priority of pigeonpea in the North is seen in the higher plant densities measured in the Northern plots (18,800 plants ha^{-1}) compared to the Southern Highlands (8,400 plants ha^{-1}). Another area of difference was in planting arrangement of pigeonpea, where pigeonpea in the North was planted between maize rows whereas in the Southern Highlands it was planted within maize rows.

Previous studies of pigeonpea production in Tanzania have focused on improved seed use over other planting arrangements and have found a major constraint to improving yields is the lack of quality seed as use of improved seeds is generally low (Simtowe et al., 2011; Amare et al., 2012). Simtowe et al. (2011) surveyed farmers in the North who grew pigeonpea and found use of improved pigeonpea varieties was around 19%. Use of improved varieties was even lower in our study, as only 7% of pigeonpea plots in the North were planted with improved varieties, and only one plot in the Southern Highlands. Additionally, seeds, both local and improved, are also often recycled from the previous year. This reduces the incentive of the private sector in supporting delivery of improved varieties, and thus provision is dependent on public institutions which lack sufficient resources to meet potential demand. Rusinamhodzi, Makoko, & Sariah (2017) addressed this seed quality issue by testing ratooning effects on pigeonpea as a way to reduce the financial burden on buying improved seeds every year. Ratooning involves cutting back the pigeonpea plant at the end of the first harvest, leaving behind a stem base from which the plant can re-sprout. Rusinamhodzi et al. (2017) found that this was a cost-effective strategy which did not reduce the productivity of maize-pigeonpea intercrops.

While pigeonpea yields on farm are currently well below potential yields, this crop overall has potential for increased cultivation. Mponda et al. (2014) evaluated pigeonpea value chains in the Southern areas of Tanzania, also noting that pigeonpea production in this area is not as intensive as in the North. However, the authors found that there is high potential for pigeonpea intensification in the Southern areas, as demand is increasing and a pigeonpea market exists through its proximity to northern Mozambique. This presents an opportunity for improved management strategies such as ratooning proposed in Rusinamhodzi et al. (2017) to be further tested for an area such as the Southern Highlands where pigeonpea cultivation has the potential to be intensified and a ratooning system may fit within the current lower population density being used.

Farmer practice around common bean management showed the many different variations that this crop is grown throughout Tanzania. In the North it was intercropped with maize whereas sole cropping with multiple planting periods was common in the Southern Highlands. Plots in the Southern Highlands also had higher input use than the North, but low use of improved seeds was found across all systems and regions. Previous characterization of bean production in Tanzania using national panel survey data found that across the country 85% of bean plots are intercropped, and that the Northern and Southern Highlands zones have some of the highest proportions of households growing beans, with 40% and 52% respectively (Stahley, Slakie, Derksen-Schrock, Gugerty, & Anderson, 2012). This national panel data also found that few plots (2%) used improved seed but in contrast inorganic fertilizer use was relatively high (18%), which is a similar input use pattern found in our study. Lack of use of improved seeds is often the focus of low legume production in the literature, with studies highlighting the extensive efforts in bean breeding, especially in Eastern Africa, to produce high yielding varieties with disease resistance and desirable market traits (Hillocks, Madata, Chirwa, Minja, & Msolla, 2006; Letaa, Kabungo, Katungi, Ojara, & Ndunguru, 2015). Despite the development and dissemination efforts of improved varieties, adoption rates are still low, with factors such as high cost, low awareness and access attributed to low uptake. However, adoption studies often only look at use of improved varieties in isolation to the other management practices of the bean cropping system. Farmers in our study, and in other studies of Tanzania, had higher use of inorganic fertilizer suggesting that while farmers may have limited resources, they are putting those resources towards fertilizer inputs over purchasing seed. This willingness to invest in fertilizer may be seen as more beneficial than use of improved seed, and the integration of these different inputs should be accounted for more in research on legume production.

Furthermore, a systems perspective, including factors such as planting sequences, household member involvement, and production objectives of common bean are rarely considered in research. For example, the use of multiple planting periods within a season for beans is often overlooked in the literature. Most studies on bean production in Tanzania are based on surveys aggregating total bean production over a season, which dilutes the complex bean management patterns found in this study and the implications for management. As such, especially in the Southern Highlands where bean production is prioritized, any bean production technology must fit within these planting period systems and therefore should first be tested with these systems in mind. Interestingly, while legume production is often reported as a "woman's crop", majority of plots were managed by men. Half of plots were managed by both men and women but very few were managed solely by women. This could reflect the changing culture of legumes as a subsistence or food security crop to one with market value and thus male household heads have become more involved in its management. This lack of decision making by women in bean production also has possible negative consequences as local knowledge of legumes is often held with women, and thus is at risk of being lost if they are not involved in management decisions (Ferguson, 1994). The focus group discussions from our study on bean production in the Southern Highlands also highlighted the use of beans as a food and market crop within households, which is a further consideration for future bean systems research.

Extension sources and types of knowledge for agriculture recommendations

A key result from this study is that extension sources of information are few with inconsistent input from research and no input from farmers. The limited sources of information that extension officers are using are also from separate institutions, from government to NGOs, which themselves do not coordinate to create unified extension messages. This is further seen in the large disconnects between extension levels and farmer practice for common bean and pigeonpea management. Rees et al. (2000) examined agricultural knowledge across extension sources in Kenya and similarly found inadequate information provided by government extension despite this being a major source of information for farmers. These disconnects and limitations to extension have broader implications towards the potential of improving smallholder production. If farmers are not being provided quality support services, this limits the ability of research to address farmers' main production challenges.

Addressing these challenges requires assessing the extension system as a whole, which consists of many different actors and entities (Figure 3.5). Birner et al. (2009) provide a conceptual framework for assessing agricultural advisory services, highlighting the many different contextual factors that need to be considered for identifying the best fit system for an area. The authors suggest using this framework to inform research on understanding which advisory services work where and under which farming systems. While this is often done as a cross country comparison, there is a need to look within a country such as Tanzania which has a large diversity of farming systems within country to identify how a particular system (e.g. maize-legume cropping systems) may be best served by a certain advisory service system.

Previous assessments of Tanzania's extension system have found similar interactions and structure as reported in our study. Mattee (1994) presents a similar analysis of the Tanzanian extension system, which over 20 years later does not appear to have changed much in function, despite the investment in increasing the number of extension officers assigned to rural areas (United Republic of Tanzania, 2013). Mattee highlights similar challenges as found in our study, such as ths issue of providing quality support to extension officers and improving the flow of information more so than increasing the number of workers. He argues that the hierachical structure of this system prohibits efficient and effective flow of information between research, government, and farmers. Our study also identified the addition of NGOs and private industries as an additional knowledge source which appears to further be fitting within this hierachical system and not providing more contextual support to farmers.

An institution within this extension system that is overlooked for improving the disconnects between research and farmers is post-secondary agricultural education institutes. Most extension officers in this study mentioned their education from agricultural training institutes as major sources of information for recommendations and thus represent a significant opportunity for improving agricultural knowledge and capacity to extension. As Spielman, Ekboir, Davis, & Ochieng (2008) note in their assessment of agricultural education training institutes in sub-Saharan Africa, these institutions often follow a top-down structure to education and are isolated from understanding local demand for agricultural knowledge in their areas. Reforms of these institutes have high potential for both improving the capacity of extension officers to support smallholder farmers and improve the connections between research and extension. Sekiya, Tomitaka, Oizumi, Assenga, & Jacob (2015) tested the potential effect of reforming training institutes (MATIs) in Tanzania simply by connecting research insitutes with MATIs, who provide training courses to lead farmers. They found that this approach did improve connection between research and farmers, as well as identifying the need for improved technical recommendations as farmer engagement highlighted the challenges that farmers still faced even with the improved technologies being promoted.

Research and farmer agricultural knowledge transfer

Previous literature cites low access to extension around legume production and attributes this to resulting low legume productivity (Muoni et al., 2019). Our study however highlights that even with access to extension, current recommendations may not be sufficient for supporting farmer challenges around legume production. Farmers need legume extension advice that accounts for the biophysical conditions of their area and the complexity of maize-legume systems that farmers are currently using. The extension recommendations by both VBAAs and government extension were focused on improved inputs and spacing. Specifics of these vary across extension levels and no extension level seemed to account for farmer cropping system in recommendations. In interviews with government ward extension officers, extension was aware of farmers intercropping and having multiple planting periods but did not take these factors into consideration for recommendations. This is indicative of the technology supply push pathway that is often promoted in connecting research with farmers using extension as the communicators. Röling (2009) describes the technology supply push pathway and others that may be used for connecting agricultural science to farmers from a historical perspective. Röling notes that the technology supply push is a common strategy for getting agricultural technologies created by researchers to farmers, most clearly demonstrated through the Green Revolution. However, he notes that this strategy is not very effective in actually reaching smallholder farmers, as adoption rates of these improved technologies is low. Our results on pigeonpea management especially are an example of this, as government extension emphasized sole cropping improved varieties of short duration types whereas farmer practice exclusively involved intercropped pigeonpea with longer duration varieties. Further, these technologies are created in isolation through component research, taken out of context with the local farming system, despite a long history of knowledge on the need for more farming systems research (Simmonds, 1986). Instead, in addition to farming systems research, for innovation that truly affects productivity institutions must be linked to producers, and accomodate farmer knowledge and demands.

Improving agricultural knowledge transfer for sustainable intensification

Improved agricultural knowledge transfer is cited as a key pathway for scaling up sustainable intensification through which smallholder production may increase while diversifying dominant maize monocrop systems (Pretty et al., 2011). This study documented the major legume management practices observed in the main maize-legume cropping system regions of Tanzania to better understand current legume production. Through this documentation these local management practices may be better integrated into future legume research and better served by extension. Especially given the regional differences in legume production, future legume research should take this site specificity into account through testing locally appropriate practices as well as an understanding of how tested practices may fit within the local system. This emphasis on farming systems research is crucial to enhancing legume production and thus creating more sustainable cropping systems.

Conclusion

Overall this study found there is limited connection between government and private sector agricultural advisory services to better address farmer priorities and practices. Extension recommendations often focus on intensification through purchased inputs, with information that can be conflicting, and provide limited attention to the integration of practices that address the complexity of farming systems. The Tanzanian Government is aware of extension knowledge system disconnects and the lack of research-extension integration, with a growing political will to address these gaps, and to incorporate indigenous farming knowledge. At the same time, Tanzania research and extension often prioritizes cash crops such as cotton, coffee, and tea, and this may lead to neglect of more rural communities and complex farming systems that address smallholder food security needs as well as income requirements. This study highlights that legume production knowledge is required that addresses the mixed single, double, and triple crop sequences pursued by farmers, and this should be prioritized as a foundation for sustainable agricultural production.

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