REDISCOVERING THE VALUE OF CROP DIVERSITY IN RWANDA: PARTICIPATORY VARIETY SELECTION AND GENOTYPE BY CROPPING SYSTEM INTERACTIONS IN BEAN AND MAIZE SYSTEMS

By

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ABSTRACT

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Traditional bean (Phaseolus vulgaris L.) and maize (Zeas mays L.) cropping systems provide multiple ecosystem services to the smallholder farmers that grow them worldwide, yet plant genotypes are rarely developed for this type of cropping environment due to the complexity of the system. Farmers have been growing these systems for generations and may have additional insight into when and how to select cultivars for intercropping systems. The objectives of this study were to investigate with farmers, climbing bean genotype by cropping system interactions (G x CS) in bean-maize intercrops and to use farmer criteria in the evaluation of the provisional services provided by three cropping systems.

This research was carried out in Northern Province, Rwanda on two research stations and 7 farmers' fields. Four cropping systems were planted in a randomized complete block design for two seasons. The cropping systems were a maize sole crop (MO), a bean sole crop (BO), a bean-maize intercrop in rows (IC), and a traditional bean-maize intercrop (TC). There were six bean genotypes and one maize genotype. Yield and morphological traits were collected and analyzed. Averaged across season and location, on-station bean yields were 3.4 mt/ha in the BO, 1.5 mt/ha in the IC, and 1.9 mt/ha in the TC. Averaged across season and location, on-station maize yields were 5.1 mt/ha in the MO, 4.8 mt/ha in the IC, and 3.1 mt/ha in the TC. There were no differences in bean yield between the genotypes in the BO, but one genotype, RWV 2070, yielded significantly higher (>0.0001) than the other genotypes in the IC. Pods/plant, the major

component of yield, had a significant G x CS interaction and was the only plant trait in the IC that was different between cultivars. On-station results indicate there are genotypes that have greater competitive ability than others in the IC, but aren't identifiable in the BO.

Participatory variety selection (PVS), group discussions and interviews were used to determine farmer genotype preferences and intercrop evaluation methods. Farmers evaluated on-farm trials in the same four cropping systems. Farmers' preferred the same genotypes for both cropping systems but they discussed different traits depending on the system. When selecting a genotype for an intercrop environment, farmers consider plant traits, adaptation, trait-based competitive ability, an intrinsic competitive ability, and various management strategies. Bean farmers in Rwanda use complex methods for identifying genotypes adapted to field conditions and different cropping systems, and add new insight into selection for bean genotypes in low-input environments.

Current agricultural policy in Rwanda encourages farmers to shift from diverse intercrop systems to sole crop systems but this may impact the types of services farmers gain from the cropping system. To identify trade-offs in cropping systems, on-station data was analyzed in terms of grain yield, protein content, caloric value, and economic returns including market value and land-use efficiencies. The IC intercrop system, planted in rows, provided more services than any other system and could be a viable alternative to the sole crop systems recommended by the government. Combined, these studies underscore the importance of intercrop systems and show that integrating knowledge systems improves our understanding of genotype by cropping system interactions.

To Butter

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There are too many friends to thank that helped me along the way and kept the laughter near. I am fearful of missing someone, so I won't list your names. Know that you are loved. Thank you to my dear family - you are always there for me and have made me who I am today. Finally, to Kurt. It was a long, adventure-filled road, and we did it together.

Obtaining my PhD has been a process of learning to communicate with myself, with individuals, with communities, and between cultures. Most of us can hear, but many more of us need to learn to listen, and in listening, accept that some differences are never bridged. These differences are beautiful in that they exist, in that there are so many unique perspectives in this world. It is with all of these perspectives that we can change worlds.

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Chapter 1 Abstract

Bean-maize intercropping systems are grown by smallholder farmers worldwide and provide multiple ecosystem services but few breeding programs have developed bean genotypes for these systems. Research has been carried out to determine the cropping system and stage of breeding best suited for selecting bean cultivars intended for production in an intercrop (IC), but there is little consensus in the literature and studies were carried out in diverse environments with numerous intercropping designs. There have also been attempts at identifying traits in a monocrop (MC) that are indicative of performance in the intercrop but with little success. The objectives of this study were to evaluate climbing bean genotypes in two cropping systems to determine which cropping system is suited for selecting bean cultivars, identify specific phenotypes that are associated with improved performance in the IC, and test whether there is a relationship between biological nitrogen fixation and yield in the two cropping systems. Trials were conducted on two research stations in Northern Province, Rwanda during Season B 2011 and Season A 2012. Six bean genotypes and 1 maize genotype were planted in a randomized complete block design, each in a MC and in a bean-maize IC, and replicated four times over the two seasons at each station. Yield, morphological traits, and plant biomass at pod-fill were collected and analyzed across the four environments (season x location). Environment or cropping system were the greatest source of variation for all traits including yield. Genotype by cropping system (G x CS) interactions were only significant for pods per plant and bean height, but genotype by environment was significant for yield and all yield component traits. Bean yields were significantly reduced in the IC but maize yields were not. Bean yields averaged across the environments ranged between 3.2-3.8 mt/ha in the MC and 1.3-2.1 mt/ha in the IC. Maize yield averaged across the environments was 5.3 mt/ha in the MC and ranged from 4.3-5.0 mt/ha in the IC. There were no differences in bean yield between the genotypes in the MC, but one genotype, RWV 2070, yielded significantly higher (P>0.0001) than the other genotypes in the IC. There were no traits in the MC that were indicative of performance in the IC. Pods/plant, the major component of yield, had a significant G x CS interaction and was the only plant trait in the IC that was different between cultivars. The IC environment increased biotic stress but was less affected by abiotic stresses whereas the MC was affected more the by abiotic (seasonal) stress. Results indicate there are genotypes that have greater competitive ability than others in the IC and that genotypes should be selected in the intended environment to identify these competitive genotypes.

Introduction

Mixed cropping systems have been understudied in agricultural research in favor of less complex farming systems yet they remain important to smallholder livelihoods. These systems, which include multi-species crop associations and intercropping, are grown by the majority of smallholder farmers in tropical regions of the world (Vandermeer, 1998) and provide numerous ecosystem services including environmental, nutritional, and social benefits (Malezieux et al., 2009). Legume-cereal intercrops are also the chief source of biological nitrogen fixation in agricultural systems and important nutrient cycling that supports sustainable production. Little attention has been directed at improving plant genotypes for these intercropping systems and the vast majority of plant breeding efforts and selection for improved genotypes occurs within monocultures under uniform, input-intensive environments (Kelly and Cichy, 2013). This field study was undertaken to evaluate the extent of genotype by cropping system interactions in Rwanda highland maize-bean systems as part of an endeavor to identify genotypes that are suited to the low-input mixed cropping systems found on smallholder farmers throughout Africa.

Maize (*Zea mays*) and common bean (*Phaseolus vulgaris*) intercrop systems are one of the most commonly grown intercrops worldwide. In East Africa, and specifically in Rwanda, common bean is considered a staple crop and it is the primary source of protein for smallholder farmers. Beans are second only to bananas in terms of land area under cultivation (16%) in Rwanda and are grown by 85% of farmers, with an average consumption of 48 kg per capita per year (Broughton et al., 2003). In northern Rwanda, climbing beans are grown in monoculture and are intercropped with various crops including maize or sorghum, or in the understory of bananas. Rwandan farmers use unique bean mixtures composed of landraces that they plant in these cropping systems, but most improved bean seed is developed on research stations in a sole crops under higher input conditions. In addition, Rwanda has 10 officially identified agroecologies (Rwanda Ministry of Agriculture, 2009) that represent diverse environments that vary greatly in terms of topography, soil type and quality, and rainfall. The development of improved bean genotypes that are adapted to these diverse environmental conditions is challenging and the additional complexity of the intercropping environment may amplify potential genotype, cropping system, and environment interactions.

The evidence is contradictory regarding the approach that is most effective at identifying genotypes suitable to the intercrop environment. The literature on genotype by cropping system interactions (G x CS) for maize-bean systems varies by the type of crop association and the growth habit of the bean. The types of bean-maize crop associations studied include relay (beans planted when corn is at physiological maturity), in association (bean and maize planted in separate rows approximately at the same date), or in an intra-row intercrop (beans and maize planted in the same row at approximately the same date). The growth habits are also varied. Most of the G x CS studies have been conducted with bush beans or semi-climbers in association (Francis et al., 1978; Zimmerman et al., 1984; Santalla et al., 2001; Atuahene-Amankwa et al., 2004; Worku, 2008), in relay systems (Francis et al., 1980), in an inter-row intercrop (Santalla, 1994; Oleary and Smith, 2004), or in multiple trials that look at several growth habits in both relay and intercrop systems (Davis and Garcia, 1983). Only a few have considered climbers, in association (Francis et al., 1978) and in inter-row intercrop (Davis and Garcia, 1983; Gebeyehu, 2006). The diversity in these studies reflects the different forms of bean-maize intercrops found around the world, but it also complicates comparisons of results about G x CS findings.

Smith and Francis (1986) and Davis and Woolley (1993) stated that one of the most important factors determining intercrop productivity was the level of species interactions, which can be modified by the choice of species or cultivars (Baudoin et al., 1997). However, there is little consensus in the literature on how to identify the most appropriate bean genotypes for intercrop environments. Plant breeders have generally followed one of two approaches: 1) selection of beans can take place in crop environments (Vieira and Ramos, 1992; Santalla et al., 2001; Atuahene-Amankwa et al., 2004; Francis et al., 1978; Davis and Garcia, 1983) or 2) breeding for qualitatively and simply inherited traits such as disease resistance, maturity, and climatic adaptation should take place on-station in sole crop conditions. Then, selection for quantitative traits such as competitive ability and yield could take place in advanced generations on-station and on-farm under intercrop conditions (from Baudoin et al., 1997; Smith and Francis, 1986; Davis and Woolley, 1993). Early generation breeding of bean cultivars specifically for cultural associations has only been attempted by a few researchers (Wien & Smithson, 1981; Zimmermann et al., 1984; Francis et al., 1985).

Few plant breeders have tried to select maize or beans within the target cropping system in early generations. O'Leary and Smith (2004) found that recurrent selection of maize in an intercrop environment generated corn families that were better adapted and the genetic variability identified in an intercrop environment was lost when selected in a monocrop environment. Likewise, comparing heritability of yield components in 16 bean families, Zimmerman et al. (1985) concluded that the magnitude of G x CS interactions detected suggested special intercrop breeding programs were needed. However, Zimmerman et al. (1996), in a later assessment of such a program in Brazil, concluded that while theoretically ideal, a special breeding program was not necessarily practical in terms of evaluations and applicability. In summary, some authors report selection of advanced lines can take place in the monocrop, others suggest it should occur in the intercrop and preferably on-farm, and still others present evidence that developing special breeding programs for multiple cropping systems may prove worthwhile but logistically difficult. In addition, authors have investigated whether there are potential bean plant traits associated with improved performance in the intercrop.

The identification of specific, predictive bean plant traits that function within the intercrop has not been successful to date. Each study found interactions for different yield component traits, but no clear picture emerged regarding which traits are important for determining adaptability in the intercrop. The G x CS interactions observed for these morphological traits varies markedly from study to study, and researchers have often focused on different traits. In a bush bean intercrop study with 25 bush bean populations, there were no G x CS interactions for any of the yield component traits measured (Santalla et al., 1994) but in Zimmerman et al. (1984) there were significant interactions for yield, number of pods, 100-seed weight, and harvest index. In semi-climbing and climbing bean studies, Gebeyehu (2006) found G x CS interactions in seeds/pod, harvest index, 100 seed weight, and yield, while Davis and Garcia (1983) identified G x CS interactions in plant height, days to maturity, and bean yield. Additionally, biological nitrogen fixation (BNF) efficiency might be a factor in genotype cropping system efficiency (Baudoin et al., 1997), but this remains unexplored.

The question of whether plant breeding efforts should occur within the target environment of mixed cropping systems in order to develop improved bean genotypes for smallholders remains unresolved. According to Baudoin et al. (1997) field studies are likely conflicting due to site-specific variability, and that much of the research was conducted on-station outside of the smallholder farm environment. The complexity of the cropping system and plant types involved presumably also plays a role, as studies have addressed a wide range of growth habit, cropping system combinations, and biophysical environments. In this study, we considered selection of advanced climbing bean genotypes for monoculture and mixed cropping systems in two on-station trials over two seasons, representative of the heterogeneous environment of the Rwandan highlands. The objectives were to determine: 1) If bean genotypes should be selected within the target cropping system type; 2) To identify potential traits associated with bean performance within monocrop and intercrop systems, and 3) To evaluate genotype and cropping system effects on biological nitrogen fixation, as an indicator of system sustainability.

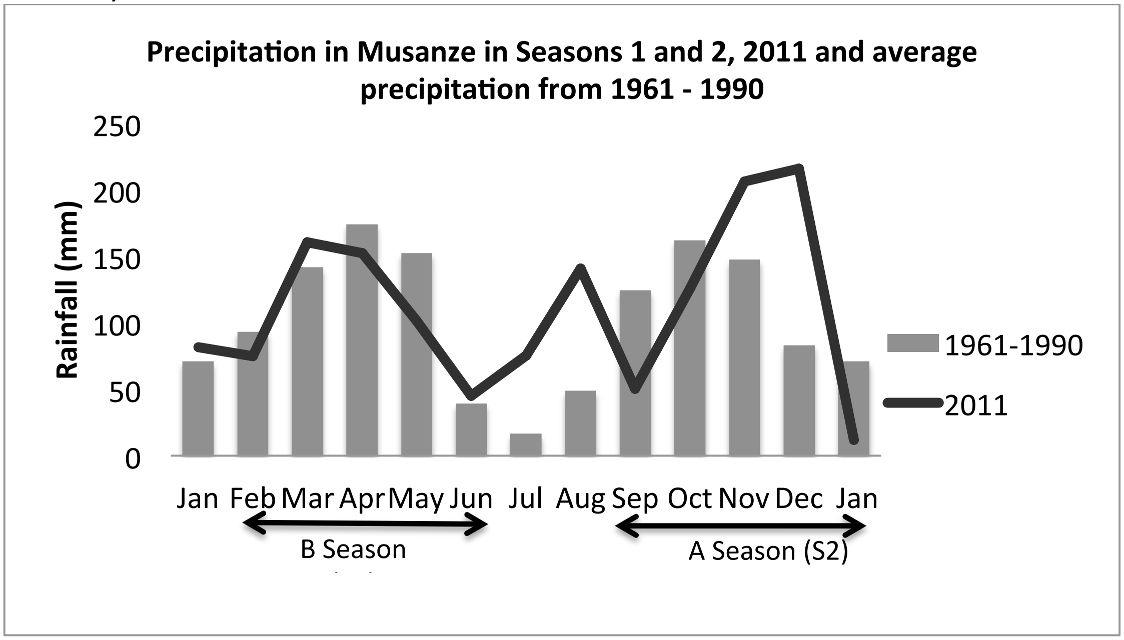
Methods

Site and soil description

Research trials evaluating the bean genotypes in an intercrop and monocrop were conducted on two research stations for two seasons in the sub-humid tropics of northern Rwanda. The two field stations, Rwerere and Musanze are located in Northern Province at S 01.48611 E029.87675 and S 01.49842 E 029.62843, respectively. Musanze Station (MS) is a mid-altitude site at 1850 m.a.s.l. and Rwerere Station (RS) is a high-altitude station in the Buberuka Highlands at an altitude of 2100 m.a.s.l.

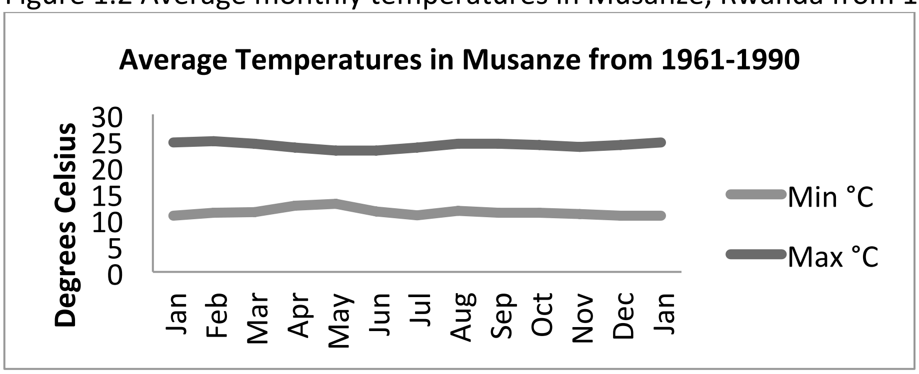
The areas have a bimodal rain distribution with the “long” rains occurring in March, April, and May and the “short” rains occurring in October, November, and December (Figure 1.1) Approximately a third of annual rainfall falls during each of these periods. The growing seasons extend on either side of these rainy seasons. The first cultivable season A is from September to January and the second cultivable Season B extends from late February through June. Yearly rainfall ranges from 1300-1600 mm in the highlands of Northern District.

Figure 1.1 Monthly rainfall in Musanze, Rwanda in Season 1 and 2, 2011-12 and averaged over 29 years



Season B 2011 (S1) was from February thru June. Season A 2012 (S2) was from September through January 2012.

Figure 1.2 Average monthly temperatures in Musanze, Rwanda from 1961-1990



Seasonal variation in temperature is low and mean monthly temperatures range from 14-17 C (Figure 1.2). However, diurnal variation in temperature is high, often as much as 10 C or more. Low temperatures range from 10-13 C and high temperatures range from 23-25 C. Multiple soil types and heterogeneous microclimates exist in Northern Province. The soil classification for MS is an umbric slandic Andosol characterized as a nutrient rich volcanic loam while RS is a dystric Regosol (Entisol) characterized as a well-drained clay soil (Jones et al. 2013) (Table 1.1).

Experimental design and layout

Four cropping systems were planted in a randomized complete block design (RCBD) in Season B 2011 (S1) and Season A 2012 (S2). The cropping systems were a maize monoculture, a bean monoculture, an intercrop of maize and beans in rows, and a traditional intercrop of maize and beans planted in a scattered pattern without rows. The experiment was designed to test cropping systems and genotype by cropping system factors, with six bean genotypes included. In this paper, we use a subset of the data and focus exclusively on analysis of the bean genotypes in the maize-bean intercrop in rows (IC), the bean monocrop (MC), and the maize monocrop (MZ9).

The RCBD of the four cropping systems consisted of 14 treatments. There were five bean genotypes, one bean mixture, and one maize genotype. Each of the five bean genotypes was planted in a monocrop and an intercrop with maize. The bean mixture was planted in a monocrop, an intercrop with maize in rows, and a traditional intercrop with maize. Maize was planted in a monocrop. Blocks were replicated four times at the two stations, for two seasons with a new site each season, so the experiment was replicated over time and space four times.

All of the maize and climbing bean varieties were adapted to the region. Pool 9A, a ubiquitously grown open-pollinated maize variety originally selected for the Volcanic Highlands of Rwanda is a Highland Late White Dent (Friesen and Palmer, 2004). It was used in all trials. All climbing bean genotypes were large seeded Andean Type IV climbing cultivars. The five bean varieties included Gasilida, RWV 3006, RWV 2070, RWV 3316, and Ngwinurare. Gasilida was an improved farmer developed variety. RWV 3006, RWV 2070, and RWV 3316 were improved CIAT varieties developed and tested further in Rwanda for release. Ngwinurare was an old CIAT variety introduced in Rwanda in the 1980s and a regional check. The bean mixture (FarmMix) was a local check and consisted of 3-5 bean types mixed by farmers and was different at each station.

All 14 plots were represented in each block. Individual plots within the block were 3 m x 4 m. There was uniform spacing between plots (0.75 m) and 1.0 m between blocks. According to farmer practice, the maize was planted first and the beans were planted 29-31 days later in every treatment.

The monocrop system plant densities were planted according to regional government recommendations. In the maize monocrop (MZ9), between the row spacing was 0.75 m and the distance between each plant within the row was 0.25 m. Two seeds were planted per hole for a target maize population density of 106,700/ha. In the bean monocrop (MC), between the row spacing was 0.50 m and the distance between each plant within the row was 0.20 m. Two seeds were planted per hole for a total bean population of 200,000/ha.

The intercrop system plant densities were according to researcher design for the IC, with beans and maize planted in the same row. Between row spacing was 0.75 m, in row spacing for beans was 0.1m and for maize was 0.3 m. Beans were planted on either side of the maize to facilitate bean climbing of maize stalks. Two bean seeds per hole were planted and thinned to one plant after emergence. The maize and bean populations in the IC were 44,400 and 106,700 plants/ha respectively, for a total plant population 151,100/ha.

Field Management

All trials were weeded with a hoe at bean planting and at least once more as needed during the season. Beans were staked with straight poles except at MS S1 where a combination of tripods and straight poles were used. At MS S2, heavy rains washed out some maize seedlings. These were replanted 2 weeks after the initial planting.

Inorganic fertilizer (Diammonium Phosphate 18-46-00) and organic material were applied at a rate of 100 kg/ha (0.12 kg/plot) and 83 kg/ha respectively, according to farmer practice (in the row for MO, BO, and IC; in the hole for TC) at maize planting. Urea (46%) was applied, at a rate of 100kg/ha to the base of maize plants mid-season to all plots.

Data Collection

Soil samples were collected before maize planting in both seasons for site characterization. A composite soil sample was collected from each station at a sample depth of 0-15 cm. At each station, 10 samples per block were collected and then combined to create the composite. Soil texture was determined using the hydrometer method (Anderson and Ingram, 1991). Soil samples were sent to A&L Great Lakes Laboratories in Fort Wayne, Indiana for further analysis that included organic matter (combustion method), inorganic P (Bray P), and pH in a 1:1 ratio in H_2O.

Total plant population was counted at peak maturity and at harvest. Both times, plant population was counted in the middle three rows and averaged.

Bean and maize heights, and bean and maize vigor time 1, were collected approximately 65 days after bean planting. In S1, heights were collected 59 (MS) and 74 (RS) days after bean planting. In S2, heights were collected 56 days after bean planting in both sites. For beans, height was measured by extending the tallest runner (normally above the stake). Ten plants of each crop were measured in the plot and then averaged for the plot. Vigor, or vegetative adaptation, was measured at pre-flowering (growth stage V5) and pod-filling (growth stage R7). The CIAT standard scale of 1-9 (CIAT, 1987) was used in which a score of 1 was excellent and 9 was very poor. The same researcher and assistant took these measurements at all locations.

The number of bean seeds/pod, bean pods/plant, and maize cobs per plant were determined just before harvest. For seeds/pod, 10 pods from randomly selected plants were counted and then averaged for the plot. For pods/plant, 10 plants were randomly selected and all of the pods on the plant were counted. In the case of the intercrop, multiple bean plants were intertwined. In that situation, all of the bean plants in the cluster were counted along with all of the pods. The number of pods was divided by the number of plants. At least 3 clusters were counted in each plot. The number of pods/plant for a plot was averaged from the 10 randomly selected plants. For maize cobs per plant, the number of viable cobs with whole grains per plant was counted on 10 randomly chosen plants in the plot and averaged.

For leaf area index (LAI), an AccuPAR LP-80 meter by Decagon Devices was used. The LP-80 measures the below-canopy photosynthetically active radiation (PAR) and the above-canopy PAR to calculate LAI. Above and below-canopy measures were taken simultaneously using the external PAR sensor. Measurements were taken 3 times in S1 and 4 times in S2. The additional measure in S2 was at bean planting, when LAI was near 0. Measurements were taken between 10am and 2pm, when the sun was at its zenith, every time. Within the plot, the meter was positioned in the same 4 locations at the same angle, away from border rows, in all plots. At each location in the plot, 10 measurements were taken for a total of 40 measurements per plot. These measurements were then averaged across replications to produce a LAI score for that plot.

Biological nitrogen fixation (BNF), or the amount of N derived from the atmosphere (Ndfa), was determined using the natural abundance method. Data was collected at peak biomass in both seasons and both locations from all plots except in S1 at RS. In S1 at RS, samples were only collected on genotypes RWV 2070 and RWV 3316 because peak biomass had already passed for the other genotypes.

In order to collect and prepare samples for the BNF calculation, a destructive sampling of the entire plant was taken at peak biomass on 2 m of a non-border row. The number of maize and bean plants was counted and they were separated. The total fresh biomass of each crop in the sample and a subsample were weighed in the field. Biomass subsamples were air-dried in the sun and the final dry weight was collected after oven drying and there was no detectable change in weight. These biomass subsamples, containing the entire above-ground biomass (stems, leaves, immature pods) were ground using a Wiley mill to pass a sieve size of 1 mm and packed according to University of California Davis (UCD) Stable Isotope Facility protocols. ^{15}N and ^{14}N was determined by mass spectrometer analysis at UCD, USA.

The natural abundance method (Shearer and Kohl, 1986) was used to determine the proportion of nitrogen derived from the atmosphere. The following formula was used to determine the %N derived from nitrogen fixation:

$$\%Ndfa = 100 \ \frac{(\delta^{15} N_{reference\ crop} - \delta^{15} N_{legume})}{\delta^{15} N reference - B}$$

Where $\delta^{15}N_{reference}$ is the $\delta^{15}N$ of the reference plant (maize) grown on the same soil as the legume; $\delta^{15}N_{legume}$ is the ^{15}N natural abundance of the grain legume crop and B is the $\delta^{15}N$ of the test legume where the only N source is atmospheric N. As an alternative to the test legume, the lowest legume $\delta^{15}N$ was utilized (Hansen and Vinther, 2001). Maize was used as the reference plant.

For yield, the entire plot was harvested (3 m x 4 m), and weighed. Moisture content was determined on all grain using a moisture meter and corrected to 12% and 15.5% for beans and maize, respectively. For bean 100 seed weight, the moisture content of the beans was determined and immediately afterwards 100 seeds were weighed and the 100 seed weight was adjusted to 12%.

Statistical Analysis

The software package SAS was used for statistical analysis. The yield and plant traits were analyzed using PROC MIXED. Season and location were combined into environment, resulting in four environments. Random factors were environment, genotypes, and replication. Cropping system was a fixed factor. The first statistical model for analysis combined all factors for yield including environment, cropping system, genotype, and replication. All interactions except replication were highly significant ($P<0.003$) and cropping system and environment were the main effects. Subsequently, models were separated first by cropping system and second by season if there were significant G x E interactions. Planned contrasts were used to identify differences between cropping systems, and differences between genotypes within a cropping system. If there was no interaction in the model, the planned contrast was adjusted with a Bonferroni correction.

Results

Environment

Precipitation was within regional averages that range from 1300 mm to 1600 mm. Rainfall in 2011 totaled 1429 mm with 534 mm in S1 and 610 mm in S2 (Figure 1.1). The remaining precipitation occurred in off-season months. In 2011, rainfall was higher than average in August and lower than average in September during planting time for S2. Heavy rainfall events in early October disrupted maize seedlings at MS and they required replanting. Precipitation was also much higher than average in November and December (Figure 1.1).

Rainfall during these two months in S2, was more than 50 mm higher than the rainiest months in S1, or the period of "long" rains (Figure 1.1).

Soil types and nutrient contents were different at each location (Table 1.1). RS soils were higher in Organic C (2.46-2.70%) than MS (1.29 - 2.19%) (Table 1.1). Total N at RS was higher in both seasons (0.27-0.29%) than at MS (0.21-0.13) (Table 1.1). Phosphorous was highest at MS S1 (297.0 mg/kg) due to legacy effects, and it was the lowest at RS S2 (14.5 mg/kg) (Table 1.1). Within the same season, P content was more than four times higher at MS than at RS. The pH of all the soils was between 5.53 (RS) and 6.00 (MS) (Table 1.1).

Table 1.1 Altitude and mean soil properties at Musanze and Rwerere Research Stations, Rwanda for Seasons 1 and 2, 2011-12

Location and Season	Elevation	Soil type	Clay	Sand	Total N	Organic C	Bray-p#	pH
	m		%	%	%	%	ppm	
Musanze Season 1	1861	Loam	18.0	46.1	0.21	2.19	297.0	6.00
Musanze Season 2	1851	Loamy Sand	7.6 (1.6)	75.7 (5.8)	0.13 (0.0)	1.29 (0.06)	111.0 (6.7)	6.00 (0.07)
Rwerere Season 1	2116	Clay	44.1 (5.2)	27.2 (2.3)	0.29 (0.03)	2.46 (0.56)	47.7 (13.7)	5.53 (0.21)
Rwerere Season 2	2109	Clay	45.8 (1.7)	23.3 (0.4)	0.27 (0.01)	2.70 (0.06)	14.5 (1.2)	5.93 (0.18)

Standard errors are in parenthesis.
#Bray extractable inorganic phosphorus
+pH in 1:1 soil/water ratio

Yield

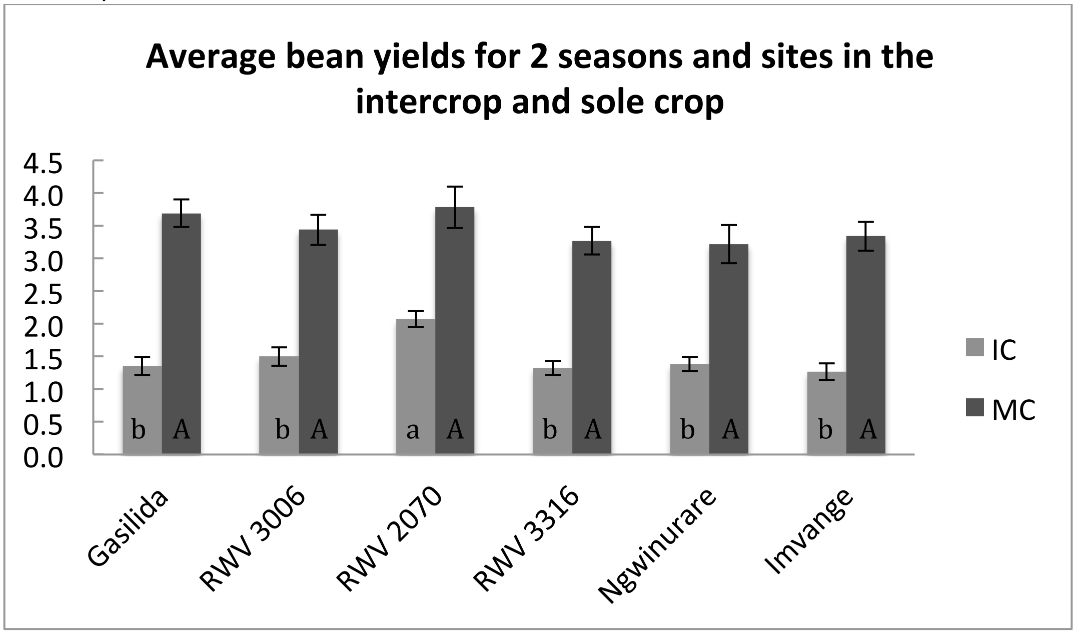
Overall, there were differences in bean traits (Figures 4-5) between cropping systems but there were no differences in maize traits (Table 1.4). There was a three-way interaction between environment, cropping system, and genotype for bean yield (Table 1.2). There were significant environment by cropping system (E x CS) interactions for all bean traits including yield (Table 1.2). There was a significant interaction between environment and genotype (G x E) for bean yield, 100 seed weight, and seeds/pod and there was a significant interaction between genotype and cropping system (G x CS) for pods/plant and bean height (Table 1.2). Environment, cropping systems, and genotype were significant factors for yield and all traits (except genotype for LAI) (Table 1.2). There were differences between the cropping systems for yield and all traits except 100 seed weight (Table 1.2).

Bean and maize yields varied between seasons, sites, and within cropping systems. Bean yields were higher in S1 than in S2 (Table 1.3). They were also higher at RS than at MS, in both seasons. In contrast, maize yields were higher in S2 than in S1 (Table 1.4) and they were higher at MS than RS in both seasons. Maize yields were not different between the two cropping systems (Table 1.4) but bean yields were different ($p = <0.0001$). The average MC yield (3.5 mt/ha) was more than two times greater than the average IC yield (1.5 mt/ha) (Table 1.2). In the MC there were no differences between genotypes and in the IC, averaged across environments only RWV 2070 yielded significantly more than the other genotypes. Variation between the genotypes, indicated by standard errors, was lower in the IC (0.11-0.14) than the MC (0.21-0.32) (Figure 1.3).

In the MC system, there was a significant G x E interaction ($P<0.001$) for bean yield with the majority of the variation occurring between environments (Table 1.2). Bean yields in the MC ranged from 2.3-4.5 mt/ha (Table 1.3) with 14-43% more grain in S1 than in S2. Averaged across environments, there were no significant differences in genotype yields (Figure 1.3). There were differences between the genotypes when seasons were considered separately. In S1, the lowest yielding genotype was RWV 3316 (3.5 mt/ha) and it was different from the highest yielding genotype RWV 2070 (4.5 mt/ha) (Table 1.3). In S2, the lowest yielding genotype was

Ngwinurare (2.3 mt/ha) and it yielded significantly less than all of the other genotypes except the FarmMix (2.8 mt/ha) (Table 1.3).

Figure 1.3 Intercrop and Monocrop bean yields for six genotypes averaged across all four environments: Musanze and Rwerere Research Stations, Rwanda in Seasons 1 and 2 (2011-12)



Error bars are standard errors. Small letters compare genotypes in the intercrop and capital letters compare genotypes in the monocrop. Genotypes within a system with different letters are statistically different. All yields in the IC were statistically different from the MC.

In the IC system, there was no G x E interaction (P=0.227) for bean yield and the environment was a greater source of variation than genotype (Table 1.2). Bean yields in the IC ranged from 0.9-2.4 mt/ha (Table 1.3) with 31-50% more grain in S1 than in S2. There were no differences in yield with the exception of genotype RWV 2070. RWV 2070 yield was significantly (P=0.00-0.001) more than all of the other genotypes in all environments. In S1, RWV 2070 yield was 2.4 mt/ha whereas all the other genotypes yielded between 1.6-1.8 mt/ha (Table 1.3). In S2, RWV 2070 yield was 1.7 mt/ha whereas all the other genotypes yielded between 0.9-1.2 mt/ha.

Maize yields

Maize yields varied across seasons and sites. Averaged across all environments, the IC and MZ9 maize yields were 4.8 mt/ha and 5.3 mt/ha, respectively (Table 1.4). Yields were higher in S2 compared to S1 (Table 1.4), and higher at MS than RS in both seasons. Average maize yields in S1 and S2 were 4.1 and 6.0 mt/ha, respectively (Table 1.4). Average maize yields at MS and RS were 6.8 and 2.9 mt/ha respectively. Yields were approximately 57% lower at RS than at MS. The high variability in yield each season was due to the differences in yield at each location.

There were no differences in maize yield between the cropping systems IC and MZ9 (P=0.07-0.11) and there were no differences in maize yields between the genotypes within the IC (Table 1.4).

Maize traits

For the maize traits measured, maize height, maize vigor, and cobs per plant, there were no differences in response by cropping system (IC and the MZ9 cropping systems), nor was there an effect of bean genotype (Table 1.4). The average maize height in the IC was 181 cm and 175 cm in the MC. The maize vigor was 5 and 6, in the IC and the MZ9, respectively (Table 1.4). The mean number of maize cobs in both the IC and the MZ9 was 0.9 (Table 1.4).

Bean traits

Bean traits varied with cropping system (P=<0.0001), as plants grew less vigorously in the IC compared to the MC. However, there were no differences in seed weight between the two systems (Table 1.2). Bean height, bean vigor, seeds/pod, and the number of pods/plant were reduced in the IC as compared to the MC (Table 1.2). All traits contributed to the yield reduction observed in the IC relative to the MC. Only the LAI was on average higher in the IC

(2.14) than in the MC (1.94) (Table 1.2), but this is expected because it was measuring the total LAI for the system.

The bean traits for each genotype were also analyzed within each cropping system. Within the IC and the MC, there were differences between the genotypes for most traits (Figures 1.4 and 1.5). In the MC, there were differences (<0.01) between the genotypes for seeds/pod, bean height, bean vigor, and 100 seed weight but there were no differences observed for pods/plant, LAI, nor %Ndfa (Figures 1.4 and 1.5). In the IC, there were differences (<0.05 - <0.0001) between the genotypes in all traits except for LAI (Figures 1.4 and 1.5). Results for each bean trait follow.

Bean traits and genotypes

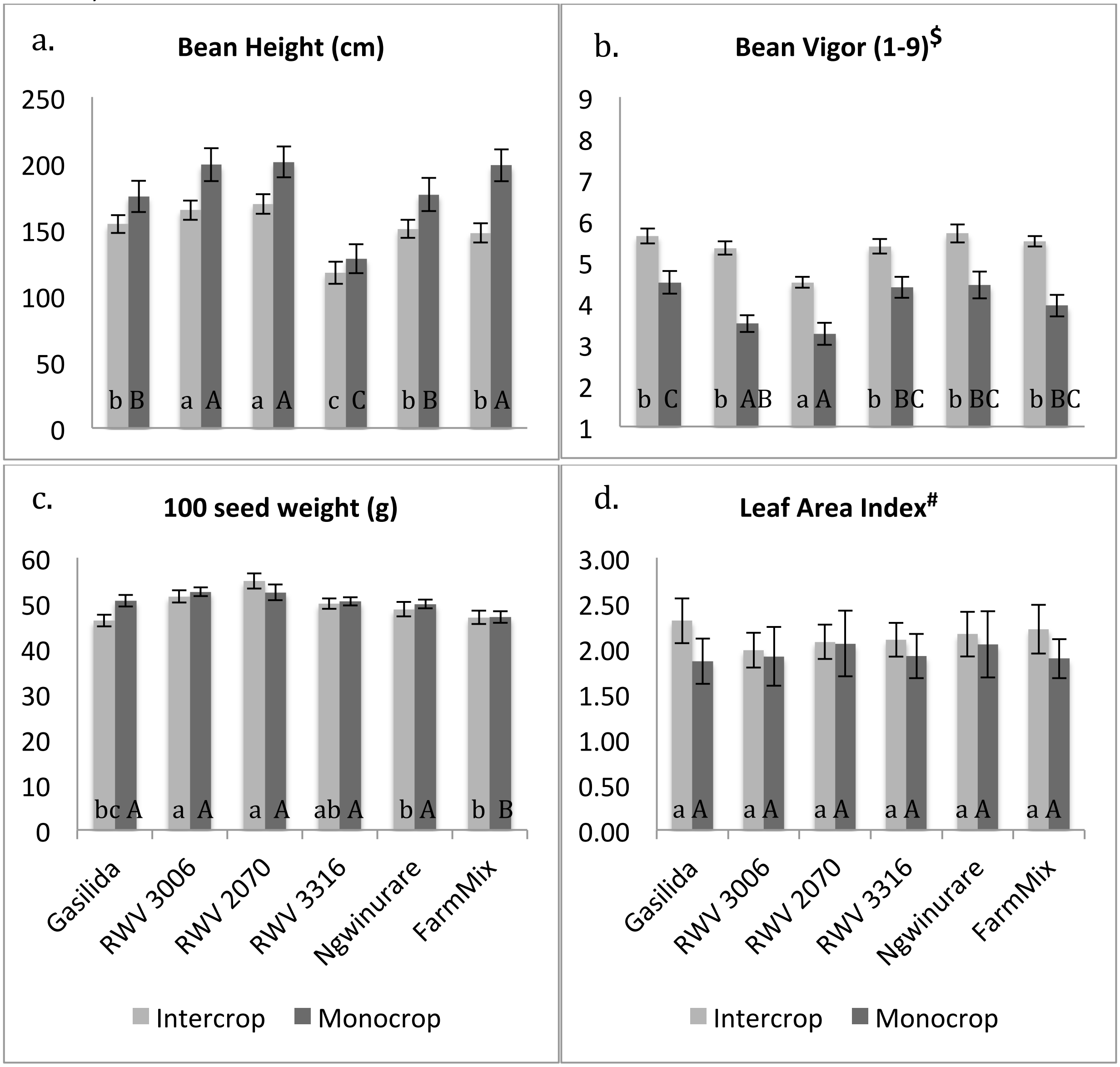
There were differences in bean plant height among the genotypes within each cropping system (P<0.0001). Bean plant height in the MC ranged from 128 to 200 cm (Figure 1.4a). The FarmMix, RWV 3006 and RWV 2070 were the tallest plants. The shortest genotype was RWV 3316 (Figure 1.4a). In the IC bean plant height ranged from 117 to 169 cm (Figure 1.4a). Similar to the MC, the tallest plants in the IC were RWV 3006 and RWV 2070 and the shortest was RWV 3316.

There were differences in the bean vigor between the genotypes within both the MC (P=0.001) and the IC (P=0.01). In the MC, vigor ranged between 2.5 and 4.0 (Figure 1.4b). RWV 2070 and RWV 3006 were the most vigorous genotypes. In the IC, vigor ranged from 4.4 to 5.4 (Figure 1.4b). In the IC, only RWV 2070 was significantly more vigorous than the other genotypes. However, in terms of overall performance, there is no appreciable difference in yield between 1 – 4 on the CIAT bean vigor scale.

There were differences in seed weight between the genotypes within the both the MC (P=0.01) and the IC (P=0.03). In the MC, 100 seed weight ranged from 46.9 to 50.5 g/100 seeds (Figure 1.4c). Only the FarmMix was significantly lower from the other genotypes. There was more variation in seed weights in the IC. In the IC, 100 seed weight ranged from 46.1 to 54.8 g/100 seeds (Figure 1.4c). RWV 3006, RWV 2070, and RWV 3316 produced the heaviest seed weights.

There were no genotype differences in LAI within either cropping system (LAI varied between 1.86 to 2.31, see Figure 1.4d). There were genotypic differences in the number of seeds/pod within the MC (P<0.0001) and the IC (P=0.001). In the MC the number of seeds/pod ranged from 4.8 to 5.5 (Figure 1.5a), RWV 3006 and RWV 3316 had the most seeds/pod and Ngwinurare had the least. In the IC, the number of seeds/pod ranged from 4.3 to 5.0 (Figure 1.5a), where Gasilida and the FarmMix had lower seeds/pod than other genotypes. There were genotypic differences in the number pods/plant in the IC (P=0.001) but not in the MC (P=0.1042). In the MC, the average number of pods/plant was 9.6 and ranged from 9 to 11 pods/plant (Figure 1.5f). In the IC, the average number of pods was 7.0 and ranged from 6 to 10 pods/plant (Figure 1.5f), where RWV 2070 had more pods/plant than all of the other genotypes, and it was the only genotype that had the same number of pods/plant in the IC as in MC.

Figures 1.4 (a-d). Bean height (a), bean vigor (b), 100 seed weight (c), leaf area index (d) for six bean genotypes in the bean-maize intercrop and bean monocrop averaged across four environments: Musanze and Rwerere Research Stations, Rwanda in Seasons 1 and 2 (2011-12)

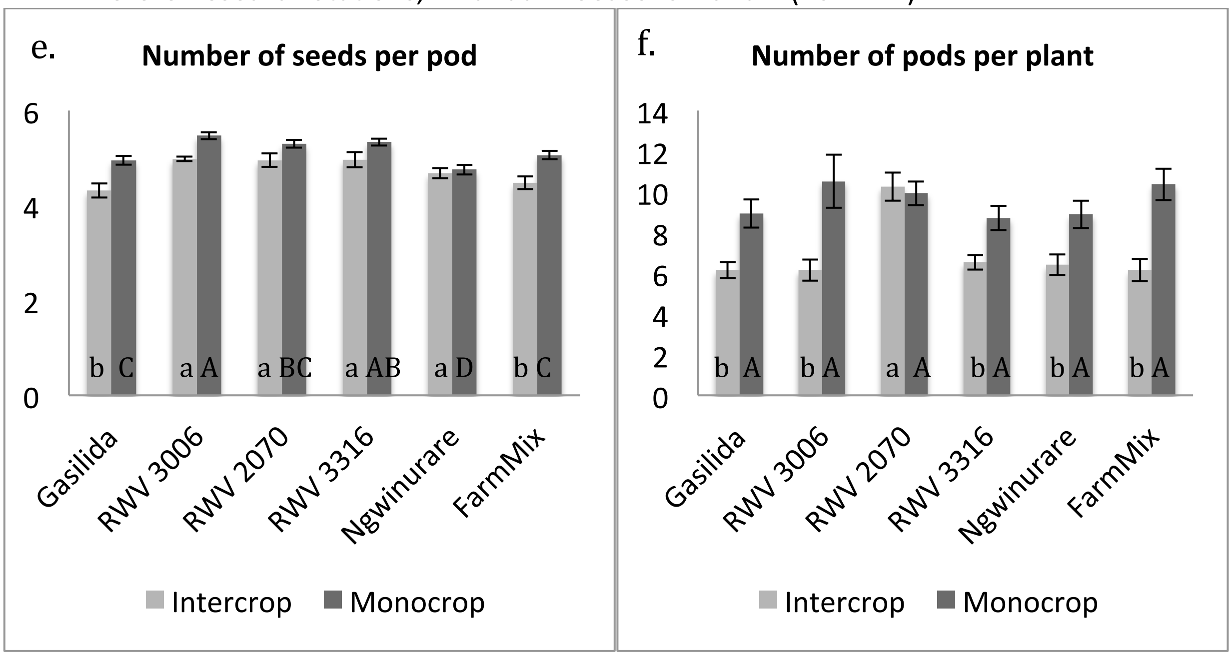


Error bars are standard errors. Small letters compare genotypes in the intercrop and capital letters compare genotypes in the monocrop. Genotypes within a system with different letters are statistically different

$This is a reverse scale: bean vigor is a scale of 1-9, 1 being the most vigorous.

#Leaf Area Index (LAI) is a measure of the cropping system LAI so it includes both beans and maize leaf area.

Figures 1.5 (e-f). Seeds per pod (e), and pods per plant (f) for six bean genotypes in the bean-maize intercrop and bean monocrop averaged across four environments: Musanze and Rwerere Research Stations, Rwanda in Seasons 1 and 2 (2011-12)

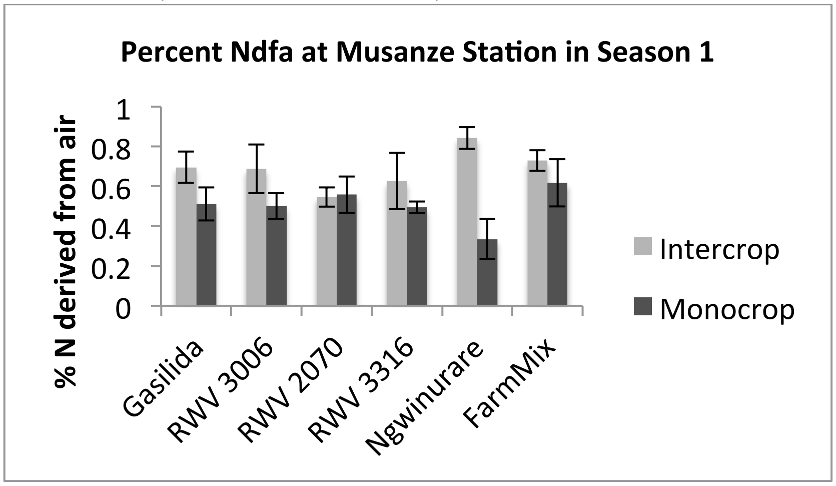


Error bars are standard errors. Small letters compare genotypes in the intercrop and capital letters compare genotypes in the monocrop. Genotypes within a system with different letters are statistically different.

Ndfa

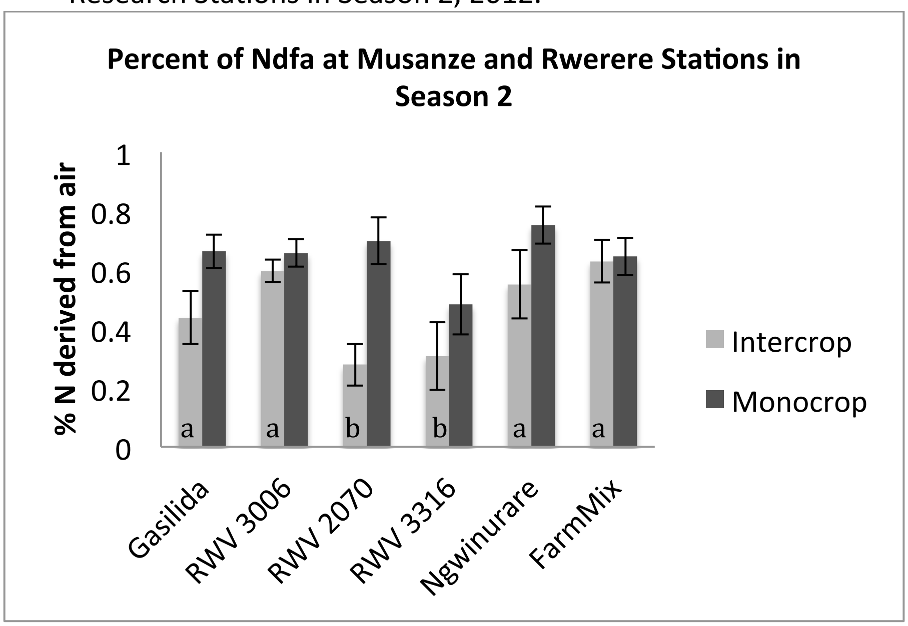
The collection of peak plant biomass for determining the %Ndfa was collected in S1 at MS whereas in S2 it was collected at both stations. Seasons were analyzed separately because there was an interaction between environment and cropping system. BNF rates ranged from 28-84%, but the majority of values were above 50%. There were differences between the cropping systems in both seasons ($P<0.001$). In general, the BNF rate was higher in the IC than the MC in S1 (%Ndfa ranged from 55-84% in the IC and 33-62% in the MC, see Figure 1.6). Interestingly, the opposite trend was observed in S2; the BNF rate was higher in the MC (48-75%) than in the IC (28-63%), see (Figure 1.7). In S2, BNF did not vary with genotype in MC, whereas genotypes RWV 2070 and RWV 3316 fixed less N than other genotypes in IC (Figure 1.7).

Figure 1.6. Percent biological nitrogen fixation for six bean genotypes at Musanze Research Station, Rwanda in Season 1, 2011.



Error bars are standard errors. There were no differences between genotypes within either cropping system.

Figure 1.7. Percent biological nitrogen fixation for six bean genotypes at Musanze and Rwerere Research Stations in Season 2, 2012.



Error bars are standard errors. Small letters compare genotypes in the intercrop. Genotypes within a system with different letters are statistically different.
There were no differences between genotypes within the monocrop.

Discussion

Cropping system x Environment (E x CS)

In this study, the E x CS interactions were of greater magnitude than G x CS interactions. Indeed, the individual factors of cropping system and environment were the largest sources of variation influencing yield, and other plant traits measured (Table 1.2). With such large E x CS interactions, the effect of the environment on the cropping system may mask the magnitude of the G x CS interactions. Santalla et al. (1994) argued that significant E x CS interactions for multiple traits could render invalid selection in a single environment. Other researchers found that the magnitude of the E x CS interaction was as great as the G x CS interaction, an indication that the selection for intercrop genotypes should be done in the target cropping system environment, or a lower selection intensity should be used to ensure more genetic potential is included (Atuahene-Amankwa et al., 2004). That is, with both E x CS and G x CS interactions, selection would be more effective in the intended cropping system environment and in this case, selection of genotypes in the intercrop environment would improve the chances of identifying a competitive genotype.

The data presented here are consistent with it being important to select within the cropping system. The E x CS interactions were several magnitudes greater than the G x CS, but there were also G x CS for the main yield component pods/plant and bean height, and G x E interactions for several traits (Table 1.2). Atuahene-Amankwa et al. (2004) also found a greater E x CS than G x CS interaction and significant G x E and G x CS interactions for other traits including pods/plant. Generally, when significant interactions between the environment and the treatment (cropping system) or the environment and genotype are found, then it is recommended to develop genotypes specifically for that environment (Palaniappan, 1996), or identify genotypes adaptive to that environment through the use of multiple screening environments. Gebeyehu et al. (2006) found E x CS and G x CS interactions for seed yield and recommended selecting genotypes for the IC in the intercrop environment. But Atuahene-Amankwa (2004) had similar results and based on 25% accurate selection rate of heredities, suggested that genotypes suitable to the IC could be identified in the MC. In this study the magnitude of the E x CS interactions for all traits combined with G x E and G x CS interactions for most yield component traits, indicate that selection of genotypes suitable for both the unpredictable (season and location) and the predictable (cropping system) environments may improve the competitive ability of genotypes in the intercropping system. Francis et al. (1978a) reported that any strong G x CS, G x Season, or G x location interactions complicates the task of narrowing a broad array of genotypes to the most widely adapted, disease resistant, and high-yielding selections. However, if populations have been exposed to diverse environments and normal year-to-year seasonal variations during the breeding process, they may have broad adaptation to the unpredictable environment and final selection in the predictable cropping system may be more effective, particularly if lower selection rates are used on a fairly large population. A larger population would increase the chances of finding competitive intercrop genotypes.

Genotype x Cropping System (G x CS)

Cropping systems represent another environment in addition to location and year. Interpretations of CS trials are complex because they include this additional environmental variable. Authors have compared heritability's of traits (Atuahene-Amankwa, 2004), correlations of yield with various traits (Gebeyehu 2006; Francis 1978), and/or G x CS interactions to assess whether suitable genotypes can be identified within a monocrop that are relevant and predict performance within diverse cropping systems.

In this study, we analyzed the environments and genotypes for G x CS interactions and looked at individual traits within the cropping systems to determine the feasibility of using specific phenotypic traits in the monocrop to identify genotypes appropriate for the intercrop. The traits that had significant G x CS interactions were bean height and pods/plant, the major component of yield (Table 1.2). It might be argued that if there is not a G x CS interaction for yield, then G X CS interactions for other traits are of little importance. But others have stated that if certain traits confer adaptation to both cropping systems then these traits may be a key to identifying genotypes in the MC that perform well in the intercrop system (Oleary and Smith, 2004). In this study there was a significant G x CS interaction on the main component of yield, pods/plant, and bean height. These two traits with G x CS interactions showed little variation between genotypes in the monocrop (Figure 1.5a&f), yet pods/plant in the IC was the only trait that indicated the best performing genotype RWV 2070 (Figure 1.5f). Bean height in the MC was similar between three genotypes (Figure 1.4a) and there were no differences between pods/plants in the MC, although the same genotypes that were the tallest trended towards a higher number of pods (Figure 1.5e). In the IC, pods/plant was the key trait that indicated the best performing genotype, but there were no differences in the MC. This G x CS interaction identified the most important trait determining yield in the intercrop, but in the monocrop there were no differences between the pods/plant and therefore no indicator of which genotype would perform better in the intercrop (Figure 1.5f). Pods/plant is the main component of yield and the G x CS interaction of pods/plant is a key finding.

Genotype by Environment (G x E)

Breeders agree that the presence of G x E interactions merit genotype trials being conducted in multiple environments. We tested genotypes in both systems in two seasons and two locations and there were G x E interactions for yield, 100-seed weight, seeds/pod and bean vigor. These results are consistent with previous findings that genotype trials should be conducted across multiple environments.

The seasons included in this study were quite different. Historical data and crop recommendations in Rwanda recognize that S1 is the optimal season for growing beans, although farmers also choose to grow beans in the less productive season S2 because beans are an important household staple. The response of bean yields over the seasons followed the expectation of S1 being a better bean-growing environment. Bean yields in the MC were on average 28% higher in S1 than in S2, and 37% higher in S1 than in S2 in the IC system. Yields were also higher at RS than at MS in both seasons. Higher temperatures during flowering are a known constraint to bean yield (Norman et al., 1995) and daytime temperatures at MS were slightly higher than at RS. The optimal temperature range at flowering is 21± 2 °C for climbing beans (Norman et al., 1995) and average daytime temperatures at MS were about 24°C. RS is at a higher elevation with slightly cooler temperatures. This likely only explains a little of the variation in the yield between seasons and locations. Another potential explanation is the variation in cloud cover and rainfall but there is insufficient data to draw conclusions.

Environments and genotypes were clearly important factors in this study. However, when we looked at G x E interactions within each cropping system, there was an interaction in the MC (<0.0001), but not in the IC. In the MC, the magnitude of variation in the environment was much greater than in the IC. In the MC, the main source of stress is the environment but in the IC, the greatest source of stress is the intercrop environment itself. This intercrop environment suppresses the yield of the IC, minimizing any response to the abiotic environment. The genotypes appear to be more sensitive to the IC environment than the biophysical environment, which minimizes the ability to observe potential genotypic responses to the abiotic stress.

Effects of the cropping system

On yield

The cropping system was an important factor in determining yield. Bean yields were reduced in the IC in all environments and were from 43% to 70% lower than in the MC (Table 1.3). Most research on bean-maize systems show that the less dominate crop, the beans, suffer a yield reduction when grown as an intercrop with maize and in a 52-year simulation model Tsubo et al. (2005) found there was no maize yield reduction but intercropping reduced bean yield. The IC reductions in bean yield were not as severe as the 77% yield reduction found by Francis et al. (1978) in climbing beans planted 15 days after maize nor were they as reduced to 65-79% levels found by Gebeyehu et al. (2006) in a similar bean plant population planted 37 days after maize. Most authors have found that the maize in maize-bean systems suffer little yield loss, as was the case in this study. Maize yields were not different between the IC and the MZ9 (Table 1.4). Similar to our findings, Muraya et al. (2006) found no differences between cropping systems for maize yield or maize traits measured. Even so, research has shown there are benefits to breeding maize populations in the intercrop environment. Muraya et al. (2006) and Oleary and Smith (2004) showed that the best maize genotype for an intercrop increased bean yields and had attributes not found in the genotype bred in the monocrop. But improvement of bean yield can lead to a corresponding decrease in maize yield (Baudoin et al., 1997).

During S1, the optimal growing season for beans, there was greater variation between the genotypes in terms of yields, which ranged from 3.5-4.5 mt/ha in the MC and 1.6 to 2.4 in the IC. In this season, the genotypes that were the highest yielding in the MC all tended to be the highest yielding in the IC. Gasilida, (the farmer improved genotype) and RWV 2070 (an improved new genotype) yielded the most in the MC and the IC. The FarmMix and Ngwinurare performed at the average. These differences nearly disappeared in S2, the optimal season for maize, and there was little variation in bean yields in each system. Aside from Ngwinurare, which had a particularly low yield, four of the genotypes in the MC yielded 3.0 mt/ha and the FarmMix yield was 2.8 mt/ha. The IC yields ranged from 0.9-1.2 mt/ha, with RWV 2070 an outlier at 1.7 mt/ha. In S2, abiotic stresses reduced yield and variation in yield in both systems but the reduction in yield from season to season was greater in the MC than the IC. The IC already presents a competitive biotic stress environment that reduces yield. The addition of seasonal stress in this system has less of an impact on the already suppressed bean plants. In contrast, the introduction of seasonal-based abiotic stress in the MC reduced the yields substantially.

Yield component traits

Three major components of yield in monocrop bean systems are pods/plant, seeds/pod and 100-seed weight. We measured these traits along with LAI, bean height, and bean vigor to identify potential traits associated with yield in the intercrop. All of the traits measured were different between the two cropping systems, except 100-seed weight. Earlier researchers have evaluated these traits in both cropping systems but the traits that are the most representative of yield in each system vary from study to study. Zimmerman et al. (1984) compared bean families in an intercrop and a monocrop using path analysis and found that the largest direct effect on yield components was 100-seed weight for both systems, but the second largest was from the number of pods/plant in the monocrop and the seeds/pod in the intercrop. Likewise Gebeyehu et al. (2006) found that seeds/pod and higher harvest indices were determinants of yield in the intercrop whereas pods/plant and 100-seed weight were determinants in the MC. In contrast, in this study, pods/plant was a key trait determining yield in the IC, but there were no significant differences in pods/plants in the MC. Aside from the FarmMix, the genotypes in this study are cultivars that have been selected for stable yields in the station environment and this may explain the low variation in yield and pods/plant in the MC. The niche environments and genotypes in which other studies were conducted may explain some of the variation from the results of this study.

The majority of the yield components were reduced in the IC system. All of the genotypes in the IC were shorter, less vigorous, and had fewer seeds/pod than the same genotype in the MC. However, the IC did see an increase over the MC in the number of pods/plant and 100-seed weight for one genotype, RWV 2070. These yield components explain the significantly higher yield of RWV 2070 in the IC. O'Leary and Smith (2004) argue that selection in a monoculture may be adequate if there are identifiable traits in the monoculture that confer adaptation in the intercrop. In this analysis there were no traits in the monocrop that indicate better performance in the intercrop.

Most of the variation in the bean traits was due to the effect of the cropping system. 100-seed weight was the only trait that was not different between cropping systems, but it was different between genotypes. Gebeyehu (2006) found a significant difference in 100-seed weight between cropping systems but multiple other authors found no difference in 100-seed weight (Francis et al., 1978; Atuahene-Amankwa et al., 2004; Davis and Garcia, 1983), which is normally the most stable plant component. The environment and the genotype were more important sources of variation in 100-seed weight than cropping system (Table 2). Genetic or hereditary components of seed size are less likely to be affected by the cropping system and in stress conditions the plant generally maintains seed size and reduces other components, such as pods or biomass, to compensate. The intercrop environment increases plant stress through increased competition, but the plant compensates in other plant attributes such as pod development or pod fill rather than seed size. This is likely an evolutionary adaptation to ensure successful reproduction through viable, if fewer, seeds.

Genotypes that had higher trait values in one system did not necessarily have higher trait values in the other system. For example, the greatest numbers of seeds/pod were in genotypes RWV 3006 and 3316 in the MC, but there was little difference between genotypes in the IC. There was also no discernible combination of traits in the monocrop that indicated better performance in the intercrop. In the MC, genotypes RWV 3006 and 2070 were similar for all of the plant traits aside from seeds/pod and pods/plant. RWV 3006 had more seeds/pod than RWV 2070, whereas RWV 2070 had more pods/plant in the MC. In the IC, RWV 3006 was different from RWV 2070 in bean vigor, pods/plant and yield. Without notable differences between genotypes in traits in the MC, there was no basis for selection in the IC.

On Nfda

Common bean is known to be a poor fixer of nitrogen (Bliss, 1993), but most evidence is derived from determinate bush type I and indeterminate bush types II and III which have a shorter growth duration than indeterminate type IV climbing beans (Singh, 1982). Days to maturity for bush types range from 65-90 days after emergence whereas indeterminate climbers can take as long as 150 days to mature in the field. This longer time in the field may increase the amount of N fixed over time, particularly if climbing beans produce more root mass during that time. Peoples and Croswells (1992) compiled BNF rates from the literature and beans derived 17-71% of N from N2 fixation. Our results are slightly higher and ranged from 33-84% in all systems, with most values falling between 50-70% (Figures 1.7 & 1.8).

In bean-maize systems maize is the dominant crop, and has a high nitrogen requirement. Under competitive conditions for N, we hypothesized that the beans would fix more N in the IC than in the MC. This was not necessarily the case. In the optimal growing season for beans, Season 1, the % Ndfa was greater in the IC than the MC (Figure 1.7) and the maize yields were lower that season (Table 1.1). However in S2 when bean yields were lowest and maize yields were the highest, the %Ndfa was greater in the MC than the IC (Figure 1.7). Under optimal conditions, the bean plants were able to fix more N in the competitive maize-bean environment. In contrast, Season 2 is a sub-optimal growing season for beans but optimal for maize. In S2, maize yields were on average 2 mt/ha more than in S1. Under S2 conditions, the beans in a monocrop were able to fix more N than beans in an intercrop. This variation across seasons in the amount of BNF may be due to external crop constraints. When there are fewer constraints to plant growth (S1), the intercrop environment may not be a limiting factor for BNF. But with additional crop constraints, such as seasonal limitations and greater competition from maize, BNF may be inhibited in the intercrop environment.

There is evidence for genotypic variability in the amount of N_2 fixed in common bean (Bliss, 1993) but in this study there were no differences between genotypes. There was no detectable difference in BNF rate among the genotypes except in S2 in the intercrop. In this case, RWV 2070 and RWV 3316 BNF rates were lower than all of the other genotypes. This suggests that BNF is not a determinate of yield, at least in the relatively fertile station environment, given that RWV 2070 was the highest yielding genotype in the IC. In this study there is no evidence that BNF improves crop performance in the intercrop, but in-depth research on farms in low input systems with climbing beans would provide further evidence of whether this is a function of fertility or there are other beneficial effects on nutrient cycling.

Conclusions

Due to the magnitude of the E x CS interactions, and the G x CS interactions for key plant traits (pods/plant and height), it appears that selection of genotypes should take place within the target environment, the intercrop system. The fact that there is no G x E interaction for the trait that determines higher yield in the IC (pods/plant), may indicate that G x E trials are not necessary for IC systems, particularly if the genotypes being tested are already adapted to the region.

The conflicting reports across multiple studies on the direct and indirect traits contributing to yield in the IC warrant further study. Authors have approached this question using several different methods of analysis including correlations, heritabilities, path analysis, and system interactions. There needs to be consensus on the analysis and interpretation of these systems. Furthermore, while there are many studies on G x CS interactions in maize-bean systems, they vary widely in terms of environments, bean growth habit, the type of crop association, and the time between maize and bean plantings. There is also a vast resource and source of variation in the inherent diversity found in bean populations. The complexity and variation found in these systems worldwide explains the variability in the studies, but it poses a challenge to analyzing and developing a way forward for releasing optimal genotypes for an intercrop. Despite this complexity, identifying optimal genotypes for the multi-functional intercropping systems found in the tropics is necessary to improve smallholder crop yields

Table 1.2 Mean squares from the analysis of variance of bean traits in monocrop and intercrop bean and maize cropping systems in four environments: Musanze and Rwerere Research Stations, Rwanda for Seasons 1 and 2, 2011-12

Source of Variation	df	bean yield	100 seed weight	seeds/ pod	pods/ plant	bean height	bean vigor[$#]	LAI T2[#]
Environment (E)[1]	3	13.6**	572.7**	1.40**	110.9**	56016**	11.2**	39.41**
Cropping System (CS)	1	173.6**	33.5	5.35**	320.5**	40714**	85.3**	1.75*
CS x E	3	1.4**	91.4*	0.32*	37.5**	13664**	5.1**	3.28**
Genotype (G)	5	1.7**	194.2**	1.43**	28.4**	16303**	6.7**	0.12
G x E	15	1.0**	70.3**	0.20*	5.2	574	0.9*	0.53
G x CS	5	0.4	38.1	0.15	22.4**	1497**	0.8	0.27
G x CS x E	15	0.5*	23.2	0.16	7.7	441	0.3	0.39
REP	3	0.4	71.4	0.14	2.0	684	1.4	0.17
G x REP	15	0.3	28.8	0.08	1.9	238	0.7	0.33
E x REP	9	0.4	33.7	0.10	3.0	813*	0.6	0.50
Residual	115	0.2	25.9	0.11	5.3	387	0.5	0.38
System Means		mt/ha	g	#	#	cm	1-9[$]	index
Monocrop mean		3.5	50.4	5.1	9.6	180	4.0	1.94
Intercrop mean		1.5	50.1	4.7	7.0	150	5.3	2.14
Mean overall		2.5	50.3	4.9	8.3	165	4.7	2.04
P-value (IC vs. MC)		<.0001	ns	<.0001	<.0001	<.0001	<.0001	0.05

[1]Each environment is a season by location combination e.g. 1 environment is Musanze Station, Rwanda, Season 1.

[$]Bean vigor is a scale of 1-9, 1 being the most vigorous.

[#]Bean vigor and Leaf Area Index (LAI) data are from time 2.

*Levels of significance are *<0.5; ** <0.005 - <0.0001

Table 1.3 Intercrop and Monocrop bean yields for 6 genotypes averaged across Musanze and Rwerere Research Stations, Rwanda in Seasons 1 and 2 (2011-12)

GENOTYPE	System and Season					
	MONOCROP			INTERCROP		
	Season 1	Season 2	**Mean**	Season 1	Season 2	**Mean**
	Beans Mt/ha (se)					
Gasilida	4.3 (0.2)a	3.0 (0.2)a	3.7 (0.2)	1.8 (0.2)b	0.9 (0.1)b	1.4 (0.1)
RWV 3006	3.9 (0.4)ab	3.0 (0.2)a	3.4 (0.2)	1.8 (0.2)b	1.2 0(.2)b	1.5 (0.1)
RWV 2070	4.5 (0.4)a	3.0 (0.3)a	3.8 (0.3)	2.4 (0.1)a	1.7 (0.2)a	2.1 (0.1)
RWV 3316	3.5 (0.3)b	3.0 (0.3)a	3.3 (0.2)	1.6 (0.1)b	1.1 (0.1)b	1.3 (0.1)
Ngwinurare	4.0 (0.2)ab	2.3 (0.3)b	3.2 (0.3)	1.6 (0.1)b	1.1 (0.1)b	1.4 (0.1)
FarmMix	3.8 (0.2)ab	2.8 (0.3)ab	3.3 (0.2)	1.7 (0.2)b	0.9 (0.1)b	1.3 (0.1)
Mean	**4.0 (.1)A**	**2.7 (0.1)B**	**3.5 (0.1)**	**1.8 (0.1)A**	**1.2 (0.1)B**	**1.5 (0.1)**

Standard errors are in parenthesis. Means for the genotypes in each season (within the column) with different letters are statistically different. The overall mean is across the bottom and each season in each system with different letters are statistically different. All differences were significant at 0.001 or smaller. Season was a main effect and almost all genotypes performed differently between seasons.

Table 1.4 Maize traits and maize yields in the bean-maize intercrop and maize monocrop for each bean genotype averaged across Musanze and Rwerere Research Stations in Seasons 1 and 2 (2011-12).

SYSTEM	GENOTYPE	Season 1	Season 2	Average S1 & S2	maize height	maize vigor t2#	cobs/ plant
		Maize mt/ha (se)			cm	1-10	#
INTERCROP	Gasilida	3.8	6.2	5.0 (0.6)	181 (9)	5 (1)	1.0 (0.0)
	RWV 3006	3.7	4.9	4.3 (0.5)	175 (10)	5 (1)	0.9 (0.0)
	RWV 2070	3.4	5.9	4.7 (0.7)	192 (10)	4 (1)	0.9 (0.0)
	RWV 3316	3.7	6.1	4.8 (0.7)	173 (11)	5 (1)	0.9 (0.1)
	Ngwinurare	4.2	5.3	4.8 (0.5)	182 (9)	5 (1)	0.9 (0.0)
	FarmMix	4.2	5.9	5.0 (0.6)	183 (11)	5 (1)	0.9 (0.0)
Mean		**3.8**	**5.7**	**4.8 (0.3)**	**203 (7)**	**5 (.4)**	**0.9 (0.0)**
MONOCROP	MZ9	4.4	6.3	5.3 (0.8)	175 (11)	6 (1)	0.9 (0.0)

Yields are averaged across locations. Standard errors are in parenthesis. There were no significant differences in maize yield or maize traits between cropping systems or between genotypes in the intercrop.

#Maize vigor T2 is vigor from time 2 (T2).

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CHAPTER 2 Learning from farmers: participatory variety selection and identification of competitive varieties for mixed cropping systems in Rwanda

Chapter 2 Abstract

Mixed cropping systems provide multiple ecosystem services to the smallholder farmers that grow them worldwide, yet plant varieties are rarely developed for these types of farming systems due to their complexity. There is little consensus on the breeding and selection process that is appropriate for developing bean varieties targeted to intercrops. Participatory plant variety selection is becoming a widely accepted methodology, but there are almost no studies that document the insights of farmers as to the most effective means of selection for superior varieties within an intercrop. In Rwanda, smallholder farmers traditionally grow mixtures of common bean with maize and other crops, and thus could well have unique insights into how to select varieties within these complex, mixed cropping systems. We documented how farmers evaluate climbing bean varieties within a monocrop, and within a bean-maize intercrop, to help inform breeding strategies for intercrops. On-farm trials were planted on 6-7 farmer associations' fields in 3 environments in Northern Rwanda and repeated over two seasons. Six bean varieties that included improved varieties, regionally adapted varieties, and farmers' mixtures were planted in a monocrop (MC) and in an intercrop (IC) with one maize variety in single-replicate farmer managed field trials. Soil baseline data, yield and plant trait characteristics were collected from all plots and analyzed. Participatory variety selection (PVS), open-ended group discussions and short-answer interviews were used to determine farmer variety preferences and intercrop evaluation methods. Emergent thematic coding was used to document the frequency of themes and descriptive text summaries developed for each theme. Farmers' first variety choice in each environment varied, but their second choice was always Gasilida, a farmer improved variety.

Farmers discussed yield (26% of the time), adaptation to the region (10-12%), and maturity (6%) evenly in both cropping systems. But farmers talked more about plant architecture (11%) in the IC than in the MC (4%) and likewise, competition and traits associated with improved competition were discussed 10% of the time in the IC and only 2% in the MC. Overall, farmers selected the same variety for an intercrop and a monocrop but they discussed different genotype traits depending on the system. The fact that farmers identified the same varieties for both systems may be an indication that environmental adaptation is the biggest challenge in selecting varieties for these low-input systems. Once varieties adapted to an environment are identified, effective selection in the intercrop may be achievable. Further research with more regionally adapted varieties might further clarify whether farmers believe the best varieties in the MC are always the best in the IC system.

Introduction

Plant genotypes adapted to low-input environments and different types of cropping systems are essential for improving agricultural production and farmer livelihoods in developing countries. These low-input cropping systems cultivated by millions of smallholder farmers have unique and diverse environmental conditions that present challenges to effective development of new genotypes. Efforts to develop suitable genotypes (Gibson et al., 2008) include multiple strategies. Plant breeding programs have increased the availability of improved genotypes, and there is growing interest in methodologies such as participatory plant breeding (PPB) and participatory variety selection (PVS) that integrate farmer preferences and knowledge (Witcombe et al., 2005; Ceccarelli and Grando, 2007).

Decentralized, client oriented participatory breeding programs such as PPB and PVS, have the goal of increasing adoption of improved varieties for target environments by ensuring farmer criteria for varieties are met (Witcombe et al., 1998; Weltzien and Chistinck, 2008). They often include co-learning and sharing of knowledge between scientists and farmers (Sperling and Berkowitz, 1994). There are also examples of farmer derived landraces, or indigenous plant breeding, of common bean (Voss, 1992), maize (Birol and Villalba, 2007), and other crops (Gibson et al., 2008). Participatory plant breeding processes have made considerable advancements in the development of improved varieties for low-input systems but the hurdles are still immense. It is particularly difficult to identify genotypes for mixed cropping systems that meet farmers' needs in the diverse microclimates that exist in Sub-Sahara Africa.

Traditional mixed farming systems, utilized by millions of farmers worldwide (Vandermeer, 1992; Lithourgidis et al., 2011), provide multiple social and environment services to the populations they support (Altieri, 2004) and have been a principle area of agriculture research for decades. These systems include diverse crop species and various forms of cropping systems, including intercrops, or the combination of two or more crops in a single field. The estimated agricultural land area in intercropping production worldwide varies from 19% in India to 94% in Malawi (Vandermeer, 1992; Lithourgidis et al., 2011; Garrity et al., 2012) and there is a lot of research on the environmental and biological advantages of intercropping systems. As neatly summarized by Lithourgidis et al. (2011) and examined by numerous others, the principle advantage of intercropping is increased land-use and resource-efficiency (Mead and Willey, 1980; Seran and Brintha, 2010) in combination with improved resilience and reduced risk for smallholder farmers (Lithourgidis, 2011). Disadvantages include the effort needed identify appropriate cultivars for the system, increased labor and management (Gliessman, 1994), and complex design issues (Vandermeer, 2011). Recent work by Jackson and colleagues (2007) advocate a biodiversity-based paradigm shift for agriculture, in which the diversity and potential resilience found in traditional, ecologically based mixed cropping systems is further developed to improve the sustainability of our current input-intensive monoculture dominated agricultural systems. Building on our understanding of farmers' knowledge about these complex cropping systems, their management of crop varieties, and their strategies for identifying varieties that improve production in intercropping systems will further advance this goal.

Cereal-legume based intercropping systems are arguably one of the most efficient forms of intercropping due to the nitrogen-fixing properties of legumes, which are complementary to the high nitrogen demand of cereals (Stern, 1993). As such, maize-bean intercropping systems are ubiquitously utilized around the world. Over the past few decades a handful of researchers have attempted to breed cultivars for these cropping systems (Francis et al., 1978ab; Zimmerman et al. 1996; O'Leary and Smith, 2004; Atuahene-Amankwa et al., 2004; Muraya et al., 2006).

Most of the emphasis has been on improving the bean portion of the system because earlier research has shown that the dominant species in the intercrop, maize, is less affected by the intercrop environment. Scientists have experimented with breeding beans in an intercrop through all stages of the breeding process: several authors explored genotype improvement in the pre-breeding phase and the earliest stages of cultivar development (Francis et al., 1978; Zimmerman et al. 1996; Oleary and Smith, 2004); while other initiated research around the F 4-5 generation when simply inherited traits were stabilized (Atuahene-Amankwa et al. 2004; Santalla et al., 2005); and still others experimented with selection at the end of the breeding process when cultivars were ready for release (Gebeyehu et al., 2006; Worku, 2008). Although there is evidence in both maize (O'Leary and Smith, 2004) and beans (Zimmerman et al., 1996) that genetic variation for competitive ability can be lost when beans are bred in a monocrop, most authors argue on practical grounds that selection for the intercrop environment could occur with advanced lines in environment trials (Atuahene-Amankwa et al., 2004; Zimmerman et al., 1996). Although assessment for performance in an intercrop early in the breeding process is an ideal, the monetary and logistical considerations of developing a breeding program focused on intercrops is a major deterrent.

In an effort to improve selection of bean genotypes for intercropping systems, researchers have attempted to understand some of the mechanisms of competition in the maize-bean intercrop and the extent to which specific traits displayed in a monocrop might distinguish an intercrop competitive bean genotype from a non-competitive one (Santalla et al., 1994; Gebeyehu, 2006). The yield components in a monocrop have been proposed as a method for identifying a competitive genotype for the intercrop, but much uncertainty remains.

The importance of local farmer knowledge and practice in development of sustainable farming systems is readily recognized in agricultural and conservation research (Jackson et al., 2007; Snapp et al., 2010), and more specifically in the improvement of cultivars through PPB and PVS (Morris and Bellon, 2004). But to our knowledge there is almost no documented information on farmer knowledge regarding the evaluation or selection of genotypes for an intercropping system. Smallholder farmers have been growing mixed cropping systems for hundreds of years and have likely built up a body of knowledge over generations that could be a potential source of innovation in the improvement of genotypes for bean-maize cropping systems.

In the late 1980's Sperling et al. (1993) conducted groundbreaking research in Rwanda that improved bean breeding for low-input systems by incorporating expert farmer knowledge into the selection of bean varieties. In concurrent work, Voss (1992) found that bean farmers have particular methods for testing bean varieties in different environments and cropping systems. He found that Rwandan farmers test a bean genotype in a monocrop first and if it performs well in the monocrop, they then test it other environments including low fertility fields and intercrops (Voss, 1992). This is evidence that farmers have unique methods in the selection of genotypes for intercropping systems and this knowledge may inform future breeding strategies. In this research, we used PVS and farmer interviews to explore the ways that farmers evaluate bean genotypes in a monocrop, and in an intercrop with maize. Our research objectives were to understand how farmers evaluate genotypes in both systems, and learn if there are specific traits that farmers associate with improved competitive ability in the intercrop.

Methods

Environment

Research trials evaluating six bean varieties in an intercrop and monocrop were conducted on farmer fields for two seasons in the sub-humid tropics of Northern Province, Rwanda. The region has a bimodal rain distribution with two rainy seasons in one year. Trials were conducted during Season B 2011 and Season A 2012. Season B (S1) is the period of "long" rains occurring from late February through June and Season A (S2) is the period of "short" rains occurring from early September through December. Yearly rainfall ranges from 1300-1600 mm in this region.

Seasonal variation in temperature is low and mean monthly temperatures range from 14-17 C. However, diurnal variation in temperature is high, often as much as 10 C or more. Low temperatures range from 10-13 C and high temperatures range from 23-25 C. Although there are only slight differences between seasons in terms of weather and rainfall, farmers and the government alike identify certain crops with specific seasons. S1 is characterized as optimal for bean cultivation whereas S2 is optimal for maize.

Site selection and characteristics

Climbing bean (*Phaseolus vulgaris* L.) and maize (*Zea mays*) variety by environment by cropping system trials were conducted in Northern Province, Rwanda on seven farmer associations' fields. Farmer associations and field sites were selected to capture the diversity of microclimates in the province and based on farmer interest.

Farmer associations were purposely identified with the assistance of a local organization, Northern Rural Development that works extensively in the area. Three different environments were determined based on agroecological areas considering elevation and soil features. Farmer associations working with the organization were approached to gauge interest in planting maize-bean field trials. Associations that participated were provided with all the seeds and inputs, the yields of the trials, at least two workshops combined with community lunches, an additional 10kg of bean seeds each season, and at the end of the programming, 50% of the cost of a young goat.

The location of the farmer associations were representative of three different environments characterized primarily by elevation but were also representative of edaphic features. These environments ranged from low to high elevations found in the region. "Low" included sites at 1600-1700 m.a.s.l.; "Mid" sites were located between 1750-1850 m.a.s.l.; and "High" sites were locations between 2000-2100 m.a.s.l. (Table 2.1). Proximity of field plots to each other and similarities in soil characteristics delineated the differences between Low and Mid sites. In each of the three environments, there were two sites each season. In S2 there were three sites in the Mid. There were a total of 13 replications (Table 2.1).

The environments were different in terms of soil types, soil nutrient content, soil pH, and elevation (Table 2.2). Soil types at Low environments were silt or sandy loams, Mid environments were clay loams, and high environments were silt loams (Table 2.2). Soil fertility varied across environments, where the Low sites were of medium fertility with total soil N ranging from 0.11-0.27%, Mid sites were the least fertile with total soil N between 0.07-0.18%, and high sites were the most fertile with total soil N between 0.11-.75%. Soil pH was generally close to neutral, and ranged from 5.0-6.8, with similar pH in the Low and High sites (6.2-6.8) and lower pH in the Mid sites (5.0-5.5). However, S1 at RU was an outlier in the High sites, with a soil pH of 5.6 (Table 2.2).

Experimental design

Agronomic trial component

This study assessed two cropping systems planted in a randomized complete block design (RCBD): a monocrop of beans, and a bean-maize intercrop with a ratio of 1 maize to 2 bean, within row. The trials were planted in a mother-baby design, with mother trials located on two research stations, and baby trials on-farm with 7 different farmer associations (Snapp et al., 2002). The experiment was designed to test variety by cropping system interactions and to carry out PVS on-farm, with six bean varieties included. In this paper, we focus on bean variety data from the on-farm trials.

Within both the monoculture and the intercrop system, 6 bean genotypes (5 varieties plus one bean mixture) were assessed, for a total of 12 plots. For each environment, Low, Mid, and High, there were two field sites in each season except at the Mid site in season 2 where there were three field sites, for a total of 13 replications of trials over two seasons (Table 2.1). Individual plots within the block were 3 m x 4 m. There was uniform spacing between plots (0.75 m). According to farmer practice, the maize was planted first and the beans were planted 29-31 days later in every treatment. In the bean monocrop (MC), the between-row spacing was 0.50 m and the distance between each plant within the row was 0.20 m (Rwanda Ministry of Agriculture recommendations). Two seeds were planted per hole for a total bean population of 200,000/ha.

The intercrop system plant density was determined by researchers, with beans and maize planted in the same row. Between-row spacing was 0.75 m, in-row spacing for beans was 0.1 m and for maize was 0.3 m. Beans were planted on either side of the maize to facilitate bean climbing of maize stalks. Two bean seeds per hole were planted and thinned to one plant after emergence. The maize and bean populations in the IC were 44,400 and 106,700 plants/ha respectively, for a total plant population 151,100/ha. The design was based on input from farmers and Rwandan scientists.

Maize and bean variety descriptions

The maize variety was a ubiquitously grown open-pollinated maize variety originally selected for the Volcanic Highlands of Rwanda. The variety, Pool9A, is a Highland Late White Dent (Friesen and Palmer, 2004) and was used in all trials. All of the bean varieties were selected from Rwerere Research Station in Northern Province, Rwanda, except the farmer mixture. Four of the climbing bean varieties were selected from varieties ready for release and two checks were included.

The six bean varieties included Gasilida (B1), RWV 3006 (B2), RWV 2070 (B3), RWV 3316 (B4), Ngwinurare (B5), and a farmer mixture (B6) (Table 2.2). Ngwinurare and the farmer mixture were the local controls. The varieties varied in origin. Three of the varieties were newer improved varieties from CIAT (B1-B3). The other three varieties, B1, B5, and B6 have been in the region for an indefinite amount of time. B1 and B6 were both developed by farmers and the national breeding program stabilized B1. B5 was originally a CIAT variety and has been in the region since 1991. All of the varieties are considered improved, except B6.

The bean varieties varied in terms of color, days to maturity, yield, and seed size. Most colors were represented except black and B6 contained many mottled beans (Table 2.3). The days to maturity ranged between 93 and 120 days for B1-B5 and 90-105 days for B6 (Table 2.3). The shortest duration varieties were B1, B5, and B6. The longest duration variety was B2. Estimated yields (from the Rwanda Agriculture Board) ranged from 3.80-4.25 mt/ha (Table 2.3). All of the beans were large-seeded Andean type cultivars except the B6.

B6 was the local check and it varied across all sites in terms of composition, seed size, and the number of beans in the mixture. The seed types varied from small to large, usually within the same mixture. At each location farmers classified their mixtures, which varied in composition from 3-10 different bean varieties. The median and mean number of varieties per mixture was 6. Site RU had the least number of beans in the mixture and CE had the most.

However, at several sites the mixture was dominated by one seed type, namely at CN and ML.

In terms of disease resistance, there was variation across the varieties (Table 2.3). B1 was resistant to anthracnose, root rot, and rust. B2, B3, and B4 were resistant to bean common mosaic virus (BCMV), anthracnose, and root rot (Table 2.3). B5 was resistant to BCMV and root rot but was notably susceptible to anthracnose. Disease resistance in the B6 was unknown but according to farmers and researcher observation varied within mixtures and across locations.

Field management and data collection

Trials were planted with farmers according to the design described above. They were managed by farmers throughout the season. Plots were weeded at bean planting and at least one more time during the season. At maize planting, inorganic fertilizer (DAP) and organic material were applied to all plots in the row at a rate of 100 kg/ha (0.12 kg/plot) and 83 kg/ha respectively, according to farmer practice. Urea was applied to the base of maize plants mid-season to all plots at a rate of 100kg/ha (0.13 kg/plot).

Maize and bean yields and agronomic bean traits were collected. For grain yield, the entire plot was harvested and moisture content was corrected to 13% and 15.5% for beans and maize. Bean trait measurements included the number of pods per plant, the number of seeds per pod, plant height, and 100 seed count weight. Due to multiple bean plants climbing one stake, pods per plant were counted based on a minimum of three random stakes or 10 plants per plot and averaged. For seeds/pod all the viable seeds in 10 randomly selected pods were counted. Plant height on ten random plants/plot was measured at approximately 50% flowering from the soil to the top node and averaged.

Participatory variety selection

Participatory variety selection (PVS) methods were used in combination with discussion groups and short-answer interviews to understand farmer preferences for bean varieties in different cropping systems. Activities were carried out at the baby-trial field sites with the same researcher and enumerators every time.

PVS votes and discussions

The PVS field activities included two rounds of voting each followed by open-ended discussions. Inspecting the field trials, farmers were given a total of 4 color-coded ribbons for each voting round. Each farmer had two “yes” votes and two “no” votes for each round. Men and women had different colors. The first round of votes was for either the monocrop or the intercrop system (the system for the first round of voting was randomly selected). Brown-paper bags were placed next to each of the six plots representing each variety in the monocrop and a clear plastic bag containing the bean seeds was next to it so that farmers could see the seed size and color. Farmers were encouraged to disguise the ribbons in their hands as they placed them in the bag to maintain voter anonymity. Once all the farmers voted, the ribbons were gathered and tied to sticks to visually represent the votes for each bean variety. Then the farmers were asked what they liked and disliked about each variety. Care was taken to hear comments from both men and women, although there were more women than men in all of the activities. Two enumerators were present during all activities and recorded all of the votes and comments from farmers and translated them. The same procedure was followed for the second round of voting on the next cropping system.

PVS was carried out both seasons, but the results presented here were from S2 because it was expected the farmers’ preferences were cumulative, building on experience and observations from the first season. Farmers were provided with these seed varieties at the end of S1 as motivation, so that farmers could have eaten and/or grown these varieties separate from the research. In all of the environments farmers initiated a taste testing of the beans during research workdays. In S2, approximately 13 farmers participated in the PVS at the Low environment, 26 at the Mid, and 19 at the High.

Interviews

As part of a larger interview, farmers were asked three short answer open-ended questions about how they identify varieties for an intercrop cropping system. From this interview, demographic information was also documented. Sixty-one individuals were interviewed, including all but one of the farmers that participated in the PVS in S2. The three questions asked of farmers were:

1. *In general, according to your observations, are there plant characteristics in a bean variety that make it better for an intercrop? If so, what are they?*

2. *Which bean variety or mixture from our research do you think is the best in an intercrop with maize?*

3. *Why was it the best in the intercrop? Do you have any observations about the variety that made it do better in the intercrop?*

The questions were designed to learn if farmers believe there are plant traits that improve performance in the intercrop and if so, to explain what they mean with a reference variety.

Analysis

Agronomic trials

Bean and maize yields and bean morphological characteristics were analyzed using proc mixed in SAS. Season and environment were considered random effects. Two-way anova model analysis was run on differences between environments and cropping systems. There were insufficient replications for further analysis.

PVS Votes

PVS votes for each variety were tallied across the Low, Mid, and High environment and the frequency of positive and negative votes for each variety were calculated based on the total number of votes in that environment and system. Total frequencies across all of the environments were based on weighted scores because there was a different number of farmers present in each environment.

PVS Discussion

The recorded comments from all of the PVS discussions (MC and IC) in S2 were coded using emergent themes to answer the question: 'How do farmers evaluate varieties?' In the first round of coding, patterns and traits that farmers discussed were identified. From this phase, it became clear that farmers talk frequently about yield and relate multiple other factors back to yield. For example, if farmers were talking about pods per plants or birds eating flowers, they explained how this affected yield. As a result, yield was coded for completely separately from the other categories in order to understand the factors other than yield behind farmers' comments. In the second round, these concepts were condensed into 13 themes (Table 2.6) which logically fell into the 6 larger thematic categories of Yield, Plant Traits, Adaptive Qualities, Market and Labor Attributes, Nutritional and Cooking Quality, and Other (Table 2.6). Men and women's comments in each theme and each variety were tallied and frequencies were calculated for each theme and cropping system (Table 2.6 and Figure 2.3). A separate frequency analysis for each variety, across all of the environments, was calculated to understand which thematic categories farmers were talking about for each variety.

In addition, the text was analyzed using text summaries. For each theme and variety, a text summary was written to encapsulate farmers' comments about that particular theme and variety. From the 72 text summaries, summaries were written for each variety. Salient comments from these summaries were placed in a thematic Table (Table 2.8). Direct quotes and text summaries were used to support analysis in both the results and methods.

Interview data

Descriptive statistics were used to analyze the demographic data from the interviews. The short answer questions were coded using emergent themes to answer the question, Are there specific characteristics farmers look for when selecting varieties for an intercrop? From the data it emerged that farmers have means of determining if a variety is suitable and they look for specific characteristics. Text summaries were written to understand concisely the themes that emerged from the data (Table 2.9). The themes that emerged were comparisons, experimentations, trait-based competitive ability, intrinsic competitive ability, management, and adaptation. Again, direct quotes and text summaries were used to support analysis in both the results and methods.

Results

Demographics

The farmer demographics varied slightly across environments in terms of age, years of education, and poverty level (Table 2.3). In general, the farmers from the Mid and the High were the most similar. Farmers were somewhat older at the Low environment (51) as compared to Mid and High environments (43 and 44 respectively). Years of education were lower at the Low environment (3.5 years) compared to Mid and High environments (4.7 and 4.8 years). The Rwandan government established 6 poverty categories and each household is in one of the categories. In this study “class” was based on these categories and was self-reported (Table 2.3). Farmers were poorest at the Mid environment with a mean class of 2.9 or “the poor.” Farmers in the Low and High environments were a mean class of 3.7 and 3.6 respectively, or the "resourceful poor". The Low environment had the lowest number of household members (4.7) while Mid and High were similar with an average of 5.7 household members (Table 2.3). The average land holding size at Low (0.4 mt/ha) was the least of all the environments. It was 0.6 mt/ha at the Mid environment and 1.0 at the High environment (Table 2.3). Although the Low had the least amount of land, the Mid was the poorest in terms of class.

Bean yields

The yield and morphology data presented here represent an average of yields across the two seasons and the three environments, for a total of 4 (Low and High) or 6 (Mid) replicates for each environment. Bean yields were higher in the MC than the IC for all of the environments ($P<0.0001$) (Table 4). The average monocrop (MC) yield was 2.4 mt/ha and ranged from 1.0-3.6 mt/ha. Yields were significantly lower ($p<0.0001$) in the Mid environment (average of 1.5 mt/ha) compared to the Low and High environments (2.8 and 2.9 mt/ha). These yield trends were similar in the IC. The average IC yield was 1.0 mt/ha and ranged from 0.4-1.6 mt/ha. Yields in the IC were significantly lower ($P=0.0002$) in the Mid environments (average of 0.6 mt/ha) compared to the Low and High environments (average of 1.2 mt/ha) (Table 2.4).

In the monocrop, B1 or B3 were the highest yielding varieties in the environments, with an average yield of 2.6 mt/ha (Table 2.4). B1, the improved farmer variety that originated in the Low environment, was the highest yielding variety in this environment at 3.4 mt/ha (Table 2.4). B3, an improved CIAT variety, was the highest yielding in the Mid (1.8 mt/ha) and High (3.6 mt/ha) environments but it was outperformed by all the other varieties in the Low environment (Table 2.4). Likewise, B1 performed very well in both the Low and High environments however it was the poorest yielding variety in the Mid environment (1.0 mt/ha). In the Mid environment, the other variety yields ranged from 1.4-1.8 (mt/ha).

The highest yielding varieties in the MC were not the highest yielding in the IC, and there was less variability between varieties in the IC (Table 4). The varieties that have been in the region for a longer period of time and are arguably more adapted, B1, B5, and B6, were the best performing varieties in the IC. In this IC system B1 yielded the most in the Low environment (1.6 mt/ha), B5 outperformed other varieties in the IC at the Mid environment (0.8 mt/ha), and the B6 developed specifically by that farmer, outperformed other varieties in the High environment (1.5 mt/ha). B1 was the best performing variety in both cropping systems in its original Low environment. With the limited number of replications, there was insufficient power to detect statistical differences between varieties in each environment for either the MC or the IC.

Environment and yields

Variety performance was more affected by soil properties than elevation. In both cropping systems, the Low and High environment yields were as much as three times higher than yields in the Mid (Table 2.4). Yields were also similar in the Low and High environments for most of the varieties, indicating the elevation difference of approximately 400 m was not a factor in variety performance. Soils in the Low and High were relatively young volcanic soils with low clay content (9-16%) (except at KI) whereas soils in the Mid were heavily eroded Ultisols with high clay content (30%). While there were differences in %C and %N, the average C/N ratio across sites was similar (Table 2.1). In a particularly wet year, as these two seasons were, the higher clay content at Mid, combined with a low pH may have increased environmental stress and suppressed yields in the Mid. Varieties adapted to Mid are likely different than those for the Low and the High sites.

Bean plant characteristics

In addition to yield, several plant traits including principal yield components traits were measured: pods/plant, seeds/pod, 100 seed weight, and plant height (Table 2.4). The number of pods per plant was higher in the MC than the IC for all of the environments and all of the varieties (Table 2.4). The average number of pods/plant was 7.2 in the MC and ranged from 2.9-11.1. Generally, the High environment had the most pods/plant (8.6), followed by the Low environment (7.7). The mid environment had the least pods/plant on average (5.3). In the IC, the average number of pods/plant was 5.3 and ranged from 2.1-9.0. The Low and High environments (6.3) had nearly double the number of pods/plant than the Mid environment (3.3).

Although the number pods/plant is the main component of yield, the highest number of pods/plant was not always the same as the highest yielding varieties. In the MC, the number of pods per plant was the highest for B5, B6, and B1 in the Low, Mid, and High environments, respectively (Table 2.4). In the IC, the pods/plant were highest for B4, B5, and B3 in the Low, Mid, and High environments. Only in the Mid environment in the IC were the highest yielding and highest number of pods the same.

The number of seeds/pod was slightly higher in the MC than the IC for all of the environments and varieties (Table 2.4), but there was very little difference between environments within each system. In the MC, the average number of seeds/pod was 5.0 and ranged from 4.1-5.6. In the IC the average number of seeds/pod was 4.4 and ranged from 3.8-5.0 (Table 2.4). B6, the smaller seeded farmer mixture, had more seeds/pod in both systems in the Low and Mid environments (approximately 5.0 and 5.5 in the IC and the MC, respectively). In the High environment, B4 had the most seeds/pod in the MC (5.3) and tied with B3 in the IC (4.7) (Table 2.4).

The 100-seed weight is a measure of seed size and was generally similar between the two cropping systems. In the MC, the average 100-seed weight was 48.9 and ranged from 36.7-59.4 whereas in the IC the average 100-seed weight was 47.0 and ranged from 35.5-55.9 (Table 2.4). 100-seed weight was lowest in the Low environment for both cropping systems, and similar in the Mid and High environments. In the MC, the heaviest 100-seed weight was B2 (53.0) and in the IC, the heaviest variety was B4 (52.6) (Table 2.4).

Plant height was measured at pod-fill onset because farmers frequently report that height is an intercrop plant trait. Bean plants were taller in the MC than the IC (Table 2.4). In the MC, the average bean height was 191 cm and ranged from 105-273 cm. In the IC, the average bean height was 152 cm and ranged from 104-197 cm. B4 was the shortest plant in all of the systems and environments (Table 2.4). In the MC, B6, B3, and B2 were the tallest varieties in the Low, Mid, and High environments, respectively. These were different than the tallest varieties in the IC. B3 was the tallest plant in the Low and Mid environments and B2 was the tallest in the High environment.

Participatory variety selection

Overview of PVS votes

When all of the votes for each variety were added across both cropping systems and environments, farmers liked the varieties B1 (80), B5 (59), and B4 (45) the most and disliked varieties B4 (54), B3 (53), and B2 (50). Importantly, the most preferred varieties were the same when the MC and the IC were considered separately (Figure 2.1). In order of preference, B1, B5 and B4 were the favorite varieties in both the MC and the IC. In the MC, B1, B5 and B4 had 35%, 24%, and 20% of votes, respectively, and in the IC, they had 30%, 24%, and 17% of the votes, respectively (Figure 2.1).

There was less consensus on which varieties were the least preferred for either system. In other words, the number of negative votes was more evenly spread across the varieties (Table 2.5; Figure 2.1). However, the three varieties with the most negative votes in the MC were B3 (23%), B2 (23%), and B4 (20%) and similarly in the IC they were B4 (23%), B3 (19%) and B2 (18%). Although there was consensus on the most and least preferred varieties when the votes were tallied, there were some differences in preferences within the three environments.

PVS votes and environment

Farmer preferences for varieties did vary across the environments, but variety preferences were similar for the monoculture and the intercrop systems. In the Low environment in the MC, all of the farmers liked B1 (54%) and B5 (46%) and there were 0 votes for the other varieties (Table 2.5). Farmers still liked B1 (33%) and B5 (30%) the best in the IC, but they also voted for B2 (27%).

In Low, farmers preferred B1 in the MC because it doesn't require larges stakes, "it grows very well from the beginning thus ensuring good production," and it tastes sweet. They also appreciated it in the IC because "it doesn't outcompete the maize," which ensures adequate harvest and the pods start at the bottom. B5 was liked because has a short time to maturity, grows well, and valued on the market. Surprisingly, although farmers voted for B2 in the IC, the only positive comments made about B2 in the IC were that it tasted sweet, was visually pleasing, and required little fuel.

In the Mid environment, farmers voted for the same varieties in both the MC and the IC but farmers' preferences were more distributed across the varieties than in Low. These differences may be because the sites were further apart from each other and there were variations in these environments or farmers preferences. In order of the most votes, farmers liked B5, B1, B6, and B4 (Table 2.5) in both systems. The number of positive votes were similar in the MC for varieties B5, B1, and B6 whereas in the IC B5 was slightly more preferred than B1 and B6 (Table 2.5). There was variability in which varieties the farmers did not like. In the MC, farmers from the Mid disliked B2 the most (36%) followed by B3, B1, and B4 (20-21%) (Table 2.5). In the IC, Mid farmers disliked B4 the most (34%) followed by B2 and B3 (20%). B6 and B1 also received several negative votes.

In Mid, B1 was appreciated for the pod architecture that started from the bottom of the plant to the top, taste, and ability to grow in the maize. B5 was liked more in one Mid site than in the other sites in Mid. It has adequate pods, short time to maturity, and farmers said it resists rain. B6 was voted for often in the other sites in Mid. Farmers said that it "gets adequate production in fertile soils and tries in the less fertile soils," does okay in the maize, and has enough pods. In one Mid site, farmers disliked B6 because due to different maturing stages and competition among bean types.

In the High environment, farmers also liked the same varieties in both the MC and the IC and the distribution of positive votes were similar across both systems (Table 2.5). In the MC farmers from High preferred B4 (40%) followed by B1 (35%). These preferences were the same in the IC, although a small portion of votes were distributed to each of the other varieties. B3 and B2 were also moderately liked in each system. Negative votes were also distributed similarly between the two cropping systems. More than 50% of farmers in High disliked B5 in both systems, but B2, B3, and B6 also had several negative votes in both systems.

In High, farmers liked B4 because pods started from the ground and went all the way up the plant and it was short which reduced competition with maize in the IC and required smaller stakes in the MC. These farmers also gave it high praise for flavor and value on the market. B1 was largely appreciated in both systems because it takes a short time to mature. Farmers also said it tasted good, was valued on the market, and "didn't obstruct the growing of maize."

PVS Discussion Groups - Traits farmers use to select varieties

Six major thematic categories emerged from the PVS discussion data (Table 2.8). These included yield, plant traits, adaptive qualities, market and labor attributes, nutritional and cooking quality, and other. Yield was talked about the most (128 times), followed by plant traits (114 times), adaptive qualities (85 times), nutritional and cooking quality (71 times), market and labor attributes (57 times), and other (37 times) (Table 6). Within each thematic category were other themes, which are discussed and defined below.

Thematic Categories

Yield

Across both systems, the most commonly talked about trait was yield, 128 times (Table 2.6). Yield was often associated with other comments about plant architecture, competition, and adaptation. It was coded any time it was mentioned and tallied separately from the other categories because it overlapped almost all of the other themes. For example, a farmer from Low said of B5 in the IC, "There are enough pods and big seeds inside which leads to adequate production which in turn increases the farmer's welfare." Farmers associated plant traits such as pods/plant and seed weight with production thus it was coded as "yield" and "plant architecture." Many of the comments coded for yield also referred to the number of pods/plant, the principle yield component. In the MC, men and women mentioned yield with nearly the same frequency (25% and 27%, respectively). In the IC, women talked about yield 24% of the time whereas men talked about it 30% of the time (Table 2.6). Because yield was salient in most of the themes and linked to other farmer descriptions of plant characteristics, it was excluded from the analysis of the remaining themes.

Plant Traits

After yield, farmers talked the most about the thematic category Plant Traits, which included the themes “plant architecture,” “maturity,” and “pest and disease” issues.

Within the theme “plant architecture,” farmers commented on plant attributes that included yield components such as pods/plant, seeds/pod, seed size; positions of pods on the plant, vine thickness, the quantity of flowers, plant height, and biomass. In the MC 14 farmers used plant architecture as a way to describe their acceptance or rejection of a variety while in the IC 30 of farmers referred to plant architecture (Table 2.6). Farmers preferred varieties that had pods starting from the bottom of the plant and growing to the top (B1 and B4) (Table 2.8). Varieties that were very tall or overgrew the maize were problematic (B2 and B3) as were pods with few seeds.

The Plant Trait theme “maturity” referred to the length of time to plant maturity. Farmers mentioned maturity 40 in both cropping systems (Table 2.6). Farmers preferred short-duration varieties (B1) but liked some varieties so well (B3) they were willing to accept the longer time to maturity. They discussed short-duration varieties as “fighting hunger” while they wait for the maize harvest and complained about some varieties (B2, B3, and B4) taking too long in the field. In the IC, the longer time to maturity increased competition according to some: For example, “(B2 in the IC) takes a long time to mature which leads to increased competition between beans and maize and lowers production.” Several farmers commented on different stages of maturity in the B6 being problematic: “Imvange has different maturing stages due to different types of seeds that are grown together, making it difficult to harvest (at once).”

"Pest and diseases," the final theme in the Plant Traits category, was defined as the presence (or lack of) or resistance to disease or pests. It was mentioned 30 times in both cropping systems (Table 2.6). A major concern for farmers in most of the varieties was the attractiveness of the bean flower to birds. Farmers complained that birds eat the flowers which in turn reduces the yield. Varieties B1, B2, and B3 were the most affected by birds, whereas B4 and B5 were minimally affected and B6 was not at all. Damage from birds was reduced in the intercrop. A few farmers each said that B1, B2, B5 and B6, were generally affected by disease.

Adaptive Qualities

Adaptive Qualities, which include the themes "adaptation" and "competition," was talked about 85 times (Table 2.6).

Adaptation was defined as the ability to adapt to the region in terms of climate, soil types and soil fertility, climate, weather (wind and rain), and different seasons. It was mentioned 26 times in the MC and 27 times in the IC (Table 2.6).

Competition was defined as comments about the two crops or varieties competing with each other for resources. This category included issues like shading, maturity and plant architecture when the farmer talked explicitly about those issues in relationship to competition. Competition was mentioned 4 times in the MC and 28 times in the IC (Table 2.6). To farmers, Competition was as important as Adaptation in the IC.

Market & Labor Attributes

Market and Labor Attributes were talked about 57 times overall, and an average of 28 times in either cropping system (Table 2.6). This category included the themes "market" and "labor and stakes." The theme "market" was coded when farmers talked about the value of the variety on the market. For example, farmers talked about a variety being less well known on the market (B3) or it being highly valued on the market (most varieties).

The theme "labor and stakes" was defined as references to a specific trait that increases or decreases the required labor to care for the variety and references to stakes, which are a labor and resource issue. For example, farmers complained that B3 was so tall and strong that it required larger stakes, which were difficult to find. Or, in reference to B6, farmers said that it required more labor during harvest because the varieties matured at different times. There were on average 8.5 comments in either system about labor or stakes (Table 2.6).

Nutritional & Cooking Quality

The thematic category Nutritional and Cooking Quality was discussed a total of 71 times across both cropping systems (Table 2.6). This category included the themes "nutritional qualities" and "cooking qualities."

The theme "nutritional qualities" was used to code any text that referred to food attributes relating to calories, protein, or sustenance for the human body in terms of nutrients. Farmers talked about the nutritional value of varieties approximately 11 times in either cropping system (Table 2.6). For example, a farmer said of B2, "It's full of protein, calories and various vitamins for the body" (Table 2.8).

Text was coded as the theme "cooking qualities" when the flavor of the beans or leaves was discussed, when farmers commented about the time it takes to cook the beans, and if the beans require more or less firewood (Table 2.8). Farmers talked about cooking qualities on approximately 24 times in either system. Farmers liked both the beans and leaves for various reasons. For example, "It tastes so sweet and fresh leaves fight hunger" and it "gives less difficulties to cook because it is not very hard by nature" e.g. the seed is not hard.

Other

The final Thematic Category includes various themes that did not have very many comments. These include the themes “aesthetics,” “information,” and “life-span,” (Table 2.8). Farmers talked about these themes evenly between the cropping systems for a total of 37 times (Table 2.6). A handful of farmers talked about the color of the beans. The theme “information” referred to comments that said there was or was not enough information about the variety. Farmers related this lack of information back to the value on the market or an inability to grow the variety properly (Table 2.6).

Men vs. Women

There were differences between men and women’s comments in each cropping system. In the MC, women talked about plant maturity and labor issues more than twice as much as men (Figure 2.3). In the MC, men focused on plant architecture, market attributes and adaptation more often than women. In the IC, women’s comments were focused on plant architecture and competition while men talked more about plant maturity, pest and disease, and slightly more about adaptation.

PVS discussion summaries by varieties

B1, the farmer adapted variety from the Low environment, was the only variety universally liked by farmers in both cropping systems and all of the environments. It had the most positive votes in the MC (35%) and the IC (30%) (Table 2.5). The overall negative votes for B1 were low (7-9%) (Figure 2.1) but 20% of farmers in the Mid did not like it, particularly in the MC.

Multiple farmers from all of the environments liked that B1 produced pods from the bottom of the plant to the top and that there were very big and long pods. Farmers said these traits increase production and improves the standard of living of the farmers. Pests (birds) and disease were a problem for farmers in the Mid and the High. Farmers from all of the environments said that B1 does well in the maize by either resisting rainfall, by not outcompeting the maize, or by not overcrowding the maize. Most farmers in Mid said it resists rain, although a few said the opposite. Many farmers from all of the environments said that B1 tastes very sweet, has various nutrients, which are necessary for the human body, and it provides great support to the body because of its calories and proteins. Farmers from each environment said it was highly valued on the market due to these qualities.

B2, a white-seeded improved variety from CIAT, was not liked by farmers, particularly in the Mid and the High environments (Table 2.5). Between 18-23% of farmers didn't like it in the MC or the IC, respectively.

Most comments about B2 from farmers were concerns about the plant architecture and competitive ability in the maize. Farmer from all of the environments said that B2 doesn't mix well with maize because it competes with the maize for light, it takes too long to mature which increases competition, or it overcrowds the maize with many leaves. Farmers also did not like that the pods tend to grow up high but not at the bottom of the plant. There were problems with birds eating the bright flowers and farmers in the Mid found that B2 was not resistant to rain and heavy rainfall caused damage to it. In the Low, farmers said it grew poorly from the beginning. There were comments in each environment about B2 not being well known which caused problems for marketing or handling.

B3, a beige-seeded improved variety from CIAT with a vigorous growth habit, was one of the most disliked varieties. 23% and 19% of farmers didn't like it in the MC and the IC (Figure 2.1), respectively. An average of 36% of farmers in Low disliked it in either system but farmers in High voted less on this variety, indicating some neutrality (Table 2.5).

Farmers from the Mid said that B3 grew well in the MC with long pods and many seeds, but in the Low farmers said the opposite. In the IC, a few farmers said it grows taller than the maize, overcrowds it, or there are empty pods and too much biomass, reducing the yield of both crops. The bright pink flowers easily attract birds, which eat the flowers. Farmers from all the environments said that it takes too long to mature and doesn't help fight hunger. Farmers also complained about a lack of resistance to rainfall, birds, and climate variation. It was less valued on the market because it is unknown.

B4, a round red-seeded improved variety from CIAT, was one of the most disliked variety in the IC (23%) and disliked in the MC (20%) but it was also the 3rd most liked variety in both systems (17-20%) (Table 2.5). The environment, rather than the cropping system, was the main reason for this discrepancy. 39-40% of farmers from the High uniformly like it in either system (Table 2.5) whereas only 0-15% of farmers from the other environments liked it. Farmers from the Low disliked it in the IC and MC between 30-47% (Table 2.5).

Farmers from all of the environments said that B4 performed well in the maize because there was less competition with the maize and it produces many pods, ensuring production of both maize and beans. However, they said it "takes a long time to mature which exposes farmers to prolonged hunger if they only relied on this one variety." Farmers found it was not resistant to infertile soils in the Mid, and a few from each environment said it didn't resist rain. All farmers agreed it tasted sweet and it has various nutrients for the human body.

B5, a kidney market class bean regionally grown since the late 1980s, was liked in certain environments. Overall, it had 24% positive votes in both systems and 16-18% of the negative votes. In Low and Mid B5 was liked by farmers for both systems (30-46% of votes) but it was the least preferred in High where it received between 50-55% of negative votes (Table 2.5). There were nearly 0 negative votes for B5 in the Low and Mid and the opposite was true in the High where there were nearly 0 positive votes for B5 (Table 2.5).

In the High farmers agreed B5 doesn't grow well in either system. They said they didn't like the variety because it doesn't resist rainfall, it isn't competitive in the maize, and it easily goes bad in the garden. In the Mid farmers had mixed opinions but were generally more positive about B5. Farmers in the Mid said it has big, long pods in both systems and a short maturation time. Some of these farmers said it is not affected by the rain unlike other seeds, while others said it doesn't grow well on infertile soils. Farmers from all the environments said it tasted sweet and a few said it had important qualities for the human body.

B6, the farmer mixture that varied from location to location, received the least number of positive or negative votes, indicating that in general farmers neither preferred it nor disliked it. Overall, it had 10% of positive votes in both systems and between 5-17% of negative votes (Table 2.5). Farmers in the Mid environment voted the most for B6 in both systems, compared to other environments (22% in the MC and 16% in the IC) (Table 2.5). Most of the votes for B6 were in the IC were 17% of the farmers, distributed across all environments, did not like it

According to farmers, the mixtures provide resilience to climatic, edaphic, and biotic variations and they provide multiple seed types to maintain this resilience. But these differences that enabled this resilience are also problematic: differences in growth types and bean varieties increases competition among the plants resulting in reduced yields; variability in time to maturation increases labor at harvest; cooking the mixture is difficult because beans are ready at different times; and sometimes the seeds are less valued on the market because they are mixed. But a few other farmers argued that it is valuable on the market because of the various advantages and qualities.

Interview data: How do farmers determine suitability for an intercrop?

Open-ended questions were used to determine if and how farmers identify varieties for an intercropping system. Emergent analysis of the short answer questions showed that within this context of field trials comparing varieties in different cropping systems, farmers use various forms of observation and comparison between varieties to determine the suitability of a variety for the intercrop system. Text also revealed that they did these types of comparisons and experimentation previously.

From the interviews, it was found that farmers have different ways of determining the suitability of a variety for an intercrop (Table 2.9). Farmers said they look at traits and assess the bean plant with the same traits they would consider in a monocrop (Universal plant traits), or they associate certain traits with competitive ability in the intercrop (trait-based competitive ability). In addition to traits, farmers indicated that varieties might have an inherent quality that makes them competitive in the intercrop (Intrinsic competitive ability). Farmers said they also consider management (Management) strategies and adaptation when identifying suitable varieties (Table 2.9). According to some farmers, management factors into the ability of a variety to perform in the intercrop. Spacing, the time between planting the different crops, and the fertilizer management influence productivity in the intercrop. Finally, farmers said that adaptation (Adaptation) to the region, either edaphic or climate features, was an important consideration when identifying varieties for the intercrop.

Discussion

How do farmers experiment with varieties for different systems?

Based on previous research in the region, we hypothesized that farmers would select different varieties for each cropping system. Voss (1992) indicated that farmers in Rwanda test varieties in a monocrop first, and then if it performs well they test it in different environments, including low fertility sites and mixed cropping systems. Presumably only some of the varieties would perform well in the intercrop. Although our research was not carried out with "expert" bean farmers, there was evidence of experimentation with varieties for different cropping systems and environments. A farmer in High said, "If we have a new variety we look at the vigor and the pods in monocropping. Sometimes beans in the intercrop could be better than in the monocrop, due to where the field is." According to this farmer, a new variety is tested in the monocrop, but then they test it in different locations where it may perform well in the intercrop. Another farmer in the same region said, "To tell if a variety works well in the intercrop, we use a single variety and see if there is resistance to the maize. We test the single variety by itself in the intercrop, not as a bean mixture." Not only are the farmers experimenting to determine if the variety has some "resistance" to the maize, but they are controlling for what they consider competition between bean varieties. Farmers stated that one of the disadvantages of B6 was that "because (there are) different seed types they compete themselves into low production." Independently, farmers have established means of testing varieties for adaptation to the region in the monocrop and testing for adaptation in the intercrop on different fields and these methods are much like those recommended by various bean breeders. Although there is not consensus among researchers, the majority agrees that germplasm should be selected in the monocrop for highly heritable traits such as seed color, maturity, adaptation to climatic factors (Baudoin et al., 1997), and then tested in the intercrop for quantitative traits like competitive ability, yield potential, and stress tolerance (Smith and Francis, 1985; Davis and Woolley, 1993; Baudoin et al., 1997). Likewise, farmers evaluate the variety in the monocrop to determine if it has desirable traits, and then test it in the intercrop. Following both farmer and researcher methodology, we would expect farmers' variety preferences for the monocrop and the intercrop would vary.

Farmers preferred the same varieties in both systems

Contrary to this hypothesis, within each environment the farmers' top choices were the same for both cropping systems. In order of preference, farmers in Low voted the most for B1 and B5; in Mid their top rated varieties were B5, B1, and B6; and in High they liked B4 and B1 the most (Table 2.5). The only exception was in Low, where farmers did not like B2 in the MC but 27% liked it in the IC. These choices didn't always correspond with yield in either system, except at Low. In every environment most of farmers' top choices were varieties that have been in Rwanda for a longer period of time and may be more adapted to abiotic stresses. B1 is the farmer-improved variety, B5 was introduced by CIAT in the 1980s, and B6 is the farmer mixture. One of the main goals of decentralized plant breeding and PVS methodologies is to understand farmer selection criteria in order to improve adoption of new varieties (Witcombe et al., 2005). In some regions, improved varieties rarely out-yield farmer varieties (Belay et al., 2005) and new varieties are not adopted for various other reasons including suitability to these low-input systems (Omanya et al., 2007). Farmers' choices in this research gravitated towards these regionally adapted varieties and other than B4, the improved varieties were only marginally liked. Despite the High's preference for the improved variety B4, the improved varieties (B2, B3, and B4) still had the most negative votes (Figure 2.1). The adapted varieties received more positive votes and the least number of negative votes whereas B2 and B3 received the least number of positive votes and the most negative votes.

Yield

Yield was one of the most important attributes to farmers and 26% of the comments were about yield or relating other traits back to yield. For example, farmers talked about increased competition reducing yield, or pest problems reducing yield. In most cases, farmers talked about yield components together with yield. A farmer in Mid said of B5, "there are enough pods and big seeds inside thus leading to adequate production which in turn increases the farmers' welfare." Even though yield was an important quality, farmers didn't always prefer the highest yielding variety in each environment. This is consistent with other studies that found farmers used multiple criteria in the selection of varieties (Omanya et al., 2007). In Low, the farmers liked the highest yielding varieties (B1 and B5) whereas in the other environments there was no clear relationship between choice and yield. B1 did perform well in most environments and was the highest yielding variety in several locations and cropping systems (Table 2.4), possibly explaining its universal acceptance.

Multiple criteria to meet multiple needs

Similar to findings from other PVS studies, we found that farmers evaluated varieties for more than simply yield characteristics (Assefa et al., 2005; Omanya et al., 2007; Brocke et al., 2010). In addition to yield, farmers considered attributes such as plant traits, adaptive qualities, market and labor attributes, and nutritional and cooking quality (Table 2.6). They related many of these themes back to farmer well-being. They said that high production, value on the market, or nutritional properties improved farmer livelihoods. Subsistence farmers depend on cropping systems for multiple services (Altieri, 1999), so it is not surprising that they evaluate varieties, no matter the system, with these services in mind (Baudoin et al., 1997). Farmers talked about plant traits and adaptive qualities that have the potential to improve yield 23% and 17% of the time, respectively. Farmers were also tuned into market, labor, and food quality attributes. 17% of comments were concerned with the value of the beans on the market and issues related to labor.

14% of the comments were about the nutritional quality, taste, and cooking time. The qualities of a variety were rarely discussed in isolation from the goal of meeting multiple needs. For example, a farmer in High said, (B1 is good because) “adequate production is realized and it is considered highly on the market which improves the welfare of farmers in terms of food and money.” And, farmers talked about the nutritional value of the varieties, “When cooked locally in the mixture of potatoes, Kaki tastes so sweet and it is full of nutrients for the human body because of its calories and proteins.” Farmers think about variety attributes and yield in terms of food, human nourishment, and as an exchangeable good on the market (Baudoin et al., 1997). While many of the bean variety attributes farmers focused on in these evaluations have also been found in other studies (Brocke et al., 2010), there is less information on the criteria farmers use to evaluate varieties specifically for an intercrop and farmer understanding of trait and competition interactions.

Plant characteristics farmers associate with improved performance in an intercrop

Farmers have determined that there are multiple factors that must be considered in the identification of varieties for their farms, and for mixed cropping systems. From the interviews, it emerged that farmers evaluate varieties for the intercrop through observation and comparisons. When asked how they identify a variety for an intercrop, farmers talked about management strategies 20% of the time, universal plant traits used to evaluate a bean in either system (34%), trait-based competitive ability of a variety in the IC (24%), intrinsic competitive qualities of the variety (12%), and adaptation (10%). Almost every farmer talked about more than one of these themes. In other words, farmers determine suitability of varieties through multiple means of comparison and experimentation. There is little known research about how farmers evaluate varieties for the intercrop environment but many of our findings are not different from researchers' experimentations with varieties for intercrop systems. Researchers have also evaluated varieties intended for an intercrop by experimenting with management strategies; using general plant traits such as yield, pods/plant, or flower set (Zimmerman et al., 1984; Gebeyehu, 2006); and have attempted with varying degrees of success to determine which traits are important for an intercrop. Farmers' strategies both confirm researchers' findings and lend new insights into identifying varieties for the intercrop.

Management

Farmers in this research had different ideas about intercrop spacing and timing and were inclined to manipulate plant density, timing of planting, and plant type. In terms of plant density, many farmers were in agreement about increasing the spacing in the intercrop. For example, a farmer in Low said that an intercrop is better "When there is different spacing than now. When the space is big the competition is lower and then there is good production for both. Due to good spacing, working inside is easy." Farmers have adjusted the plant densities and timing of planting to optimize yield in their specific environment. Indeed, of the maize-bean breeding for intercropping research that exists, there are few similarities between the studies in terms of the intercrop plant density, plant type, or planting time (Francis et al., 1978; Santalla et al., 1994) and some have found that even when the plant densities are held constant, the spatial arrangement can affect yield (Rapaso et al., 1995). The variability in intercrop studies demonstrates the diversity found in intercrop farming systems worldwide and the multitude of ways these systems can be planted (Graham and Ranalli, 1997). Vandermeer (2011) suggested that the only way to determine the optimal intercrop in terms of spacing, density, and timing is through modeling but this would only be effective if the system accounted for the multiple services farmers desire from the cropping system.

Some farmers said that beans should be planted two weeks after maize as opposed to the four weeks the farmer associations agreed upon for the research. But most farmers felt that the four-week interval allowed the maize to grow tall enough in order to support the beans and not overgrow the maize. From Low, "Ngwinurare has more pods that start near the ground. It doesn't make competition to the maize because it doesn't grow the whole length of the maize. If I leave 4 weeks between maize and bean planting then the beans aren't taller than the maize when it's ready to harvest." Researchers have found that aggressive climbing beans need to be planted a fair amount of time after the maize to reduce smothering of the maize (Davis and Woolley, 1993). Farmers also stated that longer duration varieties increased competition with the maize: "Umweru takes a long time to mature which leads to increased competition between beans and maize which insures inadequate production of the farm." Farmers preferred quickly maturing varieties in general but they also stated that fewer days to maturity was better in the maize. This is similar to researchers' findings that there was less competition in a relay crop in which beans and maize overlap in the field for a brief period of time (Davis and Woolley, 1993).

Trait-based competitive ability

There has been work attempting to identify plant traits that correlate with better performance in the intercrop (Baudoin et al., 1997). But besides yield components such as pods per plant, there is no clear story on which plant traits are best in the intercrop. In a region where intercropping was ubiquitous and farmers have a long history of intercropping multiple different crops including beans and maize, farmers have insightful criteria into which plant traits are important in an intercrop. These included characteristics such as plant height, leaf biomass, and plant structure.

Plant Height

There is evidence from both voting preferences and discussion that farmers think shorter plants are more competitive in the IC. They said varieties such as B2 “overcrowds” the maize with “too many pods on top” and B3 overgrew the maize and reduced competitive ability. A farmer in High said, “Kaki creeps longer on the top of maize thus leading to difficulties in harvesting both maize and beans.” In contrast, B5 was appreciated for its shorter stature, “Ngwinurare doesn’t make competition to the maize and the maize doesn’t compete with the beans because it doesn’t have too many leaves and the stems are not big. If I compared Ngwinurare with kaki, kaki is tall and grows beyond the maize and can make it fall down. Ngwinurare will not and doesn’t grow that tall.” In accordance with these farmers observations, Francis et al. (1978) and Wortman and Sengooba (1993) found that there was lower variety by cropping system interactions in bush bean-maize intercrops as compared to climbing bean-maize intercrops, indicating that the shorter plant was less affected by the cropping system environment. B4 was also generally appreciated in the maize for its short stature.

Competition for light

Farmers in this research have identified competition for light as an important variant in variety performance and associate this with both plant height and leaf biomass. Interestingly, farmers commented often about competition for light and associated less leafy biomass with improved competitive ability, particularly in the cases of B1 and B5. A farmer in Mid talked about the effect of leaves on competition, “Gasilida was growing well to the maize. The leaves are not too many which helps avoid competition to the maize, but they also weren’t too few” and “Gasilida doesn’t have many leaves…so the sunlight can penetrate through to the plants.” Another farmer also said leaves near the bottom of the plant are important for light competition:

"the leaves don't avoid the sunlight (and are able to) penetrate to the ground." Farmers seem to agree across the environments that there is an optimal amount of leaves that ensures a harvest of both crops. One advantage of intercrops is the increased light-use efficiency (Tsubo et al., 2003), and farmers have determined there is also an optimal plant structure that correlates with competitive ability. Baudoin et al. (1997) and Davis and Woolley (1993) have suggested this, although the ideal structure has not been determined.

Plant architecture

In all of the environments, farmers said the thickness of the bean stem and the vine was an important determinate of adaptability to the intercrop. There is limited information from the literature indicating there is a preferable or advantageous stem thickness. Although in a review Baudoin et al. (1997) stated the probability of finding varieties with a high harvest index and good yield depends on the plant architecture. Farmers believed stem thickness was important in the intercrop, but some believed a thin stem was better and others preferred a thick stem. Farmers associated a thick stem with lodging, "Imvange (B6) also doesn't make competition to the maize in terms of making it fall down because the stems aren't big" but many said that a thick stem was good in the intercrop, (you can tell a variety is good in the intercrop when) "The beans grow well to the maize – when the stem is big, there are more pods, and there are fresh beans. When the pods are long." On the other hand, others said a smaller stem reduced competition: "Gasilida does well because there aren't too many leaves. Also the stems aren't too big so they don't compete with maize. There are many pods and I can harvest both maize and beans." Studies have looked at bean plant types and maize lodging, but to our knowledge there is no information on the affect of stem size on competition. This is a unique characteristic that farmers use to identify varieties for an intercrop.

Intrinsic competitive ability

While about 34% of farmers talked about trait-based competitive ability, a smaller percentage of farmers (12%) also talked about an intrinsic competitive ability they observed in the different bean varieties. Intrinsic competitive ability was defined as an innate quality in the variety that enabled it to “grow well to the maize” or “resist the maize” and when questioned further, farmers did not associate certain traits with this ability to resist the maize or they considered it a separate quality from other traits. For example, a farmer from Mid said, “Gasilida grows well to the maize and produces fresh beans from the ground to the top and has more pods” and a farmer from High said, “Some varieties can resist being close to the maize, others cannot.” This intrinsic ability may be related to genetic variation in competitive ability, or a genetic resistance to disease. A farmer in High elaborated on what she meant by an ability to resist: “When a bean can resist in the maize. When the rain stops there are drops from the maize onto the beans that some beans resist and some beans don’t…Some varieties can resist being close to the maize, others cannot.” Other farmers said things similar to this farmer in Low, “It is better in the maize and it is good to eat. I don't know why it does well in the maize, I just tried it to find out.” Farmers identify an intrinsic competitive quality in bean varieties (mostly in B1) that improves its performance in the intercrop, and some even state they have to test the variety to find out. Breeders have found that competitive ability is a highly inherited trait in climbing beans (Baudoin et al., 1997) and farmers’ conclusion that there are intrinsically competitive varieties supports this argument. Researcher led trials have found evidence that there are genetic qualities that improve the competitive ability of a bean variety in the intercrop. O’Leary and Smith (1986) and Muraya et al. (2006) showed that breeding maize in the intercrop from the onset improved genetic performance in that system and Zimmerman et al. (1984) and Davis and Woolley (1993) concluded the same for beans. Despite both of these findings, others still recommend breeding in the monocrop.

Adaptation and genetic variation

Farmers discussed adaptation equally in both cropping systems and farmer selection of the same genotypes for both systems may be related to the effect of environment on genotype adaptation. Farmers frequently said B1, B5, and B6 had resistance to the region or the soil. For example, a farmer said (Table 2.9), "B1 is good in the intercrop, B2 is good in the mono. B1 and B5 can grow anywhere, in each place, but the others can only grow in the good places." These same genotypes that were adapted to the region were favored for their performance in the intercrop.

It is particularly difficult to determine genetic variation in low input systems (Banziger and Cooper, 2001) because abiotic stress represses phenotypic expression of the traits in question. The intercrop environment can create an additional environmental stress that represses genetic variation (Davis and Woolley, 1993). The low variation in IC yields in this study compared to greater variation between varieties in the MC (Table 2.4) is evidence of this phenomenon. For the same reason that breeders conclude varieties should be bred and stabilized in the monocrop and later selected in the intercrop environment, breeders prefer to develop varieties for any environment (low or high input) in well managed high input systems because the chances of identifying favorable genetic variation is greater (Banziger and Cooper, 2001). However, there is evidence from this study that it is possible to identify genotypes with better competitive ability in the low-input system and in an intercrop. Farmers' methods of testing and selecting in different systems demonstrates that this is possible with advanced lines.

Once varieties with ideal traits are determined, adaptation to the intended environment can be tested in various locations. Evidence from this research and Voss' earlier work (1992) suggest that farmers are likely familiar with the effect of environmental conditions on genotypic variation and Woolley et al. (1991) further notes that farmers' cropping systems are fine tuned to existing physical, biological, and socioeconomic determinants. These fine adjustments allow them to respond to changes in their conditions (Davis and Woolley, 1993), which may be static (soil types) or dynamic (weather). Coping with various environmental stresses, farmers have developed a similar strategy over time by testing and identifying preferable varieties in the monocrop first, because adaptation or "resistance" to the region is essential for performance in either system. Finally, farmers test the varieties in low fertility sites and intercrops; an additional layer of abiotic stress, to ensure the variety is adapted to their field conditions.

An ideal genotype and improved adoption

Through these discussion groups and interviews it emerged that farmers have specific preferred attributes for intercrop varieties and breeders could use this information to develop bean varieties for intercropping systems in this region. The plant characteristics farmers preferred were normally related to reducing competition between the maize and the beans. The attributes farmers looked for in intercrop varieties were early maturing, less aggressive and shorter plant types with an evenly distributed pod structure to prevent lodging, plants with fewer leaves, and adaptation to the environment. Adaptation and a natural competitive ability were of primary importance to farmers and essential to performance in the intercrop. Bean breeders could use these criteria to develop more suitable varieties for intercrops in this area and similar methodologies might be used in other intercrop regions to understand farmer preferred intercrop traits. However, developing varieties adapted to niche regions remains resource intensive and challenging for breeding programs.

Due to the highly heterogeneous nature of smallholder farming environments, identification of varieties adapted to both the environment and the cropping system is challenging for breeding programs. Evidence from this research alone indicates that distinct environments exist within a small radius and varieties that work in one area aren't necessarily appropriate for another. Breeding for either low input environments or intercropping systems in considered highly resource intensive and is usually not feasible in national breeding programs. However, this research has also revealed that farmers have considerable knowledge and preferences about selecting varieties for abiotic environments and multiple types of cropping systems. Improving farmer access to large and diverse bean populations may be a feasible alternative to resource intensive genotype by environment (by cropping system) trials and would increase the identification of suitable varieties for on-farm cropping systems and conditions.

Conclusions

Bean farmers in Rwanda use diverse and complex methods for identifying genotypes adapted to both their field conditions and cropping systems. They have determined that, in addition to universal plant traits like yield and pods per plant, there are trait-based and intrinsic competitive qualities that improve variety performance in the intercrop. These qualities include early maturing time, less aggressive plant types, fewer leaves, pod structure, environmental adaptation, and a natural competitive ability. Farmers combine these characteristics with management strategies and testing techniques to identify optimal varieties for distinct cropping systems and field conditions. Foremost in farmers' selection criteria attributes are yield and adaptation to the region. Both their intercrop selection methodology and attunement to these various traits demonstrate that the best genotypes in the monocrop are not necessarily the best in the intercrop in low-input farming systems. These findings both confirm and add richness to over

30 years of research on intercropping systems. Likely developed over generations of growing intercrops, farmers have a profound understanding of variety by cropping system interactions and their strategies lend insight into ways to move forward with improving varieties for both low in-put systems and/or intercrop environments.

This research also demonstrates the importance of variety adaptation, farmer selection criteria, and is further evidence that the inclusion of farmers in variety trials can improve adoption. Improved varieties, even ones tested in multiple sites, are not necessarily adapted to these highly heterogeneous environments. The varieties from this research have been growing on the research stations for several years, but farmers preferred only one of the new varieties (B4) or ones that have been in the region indefinitely (B1 and B5). Adaptation to a region is essential for optimal performance, and farmers' strategies of testing varieties in different field types and cropping systems demonstrate their knowledge and ability in the selection of such varieties. Involvement of farmers in the selection process of large bean breeding populations on-farm and in mother-baby trials could improve identification of favorable and adapted varieties, and increase dissemination and adoption.

Finally, breeding programs designed specifically for intercropping systems are normally considered cumbersome and expensive, but empowering farmers through on-farm testing of diverse varieties may be a practical solution. Giving farmers the opportunity to experiment and test genetically diverse varieties according their own methodologies may be an effective and practical means of developing genotypes for intercropping systems.

Table 2.1 Characterization of the seven farmer field sites in Northern Province, Rwanda.

Environment	Site	Season	Elevation	Soil Type	Clay	Sand	Total N	Organic C	P	soil pH
Unit			m.a.s.l.		%	%	%	%	(bray)	
Low	MI	1	1668	Silt loam	9.0	30.3	0.27	2.46	59	6.6
		2	1681	.	.	.	.	.	.	.
	ML	1	1664	Sandy loam	10.1	64.6	0.14	3.19	102	6.3
		2	1669	Sandy loam	8.9	54.3	0.11	0.97	122	6.3
Mid	CE	1	1835	Sandy Clay Loam	21.5	62.1	0.11	1.04	15	5.5
		2	1786	Clay Loam	35.5	41.4	0.07	0.61	3.25	5.1
	CN	2	1758	Clay Loam	30.3	34.3	0.09	0.78	2	5.0
	NP	1	1813	Clay loam	32.9	30.5	0.18	1.89	11	5.5
		2	1833	Clay loam	27.8	27.9	0.10	1.01	5	5.1
High	KI	1	2076	Silt Loam	14.0	30.1	0.11	0.81	10	6.8
		2	2059	Loam	27.2	28.8	0.24	2.57	7	6.2
	RU	1	2064	Silt Loam	10.7	40.0	0.75	7.53	17	5.6
		2	2035	Silt loam	11.1	36.1	0.11	0.81	4	6.3

Table 2.2 Bean genotype characteristics.

CHARACTERISTICS	GENOTYPES					
	Gasilida B1	RWV 3006 B2	RWV 2070 B3	RWV 3316 B4	Ngwinurare B5	Farmmix B6
Farmer Name	Gasilida	Umweru	Kaki	Umutuku	Ngwinurare	Imvange
Origin	Farmer	CIAT/RAB	CIAT/RAB	CIAT/RAB	CIAT/RAB	Farmers
Release Date	2010	2012	2010	2012	1991	N/A
Germplasm	Improved Landrace	Improved	Improved	Improved	Improved Landrace	Mixture of Landraces
Days To Maturity	93	120	110	110	93	90-105
Seed Color	Purple	White	Beige	Red	Kidney	Mix
100 seed weight (g)	48.3	52.0	53.6	52.0	49.2	46.9
Flower Color	Pink White	White	Pink	Pink	Pink	Purple Pink White
Yield (mt/ha^{-1})	4.25	3.8	4.25	4	4.24	Variable
Disease Resistance	Anthracnose Root Rot Rust	Anthracnose Root Rot BCMV	Anthracnose Root Rot BCMV	Anthracnose Root Rot BCMV	Root Rot BCMV	Unknown

Data is according to official release information from the Rwanda Agricultural Board. During the research, the farmer names for the genotypes were used. Here forward they are referred to as B1-B6.

Table 2.3 Farmer demographics from 61 farmer interviews in Northern Province, Rwanda.

Environment	Site	Age	Education	Class*	Members in household	Land owned	N
Unit		years	years	1-6	Total < 18	mt/ha^{-1}	Farmers
Low	MI	48	4.6	3.6	5.3	0.4	11
	ML	58	1.3	3.7	3.9	0.3	7
average		51	3.5	3.7	4.7	0.4	
Mid	CE	48	3.9	3.0	5.8	0.6	9
	CN	45	5.6	2.5	6.2	0.7	11
	NP	31	3.8	3.5	4.0	0.6	4
average		43	4.7	2.9	5.7	0.6	
High	KI	38	3.0	3.4	5.8	1.0	7
	RU	47	5.8	3.8	5.7	1.0	12
average		44	4.8	3.6	5.7	1.0	
average (sd)		**46** (13)	**4.3** (3.0)	**3.3** (0.9)	**5.4** (2.3)	**0.6** (0.6)	**Total** 61

All values are averages for each location. (n=61). Data collected during interviews from farmers that participated in the PVS. In bold are environment means and overall mean with standard deviation in parenthesis.

*The Rwandan government developed six poverty categories that range from (1) “abject poverty” to (6) “the money rich.” The farmers in this study were mostly (3) “the poor” and (4) “the resourceful poor” (Howe and McKay, 2004). See methods for more information.

Table 2.4 Bean yield and plant morphology at each environment averaged across farmer field sites and Season 1 and Season 2, 2011-12 in Northern Province, Rwanda.

PLANT TRAIT	ENVIRONMENT	UNIT	MONOCROP							INTERCROP						
			B1	B2	B3	B4	B5	B6	**Av.**	B1	B2	B3	B4	B5	B6	**Av.**
Yield	Low	mt/ha^{-1}	3.4	2.7	2.5	2.6	2.9	2.8	**2.8**	1.6	1.1	1.1	1.2	1.2	1.2	**1.2**
	Mid		1.0	1.4	1.8	1.6	1.5	1.6	**1.5**	0.5	0.4	0.5	0.6	0.8	0.6	**0.6**
	High		3.4	2.7	3.6	2.8	2.1	2.8	**2.9**	1.2	1.0	1.3	1.2	1.0	1.5	**1.2**
	mean		**2.6**	**2.3**	**2.6**	**2.3**	**2.2**	**2.4**	**2.4**	**1.1**	**0.8**	**1.0**	**1.0**	**1.0**	**1.1**	**1.0**
Pods/ plant	Low	#	8.4	7.1	5.8	6.7	9.6	8.7	**7.7**	6.4	3.5	7.5	9.0	7.6	4.1	**6.4**
	Mid		4.3	2.9	5.5	5.2	6.0	7.8	**5.3**	3.5	2.4	2.1	3.5	4.6	3.8	**3.3**
	High		11.1	7.4	9.3	7.7	8.7	7.4	**8.6**	5.7	5.7	8.1	5.0	7.5	5.4	**6.3**
	mean		**8.0**	**5.8**	**6.9**	**6.5**	**8.1**	**8.0**	**7.2**	**5.2**	**3.9**	**5.9**	**5.8**	**6.6**	**4.4**	**5.3**
Seeds/ pod	Low	#	5.1	5.1	5.1	4.9	4.1	5.6	**5.0**	4.5	4.3	4.2	4.6	3.8	5.0	**4.4**
	Mid		4.8	4.3	5.2	5.3	4.3	5.4	**4.9**	4.3	4.2	3.8	4.6	4.0	4.9	**4.3**
	High		5.0	5.0	5.2	5.3	4.8	5.1	**5.1**	4.0	4.6	4.7	4.7	4.0	4.4	**4.4**
	mean		**5.0**	**4.8**	**5.1**	**5.2**	**4.4**	**5.4**	**5.0**	**4.3**	**4.3**	**4.2**	**4.6**	**3.9**	**4.8**	**4.4**
100-seed weight	Low	g/100	38.8	44.6	39.9	.	36.7	37.0	**39.4**	37.0	46.5	40.6	.	41.6	35.5	**40.2**
	Mid		58.1	59.5	57.3	46.1	58.5	39.2	**53.1**	47.0	53.0	47.6	49.8	52.4	39.0	**48.1**
	High		49.1	55.0	59.4	55.0	50.5	44.1	**52.2**	45.8	53.8	55.9	55.4	47.7	44.4	**50.5**
	mean		**50.0**	**53.0**	**52.9**	**50.5**	**52.5**	**40.0**	**48.9**	**43.8**	**51.1**	**48.0**	**52.6**	**47.2**	**39.6**	**47.0**
Plant height	Low	cm	217	228	231	138	209	273	**216**	162	182	197	123	165	140	**161**
	Mid		193	220	222	150	220	210	**203**	172	137	178	130	173	161	**159**
	High		155	181	178	105	142	157	**153**	133	161	147	104	133	141	**136**
	mean		**189**	**210**	**210**	**131**	**191**	**213**	**191**	**156**	**160**	**174**	**119**	**157**	**147**	**152**

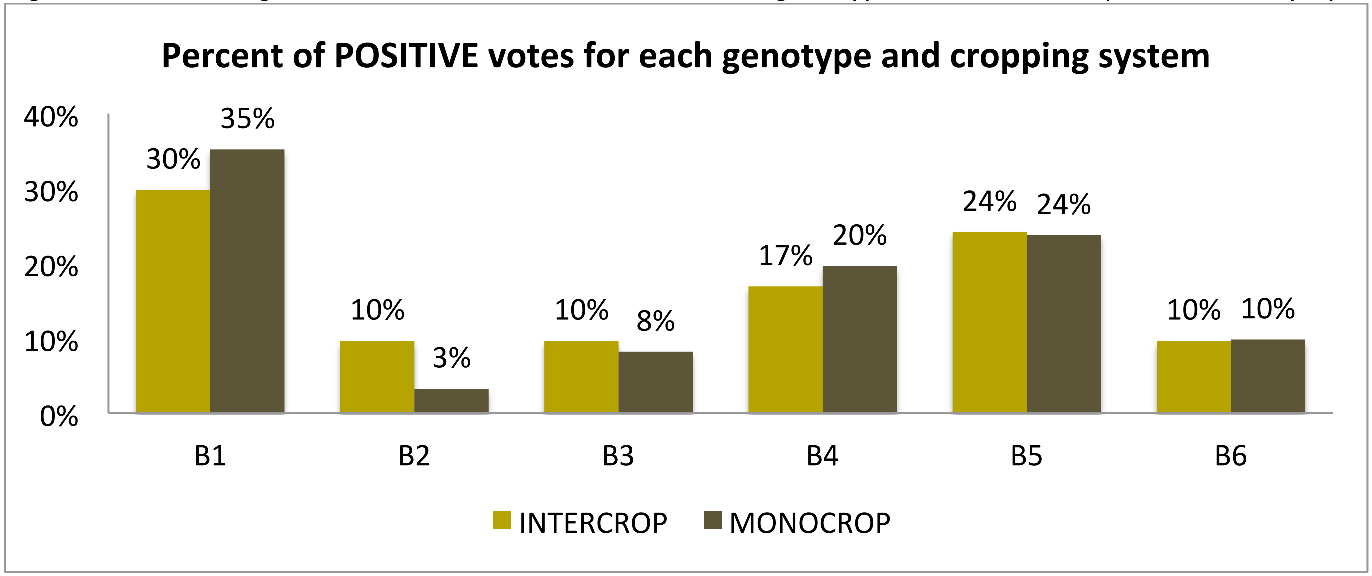
Results are averaged across sites and seasons in each environment. In bold, the means for each genotype are presented in addition to the means for each environment. Values for each environment are from 2 sites and 2 seasons (n=4) for the Low and High environments. The Mid environment includes 2 plots in Season 1 and 3 plots in Season 2 for a total of n=5.

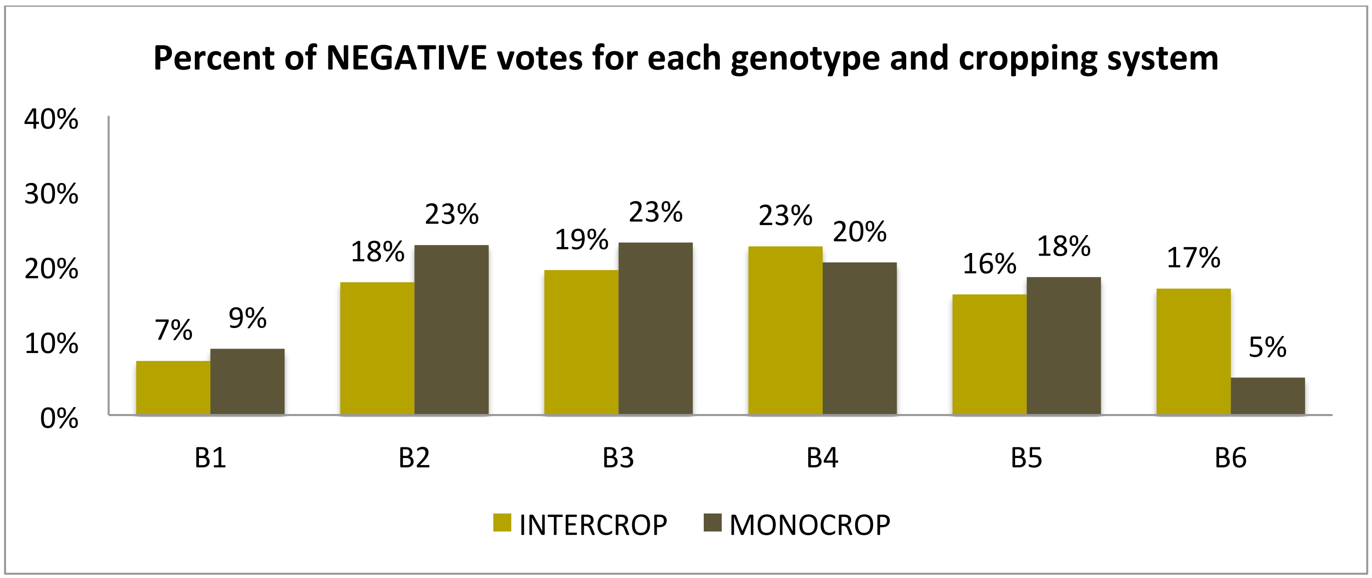
Table 2.5 Positive and negative votes from Season 2 PVS votes for each genotype in the monocrop and the intercrop as a percentage of total votes in each environment.

CROPPING SYSTEM	ENVIRONMENT	GENOTYPE					
		B1	B2	B3	B4	B5	B6
		% POSITIVE VOTES					
MONOCROP	LOW	54%	0%	0%	0%	46%	0%
	MID	26%	0%	7%	15%	30%	22%
	HIGH	35%	10%	15%	40%	0%	0%
	Total	**35%**	**3%**	**8%**	**20%**	**24%**	**10%**
INTERCROP	LOW	33%	27%	0%	3%	30%	7%
	MID	29%	0%	11%	9%	36%	16%
	HIGH	29%	11%	16%	39%	3%	3%
	Total	**30%**	**10%**	**10%**	**17%**	**24%**	**10%**
		% NEGATIVE VOTES					
MONOCROP	LOW	0%	3%	40%	47%	0%	3%
	MID	20%	36%	21%	20%	2%	0%
	HIGH	0%	18%	13%	3%	55%	13%
	Total	**9%**	**23%**	**23%**	**20%**	**18%**	**5%**
INTERCROP	LOW	0%	10%	33%	30%	0%	27%
	MID	11%	20%	20%	34%	2%	14%
	HIGH	8%	21%	8%	0%	50%	13%
	Total	**7%**	**18%**	**19%**	**23%**	**16%**	**17%**

Total percentages are weighted averages of votes at each environment.

Figure 2.1 Percentage of votes from Season 2 PVS for each genotype in the monocrop and intercrop systems across all environments.





Values are weighted averages of votes at each environment.

Table 2.6 Frequencies of traits mentioned by farmers in monocrop and intercrop assessments in the participatory variety selection interviews.

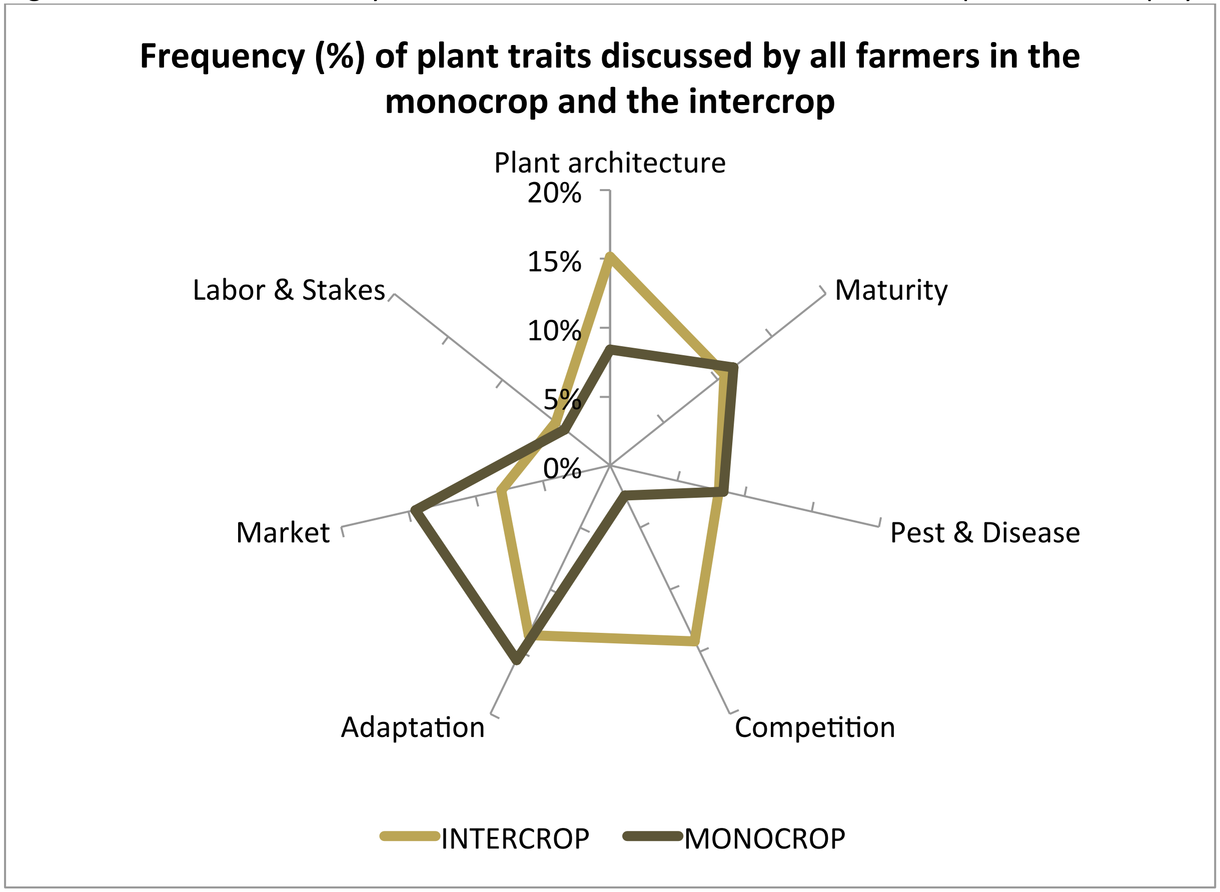
THEMATIC CATEGORIES	Themes	MONOCROP				INTERCROP				Total IC + MC	**% TOTAL**
		Women	Men	Total	MC %	Women	Men	Total	IC %		
YIELD	Yield	**35**	**23**	**58**	**26%**	**43**	**27**	**70**	**26%**	**128**	**26%**
PLANT TRAITS	Plant Architecture	6	8	14	6%	23	7	30	11%	44	9%
	Maturity	15	4	19	6%	12	9	21	6%	40	6%
	Pest & Disease	8	6	14	8%	9	7	16	8%	30	8%
	subtotal	**29**	**18**	**47**	**21%**	**43**	**23**	**67**	**25%**	**114**	**23%**
ADAPTIVE QUALITIES	Competition	3	1	4	2%	20	8	28	10%	32	7%
	Adaptation	15	11	26	12%	17	10	27	10%	53	11%
	subtotal	**18**	**12**	**30**	**13%**	**33**	**18**	**55**	**21%**	**85**	**17%**
MARKET & LABOR ATTRIBUTES	Market	13	11	24	6%	11	5	16	3%	40	5%
	Labor And Stakes	6	1	7	13%	9	1	10	7%	17	10%
	subtotal	**19**	**12**	**31**	**13%**	**20**	**6**	**26**	**10%**	**57**	**12%**
NUTRITIONAL & COOKING QUALITY	Nutrient Qualities	11	3	14	3%	5	4	9	4%	23	8%
	Cooking Qualities	18	10	28	11%	15	5	20	6%	48	3%
	subtotal	**29**	**13**	**42**	**13%**	**20**	**9**	**29**	**11%**	**71**	**14%**
OTHER	Life-Span	5	5	10	4%	6	4	10	4%	20	4%
	Info	4	0	4	1%	5	4	9	3%	13	3%
	Aesthetic	1	1	2	2%	2	0	2	2%	4	1%
	subtotal	**10**	**6**	**16**	**7%**	**13**	**8**	**21**	**8%**	**37**	**8%**
	TOTAL	140	84	224	100%	177	91	268	100%	492	100%

Absolute values based on thematic coding of recorded discussion groups. The percentages are relative to the total number of comments made by farmers in each section (last row of each column).

Table 2.7 Distribution of comments across genotypes from Season 2 PVS discussions in Northern Province, Rwanda.

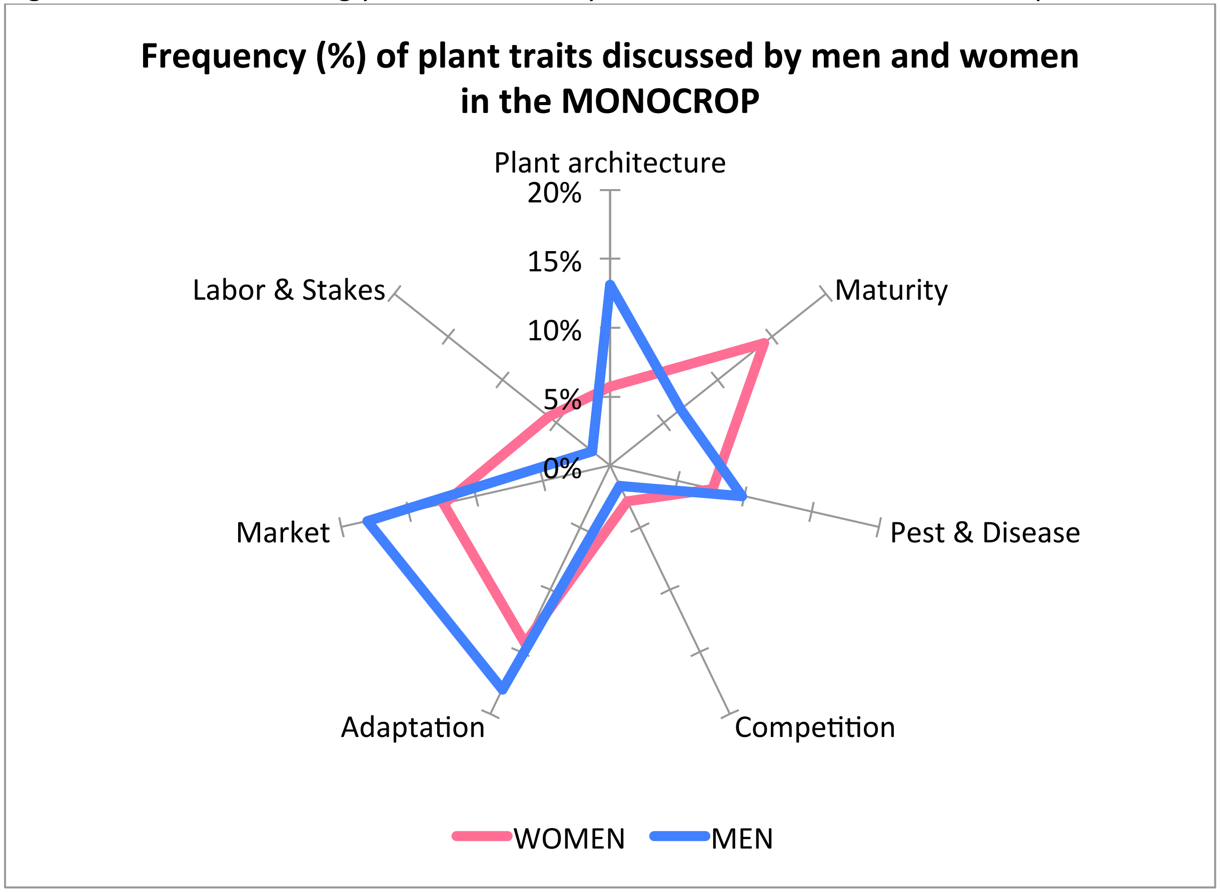
THEMATIC CATEGORY	GENOTYPES					
	B1	B2	B3	B4	B5	B6
PLANT TRAITS	29%	39%	44%	29%	16%	35%
ADAPTIVE QUALITIES	18%	26%	10%	20%	38%	28%
FOOD QUALITY	28%	11%	19%	27%	24%	2%
MARKET & LABOR ATTRIBUTES	19%	5%	17%	14%	13%	28%
OTHER	6%	19%	10%	10%	10%	7%
	100%	100%	100%	100%	100%	100%

Figure 2.2 Traits discussed by all farmers in Season 2 PVS for the monocrop and intercrop systems in Northern Province, Rwanda.



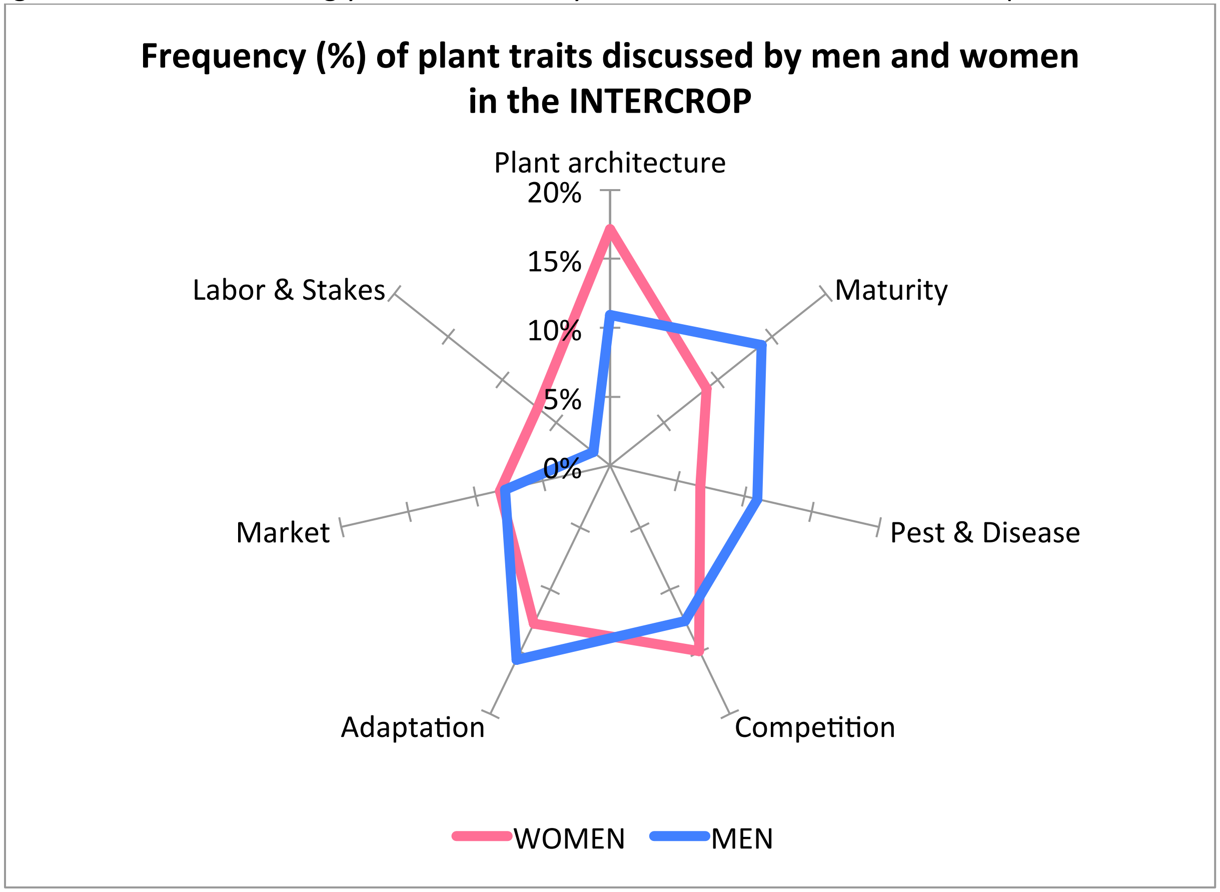
There were a total of 166 comments in the monocrop and 198 in the intercrop. This figure includes only traits relevant to performance or issues associated with the cropping system.

Figure 2.3 Traits, excluding yield, discussed by men and women in the monocrop in Season 2 PVS in Northern Province, Rwanda.



In the monocrop, there were 105 comments from women and 61 from men. This figure includes only traits relevant to performance or issues associated with the cropping system.

Figure 2.4 Traits, excluding yield, discussed by men and women in the intercrop in Season 2 PVS in Northern Province, Rwanda.



In the intercrop, there were 134 comments from women and 64 from men. This figure includes only traits relevant to performance or issues associated with the cropping system.

Table 2.8 Thematic categories and selected examples for each genotype from PVS discussion groups in Season 2 in Northern Province, Rwanda.

THEMATIC CATEGORIES Themes	GENOTYPES					
	GASILIDA (B1)	RWV 3006 (B2)	RWV 2070 (B3)	RWV 3316 (B4)	NGWINURARE (B5)	IMVANGE (B6)
PLANT TRAITS Architecture Maturity Pest & disease	★★★ Pods from the bottom to the top of the plant. Short time to maturation which reduces hunger & encourages more harvest in a limited time.	★★★ Has pods up high and doesn't grow well at the bottom of the plant, but 50% of farmers like this and 50% did not.	★★★ In the Mid and High farmers complained birds eat the bright flowers. B3 takes too long to mature thus it doesn't help fight hunger.	★★ The pods start from the ground and they go all the way up but it takes a long time to mature which exposes farmers to prolonged hunger if they only rely on this variety.	★★ In the Mid, it has big and long pods with many seeds inside and does well in both systems.	★★ The beans mature at different stages, making it difficult to harvest at once.
ADAPTIVE QUALITIES Competition Adaptation	★★★ Performs in maize by either resisting rainfall, by not out-competing the maize, or by not overcrowding the maize; all of which ensures good production.	★★ it doesn't mix well with maize because it competes for light, it takes too long to mature which increases competition, or it over crowds the maize with many leaves. This reduces the yield.	★ It affects how the maize grows because it overcrowds it or grows taller than it so the maize receives less light, which is necessary for production.	★★ It doesn't resist rain or infertile soils. In the maize there is less competition and it produces many pods, thus ensuring the production of both beans and maize.	★★★ In the High, it doesn't perform well in the IC due to competition for light, nutrients, and leaf shedding. It doesn't resist rainfall in High, but in Mid some farmers say it does.	★★ Mixtures provide resilience to variations in edaphic features and climate; but there is increased competition in the mixture due to different growth habits and time to maturity.

Stars indicate the frequency with which comments were made for that specific thematic category and genotype. ★★★ indicates ≥ 20 comments, ★★ indicates ≥ 10 comments, and ★ indicates ≤ 10 comments.

Table 2.8 (cont'd)

THEMATIC CATEGORIES Themes	GENOTYPES					
	GASILIDA (B1)	RWV 3006 (B2)	RWV 2070 (B3)	RWV 3316 (B4)	NGWINURARE (B5)	IMVANGE (B6)
MARKET & LABOR ATTRIBUTES Market Labor & stakes	★★ It's highly valued on the market due to various qualities. It can sustain itself without any support.	★ This variety is unknown to sellers and buyers. The vine must be oriented everyday.	★★ it's less valued on the market, sometimes because it is not known to the buyers. Long and strong stakes are needed to support it and they are difficult to find.	★ It is highly valued on the market which increases the welfare of farmers. It is short so it is easy to find stakes.	★ Some value it for its qualities on the market, but others say it is not valuable compared to other seeds. The leaves naturally fall off, reducing work for the farmer.	★★ Depending on the location, the value of mixtures varies. There is more labor involved in harvesting b/c seeds mature at different times.
NUTRITIONAL & COOKING VALUE Cooking qualities Nutrient qualities	★★ It tastes sweet and has various nutrients necessary for the human body.	★ It tastes sweet and one said it didn't require much fuel. It's full of protein, calories and various vitamins for the body.	★★ It "gives less difficulties to cook because it is not very hard by nature."	★★ It tastes so sweet and fresh leaves fight hunger. It has various nutrients and it "resembles meat and the proteins it shares with meat."	★★ It tastes very sweet to eat, has various important qualities for the human body, and it requires less fuel for cooking.	★ Mixtures are difficult to cook well because some varieties are ready while others need more cooking time.
OTHER Aesthetic Information life-span	★ It grows very well from the beginning, which ensures good production.	★★ Farmers lack knowledge about the variety so they don't know how to handle it or market it.	★ It grows well which leads to high production.	★ "It looks so nice in the garden, and on the plate." Grows well from the beginning.	★ Difficult to plant because the farmers don't know the genotype.	★ Various seeds are available to the farmer when they grow mixtures.

Table 2.9 Emergent themes from interview data in Season 2 in Northern Province, Rwanda. Text are direct quotes.

VARIETY CHARACTERISTICS	**WAYS FARMER DETERMINE SUITABILITY FOR AN INTERCROP**	
	OBSERVATIONS AND EXPERIMENTATION	COMPARISONS
Trait-based competitive ability	“There are varieties that have many leaves which can affect the maize, the ones that don't have many leaves are better in the intercrop.” “Imvange produces pods at different places, some at the bottom, some in the middle, some at the top. Imvange also doesn't make competition to the maize in terms of making it fall down because the stems aren't big.”	“B5 doesn't make competition to the maize and the maize doesn't compete with the beans.” ‘How so?’ “Because it doesn't have too many leaves and the stems are not big. If I compared B5 with B3 – B3 is tall and grows beyond the maize and can make it fall down. B5 will not and doesn't grow that tall.”
Intrinsic competitive ability	“When a bean can resist in the maize. When rain stops there is drops from the maize onto the beans that some beans resist and some beans don't.” “To tell if a variety works well in the intercrop, we use a single variety and see if there is resistance to the maize. We test a single variety by itself in the intercrop, not as a bean mixture.”	“When I saw B1 in the maize and compared it to B3, B1 grew well to the maize and has resistance in this region.”
Universal plant traits	“When there is good production: there are lots of pods, and there are many seeds in the pods. When the leaves are fresh and big. There are more flowers and the beans are beautiful.”	“If everything in the soil is the same. There is high production, more flowers, and more pods. If there are no birds during flowering and the taste is good. As in B1, it's okay in the maize and comparing it with nyiragisenyi, B1 is better. In B1 I harvested 400g whereas with nyiragisenyi I only harvested 300. It also tastes better.”

Table 2.9 (cont'd)

Adaptation	"When the sun is strong beans are better, the maize leaves protects the beans from hail and even from the sun so flowers don't fall off from the weather." "When some of the beans survive it means they have resistance to the soil, the beans are used to the soil. Different ones survive each year. When there are three-four varieties, 1 remains because the rest die – so it has the ability in soil and resistance to the soil. I keep the survivor and I don't replace it with new types or mixtures."	"The mixture has resistance to this region and the other varieties do not." "I hope to harvest more beans this season because last season wasn't good. B1 is good in the intercrop, B2 is good in the mono." 'How is B1 different then B2? What about it?' "B1 and B5 can grow anywhere, in each place, but the others can only grow in the good places."
Management	"There should be more spacing – beans should be further apart when there is maize."	"I first plant maize at a large distance. The spacing for the baby trial was very close – if use 70 cm between maize plants (it is better) and then plant nyiragisenyi. The day that you plant the beans you accumulate the soil so the plants grow well. Then you will get maize yields too."

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CHAPTER 3 Simplification of maize-bean cropping systems: tradeoffs assessed through field experience in Rwanda

Chapter 3 Abstract

Smallholder farmers in Rwanda are both producers and consumers, growing various crops to maintain dietary diversity and for exchange of goods and services on the market. With the implementation of a crop intensification policy in 2008, these mixed cropping systems are disappearing. Under this policy, farmers in Northern Province are incentivized to grow climbing bean monocultures in season B (S1) and maize monocultures in season A (S2). These single-crop recommendations are in contrast to the systems farmers traditionally grow and may change the services the cropping systems provide. To identify trade-offs in cropping systems, we assessed maize and bean monocultures (MC) and two different maize-bean intercrops (IC), in two environments during two seasons in Northern Province, Rwanda. System performance was analyzed in terms of grain yield, protein content, caloric value, and economic returns including market value and land-use efficiencies. Results showed government crop and season recommendations were appropriate in terms of grain yield production. In S1, mean bean yields ranged from 1.7-4.4 mt/ha, whereas in S2, mean bean yields ranged from 1.0-3.0 mt/ha. Conversely, in S1 mean maize yields ranged from 1.4-6.4 mt/ha and in S2 they ranged from 1.9-8.8 mt/ha. Total protein content was highest in systems with beans and kilocalorie content was highest in systems with maize. Mean protein content was 500g/ha in the maize MC and approximately 800g/ha in the ICs and bean MC. Mean kilocalorie content ranged from 11.3 Mcal/ha in the bean MC to 22.4 Mcal/ha in the IC. Mean land-use efficiency was higher in the IC (1.38) than all other systems (1.00-1.19). Economically, the IC was the most lucrative across seasons in 8 out of 10 price scenarios. Considering nutritional and economic returns, IC systems

resulted in better returns than a single MC for a subsistence farmer with limited land but this was dependent on both site and season. Though the single crop per season policy in Rwanda aims to improve rural incomes and agricultural sector viability, it fails to acknowledge the multiple and currently non-replaceable services provided by diverse cropping systems. Overall, this policy could reduce farmer ability to meet these needs. Farmers plant diverse cropping systems to produce a range of services and these factors should be taken into consideration when analyzing a system.

Introduction

Agronomic and ecological assessments of intercropping systems have been explored extensively (Vandermeer, 1992; Connolly et al., 2001; Seran and Brintha, 2010; Lithourgidis et al., 2011) but evaluating them based on farmers' expectations of the system is less common. The main advantages of an intercropping system are the potential for increased resource efficiency (Trenbath, 1986; Francis, 1989; Ghanbari et al., 2010) and the mitigation of risk associated with crop loss (Jodha, 1980; Lithourgidis et al., 2011; Rusinamhodzi et al., 2012). As a result, most of the agronomic and ecological studies have looked at competitive and facilitative dynamics (Vandermeer, 1992; Midmore, 1993; Hauggaard-Nielsen and Jensen, 2005; Andersen et al., 2007; Li et al., 2014), light-use efficiency (Keating and Carberry, 1993; Tsubo and Walker, 2002), resource-use efficiency in terms of land (Mead and Willey, 1980) or nutrients (Stern, 1993; Li et al., 2003; Szumigalski and Van Acker, 2006) including water-use (Morris and Garrity, 1993), while still others have explored economic returns (Francis and Sanders, 1978; Mucheru-Muna et al., 2010), cultural pest control (Trenbath, 1993; Bourdreau, 2013), and of course productivity (Fukai and Trenbath, 1993). Scientists also study the biodiversity found in species rich cropping systems to understand the potential ecosystem services provided by the system (Altieri, 1999; Hooper et al., 2005, Thrupp, 2000; Tscharntke et al., 2005; Kremen and Miles, 2012). The majority of this body of literature is focused on the important mechanisms underlying potential intercrop advantages, but farmers are concerned with the more immediate services the cropping systems provide such as reducing crop loss and having sufficient food, nutritional diversity, economic returns, and maximized return from limited land and input resources.

Agroecologists look at the mechanisms driving intercrop advantage, while farmers are thinking about the tangible benefits of growing multiple crops. Intercropping and monocropping systems are generally designed to provide different services but the assessment of the system doesn't always take this into consideration. Intercrop systems are traditionally grown by smallholder farmers for consumption to meet provisional needs and income requirements whereas monoculture farmers are more likely to grow cash crops to exchange on the market for provisional needs and income. Both systems are assessed based on efficiency, yield, labor requirements, and factors affecting yield such as disease and insect pressure. While constructive, this type of evaluation developed in the context of highly controlled mechanized agronomic conditions and efficient and functioning markets. Traditional systems, on the other hand, have developed over generations of practice and observation of natural ecosystems and are designed to elicit multiple provisional services (Power, 2010). These systems are often reliant on integrated management of local natural resources (Malezieux, 2012) because efficient markets and input resources are unreliable or don't exist. Farmers that use these systems have different needs that are specific to their own agronomic and socio-economic situations (Ashby and Sperling, 1995) and are embedded within culture and local knowledge systems.

The assessment of the services these cropping systems provide to the farmer may be more meaningful if done in the social and environmental context in which the system exists, and incorporates the expectations that farmers have of the system. We explored some alternative methods of intercrop assessment and evaluated the provisional services farmers expected from the cropping system in a case study of bean and maize cropping systems in Rwanda.

Methods of assessing intercropping systems

Analysis of intercropping systems is complex because the component parts of the system have unique units of measurements. In order to analyze these systems, the principle of comparing "like with like" must be adhered to (Mead et al., 1986). In a bean and maize system, simply comparing yields of each crop would be misleading. Several different methods have been used to assess the systems and these include measures of biological efficiency and conversion to nutritional or economic units such as protein or dollars.

To assess biological indicators of cropping system viability, researchers frequently use the Land Equivalent Ratio (LER), which compares relative yield per unit land area. The LER indicates how much land is necessary to produce an equivalent yield in an intercrop of two separate monocrops (Vandermeer, 2011). Such a measurement may be the most relevant in contexts where farmers face land constraints because it indicates the most efficient use of land. However, there are some disadvantages to the measure. Vandermeer (2011) argues it should be computed for an optimal system design rather than for one particular design, and it should only use an optimal monocrop for comparison. But this merely turns the LER into a theoretical concept rather than an applied measure with relevance to a specific context. Importantly, an optimal system must be optimal in the local context and preferences of smallholder farmers. The optimality of the system is not based purely on biological factors, but defined by the contextual social-ecological reality. Farmers design an intercropping system based on its multi-functional properties and these properties fulfill only a portion of services farmers desire from their entire farming system. While these systems may fail to be optimally multi-functional, a comparison of this system to an optimal system based solely on biological parameters outside of the regional context is inappropriate. Alternatively, Federer (1993) suggests using external data within the region to determine the mean yield on-farm. This method maintains the comparisons within the local environmental context.

Besides LERs, yields can be converted to a single scale of measurement for comparison. Frequent scales include conversion of yields to protein content or kilocalories, and market value. These measures, combined with LER of the intercropping system may more accurately reflect the multi-functional uses, including economic returns and nutritional value, farmers desire from a cropping system.

Traditional cropping systems in Rwanda

Rwanda is one of the most densely populated countries in Africa and approximately 82% of the population is engaged in small-scale food production (NIRS, 2009). Landholdings are small and often scattered within one household, with more than 60% of farm households cultivating less than 0.5 ha (MINIAGRI, 2012) and 40% of crops grown on steep slopes prone to heavy erosion. Food crops account for 92% of the total land cultivated while cash crops coffee and tea account for 6.3 and 1.6%, respectively (PSTA II, 2009). The traditional farming systems found in the Rwanda highlands are representative of other highland agriculture in East Africa where over 65 million people cultivate mixed cropping systems (Garrity et al., 2012). Farmers traditionally grow at least four to ten crops in both polycultures and monocultures, with common beans (Phaseolus vulgaris L.), bananas (genus *Musa*), maize (Zeas mays L.), and sweet potatoes (Ipomea batatas) dominating (Voss, 1992). Farmers also use mixed varieties of a single species and maintain them for different soil types and cropping patterns (Saad et al., 2003).

Beans are one of the most important staple crops in Rwanda and the main source of protein for Rwandan smallholder farmers. They are grown by 95% of farmers in all major regions of the country (Sperling and Berkowitz, 1994). Bean consumption per capita in Rwanda is one of the highest in the world with an average annual consumption of 48kg per year (Broughton et al., 2003) and the grain, leaves, and pods are consumed (CIAT highlight 41; Sperling et al., 1993).

Agricultural Policy in Rwanda

The diverse cropping systems found in Rwanda did not develop without the guidance of agricultural policies. At least as early as colonization, governance has played an important role in formulating agricultural structure in the country (Kangasniemi, 1998). Historical records indicate that crop diversification was pursued early on as a means to improve food security (Kangasniemi, 1998) and more recently policy has promoted the intensification of agriculture production under the Strategic Plan for the Transformation of Agriculture in Rwanda (PSTA I&II, 2004-2012). The principal goal of PSTA is to improve the livelihoods of rural Rwandans through the commoditization of agricultural production. One of the main components of the policy, the Crop Intensification Program (CIP), promotes a shift from the traditional segmented landholdings that produce diverse crops to consolidation of parcels that produce single crops. Monocultures, land consolidation, and the use of subsidized inputs are highly encouraged while traditional systems intercrop systems are discouraged and even banned (Huggins, 2011). In contrast to the government-directed intensification strategies being pursued in Rwanda, there is increasing global support in agricultural research for ecologically-based cropping systems that integrate biodiversity and landscape-level resource management (Snapp et al., 2010; Malezieux, 2012; Jackson et al., 2012).

While PSTA aims to improve cultivation practice and develop sustainable production systems, the implementation of the program in the form of requiring monocropping may ignore some of the benefits farmers derive from multi-crop agricultural systems and may expose farmers to higher risks associated with such narrowly defined agricultural systems (Walker et al., 2010). In addition, the impact of transitioning from a food-based agricultural system to a market-based system in marginalized regions of Rwanda is unknown.

In this paper we consider four cropping systems and the impact of intensification, e.g. the transition to monocultures, on the various services Rwandan farmers expect from farming systems. The primary objective of this research was to compare some of the services provided by maize and bean monocropping systems with intercropping systems. Performance indicators of the cropping systems included evaluation of grain yield produced, protein and kilocalorie content, land-use efficiency, and market value. The field experiments were carried out over two seasons and in two environments to understand how cropping systems and their associated services are affected by different environments.

Methods

Site and soil description

Research trials evaluating four cropping systems were conducted on two research stations for two seasons in the sub-humid tropics of northern Rwanda. The two field stations, Rwerere and Musanze are located in Northern Province at S 01.48611 E029.87675 and S 01.49842 E 029.62843, respectively. Musanze Station (MS) is a mid-altitude site at 1850 m.a.s.l. and Rwerere Station (RS) is a high-altitude station in the Buberuka Highlands at an altitude of 2100 m.a.s.l.

The areas have a bimodal rain distribution with the “long” rains occurring in March, April, and May and the “short” rains occurring in October, November, and December. Approximately a third of annual rainfall falls in each of these periods. The growing seasons extend on either side of these rainy seasons. The first cultivable season A is from September to

January and the second cultivable Season B extends from late February through June. Yearly rainfall ranges from 1300-1600 mm in the highlands of Northern District.

Located near the equator, average temperatures do not vary greatly over the year. Seasonal variation in temperature is low and mean monthly temperatures range from 14-17 C. However, diurnal variation in temperature is high, often as much as 10 C or more. Low temperatures range from 10-13 C and high temperatures range from 23-25 C.

Multiple soil types and heterogeneous microclimates exist in Northern Province. The soil classification for MS is an umbric slandic Andosol characterized as a nutrient rich volcanic loam while RS is a dystric Regosol (Entisol) characterized as a well-drained clay soil (Jones et al., 2013).

Experimental design and layout

Four cropping systems were planted in a randomized complete block design (RCBD) in Season B 2011 (S1) and Season A 2012 (S2). The cropping systems were a maize monoculture (MO), a bean monoculture (BO), an intercrop of maize and beans in rows (IC), and a traditional intercrop of maize and beans (TC) not planted in rows. The experiment was designed to test cropping systems and genotype by cropping system factors, with six bean genotypes included. This paper focuses exclusively on analysis of the cropping systems and excludes genotype analysis.

The randomized complete block design of the four cropping systems consisted of 14 treatments. There were five bean genotypes, one bean mixture, and one maize genotype. Each of the five bean genotypes was planted in a monocrop and an intercrop with maize. The bean mixture was planted in a monocrop, an intercrop with maize in rows, and a traditional intercrop with maize. Maize was planted in a monocrop. Blocks were replicated four times at the two stations, for two seasons with a new site each season, so the experiment was replicated over time and space four times.

All of the maize and climbing bean varieties were adapted to the region. A ubiquitously grown open-pollinated maize variety originally selected for the Volcanic Highlands of Rwanda, Pool9A (Highland Late White Dent) (Friesen and Palmer, 2004) was used in all trials. All climbing bean genotypes were large seeded Andean Type IV cultivars. The five bean varieties included Gasilida, RWV 3006, RWV2070, RWV3316, and Ngwinurare. Gasilida was an improved farmer developed variety; RWV3006, RWV2070, and RWV3316 were improved CIAT varieties tested further in Rwanda for release; Ngwinurare was an old CIAT variety introduced in Rwanda in the 1980s and a regional check. The bean mixture was a local check and consisted of 3-5 bean types mixed by farmers and was different in each site.

All 14 plots were represented in each block. Individual plots within the block were 3 m x 4 m. There was uniform spacing between plots (0.75 m) and 1.0 m between blocks. According to farmer practice, the maize was planted first and the beans were planted 29-31 days later in every treatment.

The monocrop system plant densities (MO and BO) were planted according to research recommendations. In the MO, between the row spacing was 0.75 m and the distance between each plant within the row was 0.25 m. Two seeds were planted per hole for a total plant population of 106,700/ha. In the BO, between the row spacing was 0.50 m and the distance between each plant within the row was 0.20 m. Two seeds were planted per hole for a total plant population of 200,000/ha.

The intercrop systems plant densities were according to researcher design for the IC and farmer design for the TC. For the IC, beans and maize were planted together in the same row.

Between the row spacing was 0.75 m and the distance between each individual plant in the row was 0.10 m. Two maize seeds were planted every 0.30 m in the row and thinned to a single plant at the same time at the time of bean planting. Two bean seeds were planted every 0.10 m from the next plant and thinned after emergence to a single plant. All rows were started with a bean seed. The beans flanked the maize such that two bean plants grew up a single maize plant. The maize and bean populations in the IC were 44,400 and 106,700 plants/ha respectively, for a total plant population 151,100/ha.

In the maize-bean traditional intercrop (TC) 2 maize seeds were planted per hole in a scattered pattern throughout the plot. Twenty-nine to 31 days later, 2-3 bean seeds were planted in different holes. There were no rows. Farmers planted a much higher density of beans to maize. The maize and bean populations in the TC were 75,000 and 458,300 plants/ha respectively, for a total plant population of 533,300/ha.

Field Management and data collection

All trials were weeded at bean planting and at least once more as needed during the season. Beans were staked with straight poles except at MS S1 where a combination of tripods and straight poles were used. At MS S2, many maize seedlings were washed out by heavy rains, particularly in the TC. These were replanted 2 weeks after the initial planting.

Inorganic fertilizer (DAP) and organic material were applied at a rate of 100 kg/ha (0.12 kg/plot) and 83 kg/ha respectively, according to farmer practice (in the row for MO, BO, and IC; in the hole for TC) at maize planting. Urea was applied to the base of maize plants mid-season to all plots.

Grain yield of maize and beans was collected. For grain yield, the entire plot was harvested (3 m x 4 m) and moisture content was corrected to 12% and 15.5% for beans and maize, respectively. Plant population was counted at harvest in the middle three rows and averaged.

Analysis

Protein and kilocalorie contents were calculated based on USDA standards for mature, raw, uncooked maize and beans (USDA, 2013). Maize had 9.42 g of protein per 100 g of grain and beans had 23.58 g per 100 g of grain. Maize had 365 kcal per 100 g of grain and beans had 333 kcal per 100 g. Total protein and kilocalorie content were then calculated from the grain yield for each cropping systems on an area basis (1 ha).

To determine the economic value of these cropping systems, we analyzed the yield data in terms of two types of land-use efficiency and market value. The land-equivalent ratio (LER) was calculated as $LER= y_i/y_{ii} + y_j/y_{jj}$ according to Trenbath (1999) where y_i and y_j are the yield ha^{-1} of the bean and maize intercrop components *i* and *j*, and y_{ii} and y_{ii} are the corresponding yield ha^{-1} of the sole crops planted at optimum density and in the same conditions of soil and crop management as the intercrop. For the sole crop data (the denominator), data from all four sites was averaged. The crop yields on-station were higher than the corresponding regional data hence such data was not used to evaluate the land-use efficiencies because it would falsely improve the efficiency of these cropping systems.

As an alternative conceptualization of land-use efficiency, we calculated the expected yields of each cropping system on a per unit land area basis. We assumed a farmer had one hectare of land and could choose to grow the entire hectare under a monocrop of a single crop, a maize-bean intercrop, or split the hectare into two half hectares and plant a half-hectare in a bean monocrop and a half-hectare in a maize monocrop. Grain yields in the half-hectare plots are simply half the yield of that cropping system on one hectare.

The systems were compared in terms of monetary value per hectare. We compared the BO and the MO to the intercrop systems (IC and TC) using five price scenarios to reflect changing prices on the market. In the base scenario, the price of maize and beans per kilogram was the same, 200 Rwandan Francs (RWF) per kilogram. In all of the other scenarios, the difference in price between beans and maize is 0 or 100 francs, a conservative difference. At the time of research, farm gate prices for a kilogram of improved bean varieties and traditional bean varieties were 500 RWF and 300 RWF, respectively. Maize cost between 120-180 RWF/kg. Scenario 1 was most similar to market prices at the time of research. We looked at all possible combinations of this price difference between crop and season and calculated the monetary value of one hectare of each cropping system for each season. The total value of the IC or the TC for each season was subtracted from the total value of the highest valued monocrop for that season and location, either maize or beans. In every location and season except RS S1, the MO was more valuable than the BO. In all scenarios of RS S1, and RS S2 Scenario 1, we subtracted the highest valued system, BO, from the value of the IC. These values were then summed for the two growing seasons. If the value Y = Intercrop – Monocrop was negative, then the monocrop was more valuable. The total value per hectare was converted to dollars at an exchange rate of 600 RWF for $1.00. This was the approximate exchange rate at the time of research.

Statistical Analysis

The software package SAS was used for statistical analysis. The grain yield and nutritional comparisons of cropping systems were analyzed using PROC MIXED with a model including fixed effects of cropping system. Random effects were season, location, and replicate. To address the different number of treatments in each cropping system in the experimental design, treatment was dropped from the model and contrasts were used to further splice the data when an interaction occurred. In the factors season and location there were significant interactions with cropping systems, except maize yield. There was no significant interaction between locations and cropping systems for maize yield, however there was a seasonal interaction. Subsequently, all comparisons were conducted separately for site and season. Planned contrasts between cropping systems were used to identify differences in yield, protein, and kilocalorie content.

Results

Environment

Rainfall were within regional averages that range from 1300 mm to 1600 mm. Rainfall in 2011 totaled 1429 mm with 534 mm in S1 and 610 mm in S2 (Figure 3.1). The remaining precipitation occurred in off-season months. In 2011, rainfall in the month of August was higher than average with 141 mm while September was lower than average at only 50 mm.

Average temperatures do not vary greatly over the year. Seasonal variation in temperature is low and mean monthly temperatures range from 14-17 C. However, diurnal variation in temperature is high, often as much as 10 C or more. Low temperatures ranged from 10-13 C and high temperatures ranged from 23-25 C. The differences between daytime and nighttime temperatures ranged between 4-7 C at MS and between 2-8 C at RS. Due to the higher elevation, RS was on average a degree C or two cooler than MS.

Soil types and nutrient contents were different at each location (Table 3.1). RS soils were higher in Organic C (2.46-2.70%) than MS (1.29 - 2.19%). Total N at RS was higher in both seasons (0.27-0.29%) than at MS (0.21-0.13). Phosphorous was highest at MS S1 (297.0 mg/kg) due to legacy effects, and it was the lowest at RS S2 (14.5 mg/kg). Within the same season, P content was more than four times higher at MS than at RS. The pH of all the soils was between 5.53 (RS) and 6.00 (MS).

Yields

Total grain yield varied between cropping systems. Averaged across seasons and sites, the total grain yield of the system was the highest in the IC (6.2 mt/ha) and the lowest in the BO (3.4 mt/ha). The MO and the TC had similar total grain yields (bean + maize) both averaging 5.1 mt/ha. The overall yield stability also varied between cropping systems. Bean and maize yields showed the least variance about the mean in the IC in all factors.

Bean yields varied between cropping systems. Bean yields averaged across seasons and sites were highest in the BO (3.4 mt/ha), followed by the TC (1.9 mt/ha) and the IC (1.5 mt/ha) (Table 3.2). In the IC, bean yields were reduced by more than half and in the TC, with a much higher plant population, there was less reduction.

There was less variation in maize yield between cropping systems. Maize yields averaged across seasons and sites were highest in the MO (5.1 mt/ha), followed by the IC (4.8 mt/ha) and the TC (3.1 mt/ha). Overall, maize yields were lower in the IC, but on a seasonal basis, there was no significant difference between maize yields in the IC and the MO. The TC had a substantially lower maize plant population than the IC.

Grain yield of beans and maize varied between cropping systems and there were significant differences between seasons and sites. Comparing seasons, beans yielded higher in S1 than S2 in all of the systems, and maize yielded higher in S2 than S1, except in the TC MS S2. Likewise, there was a location effect. In all scenarios except TC MS S2, bean yields were higher at RS than at MS and maize yields were higher at MS than at RS. In the TC MS S2, there was more damage than in the other systems to the maize plants from heavy rains and this reduced final plant population and likely maize competition with the beans. Further comparisons are at the seasonal and location level.

Bean yields were higher in S1 than in S2. Bean yields in S1 in the IC ranged from 1.7 at MS to 1.9 mt/ha at RS, whereas in S2 they ranged from 1.0 to 1.2 mt/ha. In S1 in the TC, bean yields ranged from 1.8 at MS mt/ha to 2.4 mt/ha at RS, whereas in S2 they ranged from 2.3 to 1.4 mt/ha, respectively. In S1 in the BO, bean yields ranged from 3.7 mt/ha at MS to 4.4 mt/ha at RS, whereas in S2 they ranged from 2.6 to 3.0 mt/ha. In S1 and S2 at both locations, the BO bean yields were significantly higher (<0.0001) than the IC and the TC. Except in S2 at MS where the TC was not significantly different than the BO.

Maize yields were higher in S2 than in S1. Maize yields in S1 in the IC ranged from 5.8 at MS to 1.9 mt/ha at RS whereas in S2 they ranged from 7.4 to 3.9 mt/ha. In S1 in the TC, maize yields ranged from 4.8 at MS mt/ha to 1.4 mt/ha at RS whereas in S2 they ranged from 4.5 to 1.9 mt/ha, respectively. In S1 in the MO, maize yields ranged from 6.4 mt/ha at MS to 2.0 mt/ha at RS whereas in S2 they ranged from 8.8 to 4.0 mt/ha. In MS S1 in the IC, there was no statistical difference between systems. In the remainder of the sites and seasons (MS S2, RS S1 and S2), the TC was statistically lower than the other systems. Otherwise, there was no difference in maize yield between the IC and the MO.

Protein

Converting the grain yields to grams of protein content per hectare allowed us to compare all components of the cropping systems in a single unit (Table 3.3). Averaged across all seasons and sites, the total protein content of the cropping system was the same in the BO and the IC (800 g/ha), followed by the TC (750 g/ha), while the MO was much lower (480 g/ha).

In both seasons all the cropping systems at MS had more protein per hectare than any system at RS, except the BO. The BO at RS had the most protein content of any system in S1. In general, systems with beans or beans and maize had the highest protein content and the MO almost always had the least amount of protein.

The seasonal and location effects on yields were compounded in the protein analysis of the cropping systems. In S2 MS, the season and location with a maize advantage, the MO (830 g/ha) out performed the BO (610 g/ha) in terms of protein. Likewise in S1 RS, the season and location with a bean advantage, the BO (1030 g/ha) had more protein than any other system (190 – 690 g/ha).

The protein content varied across seasons and sites. In S1 MS, protein content was similar in the intercrops and BO (870 – 950 g/ha) but statistically different from the MO (610 g/ha). In S1 RS, the BO had higher protein content (1030g/ha) followed by the TC (690 g/ha) and IC (620 g/ha). The protein content of MO was the lowest, at 190 g/ha.

In S2 MS, protein content in the IC (950 g/ha) and the TC (950 g/ha) were similar. The MO had higher protein content (830 g/ha) than the BO (610 g/ha), but it wasn't statistically significant. In S2 RS, the protein content was similar in the BO (700 g/ha) and the IC (660 g/ha). The MO and the TC were much lower at 380 and 470 g/ha, respectively.

Kilocalories

Grain yields were also converted to kilocalorie content on a per hectare basis (Table 3.4). Averaged across all seasons and sites, the total kilocalorie content of the cropping system was highest in the IC (22.4 Mcal/ha) and the MO (18.5 Mcal/ha), followed by the TC (17.8 Mcal/ha). The BO had the lowest amount of kilocalories at 11.3 Mcal/ha. In general, systems with both maize and beans or maize had the highest kilocalorie value while the system with only beans (BO) had the least.

In both seasons all the cropping systems at MS had more kilocalories per hectare than RS, except BO. The BO at RS was higher than the BO at MS both seasons because the bean yields were higher. Systems with maize were detrimental to kilocalories content per hectare at RS whereas these systems were adventitious at MS.

The kilocalories per hectare varied across seasons and sites, and systems with maize were adventitious (Table 3.4). In S1 MS, kilocalorie content was similar in the intercrops and MO (23.5 – 26.9 Mcal/ha) but statistically different from the BO (12.3 Mcal/ha). In S1 RS, the BO and the IC had more kilocalories (14.6 and 13.2 Mcal/ha, respectively) followed by the TC (12.9 Mcal/ha) and the MO had the least (7.2 Mcal/ha).

In S2 MS, there were more kilocalories in the MO (32.2) and the IC (30.6) and they were statistically different that the TC (23.8) and the BO (8.6). In S2 RS, the kilocalories were highest in the IC (18.4) and the MO (14.5) and lowest in the TC (10.9) and the BO (9.9)

Land-Equivalent Ratio

The LER is a way to determine the land-use efficiency of the cropping system. Values greater than 1.0 indicate the intercrop yields more on the same amount of area as growing respective monocrops. Averaged across the seasons and sites, the LER was higher than 1.0 in both the IC (1.38) and the TC (1.19). Averaged across the year at each location (more indicative of how a farmer might analyze the system), the IC is the most efficient system at MS (1.72) and the BO (1.09) and the IC (1.04) are the most efficient at RS. However, there were season by location interactions in the yield data and subsequently in the LERs (Table 3.5).

LERs fluctuated based on the crop yield advantage for each seasonal and location. In S1 MS, the LERs for every system were above 1.00 and ranged from 1.09-1.65. The IC was the best system and the BO was the worst system in terms of LER. In S1 MS systems with maize were more efficient. In contrast, in S1 RS, the BO was the most efficient system at 1.29 and the only system with an LER greater than 1.00. The MO had the worst LER at 0.39. In S1 RS systems with maize were detrimental to land-use efficiency.

In S2 MS, all of the systems except the BO (0.76) were above 1.00, ranging from 1.55 to 1.78. The IC (1.78) and the MO (1.74) were the most efficient systems. In S2 RS, the only LER above 1.00 was the IC (1.14). Systems with maize were still detrimental to efficiency at RS.

Alternative Land-Equivalent Ratio

Alternatively, we calculated the land-use efficiency in terms of yield on a single hectare of land. Results were similar to the LER; this is only a different method for conceptualizing land-use efficiency in terms of farmer reality. In table 3.6, monocrop yields of beans on ½ ha and maize on ½ ha were compared to intercrop yields on 1 ha. Averaged across all seasons and sites, growing an IC yielded the highest amount of grain (6.2 mt/ha) as compared to 1 ha of a MO (5.3 mt/ha) or a TC (5.1 mt/ha). Growing 1 ha of BO yielded the least grain (3.4 mt/ha). Growing ½ ha of each crop also yielded less than the other systems (4.4 mt/ha). Separated by location and averaged across the season (1 calendar year), the results were the same: growing an IC yielded the highest total grain.

There was a season by location interaction. In S1 RS, 1 ha of BO (4.4 mt/ha) was the best system while in S2 MS, 1 ha of MO (8.8 mt/ha) was slightly higher than 1 ha of IC (8.5 mt/ha) (Table 3.6).

Price Scenarios

The price scenarios indicated the value of the cropping system if sold at various market prices. On average, the IC was more profitable than the best performing monocrop and the best performing monocrop was more profitable than the TC (Table 3.8). The IC was more profitable than the best monocrop in 8 out of 12 scenarios. The TC on the other hand, was less profitable than best monocrop in 11 out of 12 scenarios.

In the price scenarios, both locations had the opposite results for each season and these matched earlier observations from the yield data that the best season and location for beans was S1 RS, and the best season and location for maize was S2 MS.

In S1 MS, the IC was more valuable in all scenarios and had the highest value in scenario 1 when beans cost more than maize (647 $/ha) (Table 3.8). Even when beans and maize were the same price (base and scenario 3), growing an IC was more profitable than an MC.

In S2 MS, the MC was the most profitable cropping system except in scenarios 1 and 5. In scenario 1, the most realistic price scenario, the IC yielded $64 more than the monocrop. The IC was the worst option in scenario 2 (-$337).

The results were the opposite at RS. In S1, growing an IC instead of a BO generated the most loses ($194 - $923), except in scenarios 2 and 3 where an IC was more lucrative (Table 3.6). The higher prices for both beans and maize in these scenarios compensated for low maize yields at RS. Growing a BO in scenario 1was very profitable ($605). When bean prices were low in scenarios Base and 4, the MC of beans was still better than the IC. In S2 RS, an IC was highly profitable in every scenario and earned between $380 - $599 more than a monocrop.

To determine the best cropping system to grow year round, we summed the value of the system across seasons. The IC was profitable at both locations in most price scenarios. But importantly, it was not lucrative in scenario 1 at RS. A monocrop was more lucrative than the TC in almost every scenario at either location.

Discussion

Yields

Total grain yield was the highest in the IC system when data were averaged across sites and seasons. The total grain yield advantage of the IC changed in the seasons and sites where there was an advantage for a specific crop (S1 RS and S2 MS). There was a location effect on the yield of both crops whereby maize performed the best at MS and beans performed the best at RS. Total maize yields at MS for both seasons were more than double maize yields in every system at RS. Bean yields were higher at RS than MS, with RS yielding approximately 1 mt of beans more than MS over the year. A seasonal effect was also at play, whereby beans performed the best in S1 and maize performed the best in S2. This two-way interaction resulted in a clear total grain yield advantage for the monocrop in the optimal season and site for that crop. This advantage was diminished in the off-season and site, resulting in the IC being more advantageous in a calendar year in most scenarios, and in most other units of comparison. These patterns are consistent with known seasonal factors for the region: it is well known that beans grow better in the longer rainy Season B (S1) and maize grows better in the short rains Season A (S2). Land-use policies require farmers to grow accordingly to these seasonal factors.

In the intercropping systems, the maize yields were not influenced by the presence of beans, but beans did suffer a significant yield loss. The cropping system substantially influenced the yield of beans, as bean yields in the IC were between 12-62% less than the yields in the BO. These findings are similar to the majority of research on intercropping bean and maize systems. Cardoso et al., (2007) observed that a non-climbing vine Type III bean cultivar yielded half to two thirds as much in the intercrop and Francis (1982) observed in a simultaneous planting of Type IV climbing beans with maize a 52% reduction in bean yield. More recently in the sub-humid highlands of western Ethiopia, Gebeyehu et al., (2006) observed a 75-91% reduction in bean yields in seven Type IV climbing bean varieties grown with maize. Most of the bean yield reductions in this study were between 45-62%, but the bean yield in the TC at MS saw only a 12% reduction in bean yields in S2. This was likely due to the poor maize plant stand in that treatment.

Most research suggests that the reduction in bean yields is due to the highly competitive nature of maize. However, the majority of studies on maize-bean intercropping systems are in maize dominant systems where maize is the principle crop of concern (Gebeyehu et al., 2006). In contrast, farmers in Rwanda view beans as primary and maize as a secondary crop thus the bean plant population was high in this study compared to other bean-maize intercrops. Even though beans were the dominant crop, there was significant reduction in bean yields in the intercrop systems. Bean yields were reduced by more than 50% in the IC while there were no significant differences between maize yields in the IC and the MO.

The reduction in bean yield is less when we consider yield in each system on a plant population basis. On a per plant population basis (see methods), the yield reduction in the intercrop was small for beans and there was actually an increase in maize yields (Table 3.7). The bean plant population in the IC is 53% of the population in the (optimal) BO resulting in a reduction in bean yields between 0-6% in the IC depending on the location and season. This means that the yield reduction in beans was primarily due to the reduction in the plant population in this modified replacement series intercrop and a small proportion of yield loss was due to competition with the maize. In addition, the maize plant population in the IC was 41% of the plant population in the optimal MO but there was no significant reduction in the maize yield between the IC and the MO treatments. In fact, on a plant population basis, there was a 23-36% increase in maize yields depending on the location and the season. In conclusion, on a plant population basis, there was a small 0-6% decrease in bean yields and a large 23-26% increase in maize yields in the intercrop compared to the monocrop of each component crop. Most intercrop studies show an expected reduction in yield in the intercrop (Connolly et al., 2001) but a proportion of this loss is due to the replacement of beans with maize and in this case, a much smaller proportion is due to competition.

The yield loss in the intercrops varied across the two seasons. In S2, the optimal season for maize, the bean yields in IC suffered a greater reduction in yield as compared to S1. Interestingly, in the same season (S2), at MS there was a greater reduction in maize yields, the best site for maize, whereas at RS the maize in IC performed as well as in the MO. At RS there was no significant difference in maize yield between the IC and MO, despite the maize population in the MO being more than double that of the IC. Differences between the TC and the MO are significantly different, but maize to bean plant ratios where much higher, at 1:6 in the TC verses 1:2.4 in the IC.

Subsistence farmers are highly vulnerable to fluctuations in yields due to both biotic and abiotic stresses and are subsequently risk adverse. Research has shown that farmers plant multiple crops to reduce the risk associated with crop failure. The yield stability of a cropping system, or the variability in yield from year to year may be a factor farmers consider when deciding which crop to grow. The variability in yield of the component parts of these cropping systems was lower for beans overall and the lowest in the IC treatments at each individual site and season except MS S1 where it was the same as the BO (0.10 mt/ha) (table 2, SE). The variability in yield for beans in the IC ranged from 0.08 to 0.1 mt/ha to 0.08 – 0.26 mt/ha for maize whereas in the monocrop systems the variability was 0.10- 0.20 mt/ha in beansand 0.30 – 1.25 mt/ha in maize. Environmental factors influence yield from year to year, and this variability is of importance to farmers that rely on yield for subsistence. In a review of multispecies agriculture in India, Trenbath (1999) observed that in two contrasting species of crop, the differing responses to environmental fluctuations might cause individual yields to be negatively correlated, as in this study. In this situation, the farmer will get a more stable food supply over time when they plant intercrops. Growing multiple crops in both seasons may be a form of insurance against crop failure and insufficient production.

Protein

The high protein content of beans is the most important nutritional advantage of the crop. Sources of animal proteins are limited in resource poor and land-limited northern Rwanda, increasing the value of protein-rich crops such as beans. The total protein content per hectare of the cropping systems varied between the two research stations and generally followed the yield data from which the protein content is derived. However, several differences arose due to the nearly threefold difference in protein content between beans (23.6g) and maize (9.4g). Combining both seasons at MS the intercropping systems, the IC and TC, provided the most protein over the entire year with 1900 and 1830 g/ha, respectively. In both seasons at RS the monocrop of beans, BO, provided the most protein per hectare with a combined total of 1730g/ha. The difference in protein content of each crop magnified the season and location interactions discussed earlier in the cropping system yield responses. Location and season had significant interactions, as did seasons within a location. As a result we looked at each factor separately.

Although maize provides only a third of the protein content that beans do, beans combined with the maize advantage found at MS made the intercrop systems the most valuable in terms of protein for each season and when summed over the entire year. In S1, the only system that was statistically different (<0.000) in terms of protein was the MO whereas in S2 only the BO was statistically different (<0.000) from the other cropping systems. These values reflect the marked benefits of growing beans in S1 and maize in S2 at Musanze Station. They also demonstrate that while maize has low protein content compared to beans, in appropriate environments the yield of maize can compensate for this deficiency through its yield advantage. Still, for subsistent farmers highly dependent on food crops for a protein source, in order to consume complete proteins (Bressani, 1973) in both seasons it is more advantageous to grow an intercrop of beans and maize.

At RS, a region that seems to have a comparative advantage in the production of climbing beans but a disadvantage for maize production, the bean monocrop provided significantly more protein compared to the other systems. Situated at 2100m (6,900ft) with slightly cooler temperatures than MS, RS is on the periphery of maize growing regions. Although the maize variety PL9A was developed for high altitude zones, the climatic conditions at RS and the highlands surrounding the station are not best suited to maize production. There was no significant different in maize yield between the IC and the MO at RS (>0.3509) but differences in bean yields between the IC and the BO were significant (<0.000). Maize yields were maintained in the IC whereas bean yields suffered in the intercrops.

In terms of protein, the maintenance of the maize yield in the intercrop systems doesn't compensate for the loss in the bean yield and the subsequent loss in protein in this region. Growing a monocrop of beans in both seasons and maize in S2 would ensure higher protein returns per area from bean yields while producing the equivalent maize yields. If the beans and maize were grown in an intercrop, there would be a decrease in the beans and a slight increase in the maize yields. Although maize yields are low in this region, maize does provide other advantages, including high caloric return for inputs that are not easily reproduced in another more suitable crop.

In regions such as these where market systems are imperfect and farmers are principally subsistent, culinary and dietary diversity are important for nutrition and well-being. Maize and beans are deficient in certain amino acids and each crop provides different sources of the 9 essential amino acids (Bressani, 1973). Bressani (1973) found that in a maize to bean ratio of 3 to 1, the two crops are complimentary and provide all of the essential amino acids. Thus the consumption of legumes and cereals together alleviates these mutual deficiencies ensuring a more balanced diet (Broughton et al., 2003).

The protein results reflected the higher suitability of beans at RS and maize at MS. Overall, if we only consider protein content, it is more advantageous to grow an intercrop or traditional cropping system at MS. At RS, it's more advantageous to grow a bean monocrop in both seasons due to the low yield of maize, however an intercrop of beans and maize may be advantageous in S2, the maize season. Based on protein alone, it is not worthwhile to plant maize only, even in highly suitable MS due to the low protein content and quality in the grain.

Calories

We used the same data from USDA to compare the cropping systems based on the caloric value. The potential value of maize in terms of yield per hectare and caloric content cannot be understated. While the calories per 100g of beans are not much lower (333) than maize (365) the yield potential of maize per hectare is much higher in the appropriate environment.

At MS, maize yields averaged over both seasons were more than double in the MO than bean yields in the BO, resulting in high caloric value in the MO (Table 3.4). Calories per hectare were highest in the IC at MS the first season, and the MO the second season, although these were not significantly different in either season. Averaged across seasons, which may be more relevant to how farmers manage cropping systems, at MS the IC and the MO had more than 2 times as many calories as the BO.

The caloric values of the cropping systems were different at RS, where beans are well adapted and maize performs poorly. Despite the potential yield of maize, beans still provided more kilocalories at RS because maize yield is so suppressed at this site. At RS S1, the BO had the most calories and in S2 when maize yielded higher, the IC had the most calories. Averaged across seasons at RS, the IC had significantly higher calories than the BO, MO, and TC.

We assessed the protein and caloric value of the cropping systems in isolation, but in reality both are essential for human nutrition. The value of protein summed across both seasons indicates that at MS, the IC returns the most protein and at RS the BO returns the most protein per hectare. For calories, at MS the IC or the MO are equally good, and at RS the IC is the best. In order for subsistence farmers to gain the most complete nutritional value from a cropping system, the IC provides the best value for both calories and protein.

The nutritional value of agricultural products is an important aspect of cropping system viability, particularly for smallholder farmers who are typically the producers *and* consumers of these products. Strategies to improve nutrition in Rwanda as outlined in the PSTA II document, emphasize a balance of energy, protein, and lipids at the same time advocating an increase in maize production and consumption. Agricultural policies advocating monocultures would likely change the composition of foods contributing to kilocalories and protein, among other nutrients.

Traditionally, high-energy crops like sorghum and maize contribute only a small amount of calories (15.4%) to the typical daily Rwandan diet whereas bananas, roots, and tubers contribute up to 60% of Rwandan daily calories (PSTA II, 2009). New agricultural policies aimed at doubling maize production (PSTA II, 2009) that require farmers to grow only maize, would likely change the primary sources of calories, the dietary diversity found in the traditional diet, and other important nutrients, unless sufficient market structures were in place.

Land-Equivalent Ratio

The efficiency of a cropping system in terms of yield per unit area is particularly important for farmers with limited land. Population density in Rwanda is one of the highest in Africa at 416 people per square kilometer, and Northern Province is the most densely populated area of Rwanda (528/sq. km) besides the capital (National Institute of Statistics of Rwanda, 2012). In a parallel study in this region, the average household size was 5.08 and the average farm size was 0.60 hectares (Waldman et al., 2014), slightly less than the estimate from the latest National Agricultural Survey of 0.65 hectares per household in Northern Province (NAS, 2010). Farmers with such small landholdings must maximize land-use efficiency while still accounting for income and nutritional needs. Growing an intercrop of beans and maize may be less risky, and provide different and more types of return per unit area.

The LER is a common measure used to determine the land-use efficiency of a cropping system and is expressed as a percentage. Values greater than 1.00 indicate that the cropping system is a more efficient use of land. In this study, the LER also magnified the crop x location x season effect we have discussed previously with the same results that at MS, systems with maize excelled, and in the season when beans dominated, the IC excelled. The opposite is also true at RS, where systems with beans excelled, and in the season when maize dominated, the IC excelled. The large location effect and the sizable differences in yields per component crop at each location skew the LER data. Using the yield data across both locations as the denominator of the LER equation combined with the dominance of maize at MS and the relatively low yields of maize at RS, results in almost all of the RS LERs below 1.0 and all of the MS LERs above it. More regional data, if it wasn't disproportionately low compared to station data could be used to compare these components. On the other hand, this measure may not be appropriate for comparing cropping systems between sites that are so disparate nor does it have much meaning for the typical farmer with land in only one location.

As an alternative to the LER, or a proof of concept of the land area efficiency of a cropping system, we can also assess these systems on a set amount of land in one location. Using the same plant densities and yield data from this study, we compared the yield of beans and maize in 1.0 hectare of an intercrop with the calculated yield of beans and maize grown in a monocrop on ½ hectare each (Table 3.6). This shows us if it is equivalent (in terms of yield here, but we can look at in terms of protein, calories and value) to grow an intercrop of beans and maize verses an equivalent area with both crops in a monocrop.

In every scenario, the IC yields more total grain than a ½ ha of each crop grown in a monoculture and the traditional intercrop. Only during S2 at MS was it better to grow an entire hectare of maize than the IC, and again during S1 RS an entire hectare of beans in monocrop was a better bet. Similar to the conclusions of the other measures of cropping system performance, these results are dependent on the context. The smallholder farmers in this region are growing different crops primarily for sustenance and secondarily for exchange on the market. Growing an entire hectare of a monocrop would only be advantageous if they have easy access to markets and can exchange goods to balance nutritional concerns.

One difference in the results between the LER and the alternative LER was in the total grain yield at RS (Tables 3.5 and 3.6). The alternative LER shows more nuanced information. In the LER, the BO 1.09) was the best option over the year, followed closely by the IC (1.04). In the alternative LER, this variation is the equivalent of 1.6 mt/ha more grain in the IC over the year.

Price Scenarios

Farmers in this region indicated that having more than one crop enabled them to exchange various crops on the market for other goods and services, including money to pay for school and health care (Isaacs, 2013). We compared the economic value of planting different types of cropping systems in 5 conservative prices scenarios. As in other analyses in this study the results depended on the season and the location. At MS S1, the bean season, it was more profitable to grow an intercrop. In S2, it was more profitable to grow a maize monocrop. At RS S1, the monocrop was more profitable because beans grow so well and in S2 the intercrop was more profitable because both beans and maize perform well in this season and location combination. Averaged across both seasons, the intercrop was the most lucrative in both MS and RS in eight out of ten scenarios. In the best-case scenario, the intercrop yielded up to $536 more than a monocrop at MS in Scenario 1 (Table 3.8). However, the same scenario produced the highest return, $312, from a monocrop of beans at RS. This scenario, in which beans are 300 RWF/kg and maize is 200 RWF/kg, was the most similar to historic market prices at the time of the research (beans cost 300 and maize cost 150 RWF/kg). The only scenario that produced a positive return on a maize monocrop, $29, was Scenario 4 at MS. In this scenario maize was 200 RWF in S1 and 300RWF in S2, the maize season, or more than double the price of maize in S2 2011. It is unlikely that the price of maize would be so high when the market is flooded at harvest. When we consider the market value of the cropping systems, the intercrop is more lucrative over the entire year, although this depends on the environmental conditions of the region. The low maize yields at RS decrease the value of the intercrop, although in most scenarios it is still more lucrative to grow an intercrop.

Conclusions

The season by location interactions in the bean and maize yields reveal the importance of evaluating cropping systems individually across heterogeneous environments. In terms of yields, government policies recommending growing beans in S1 and maize in S2 are reasonable, in general, over the large area of Northern Province, Rwanda but they fail to accommodate microenvironments such as RS where maize performs poorly and beans have a comparative advantage. While the formal evaluation of cropping systems may not be feasible across the diverse landscape of this region, reliance on, and acknowledgement of farmer ability to identify suitable cropping systems, is an obvious but overlooked and underutilized resource in the Rwandan context. A government policy that is flexible and enables farmers to make decisions based on their unique growing conditions, would be more effective in improving agricultural livelihoods.

The livelihoods of smallholder farmers in this region are dependent on their ability to grow sufficient crops, in terms of quantity and quality. Some of these qualities include nutritional diversity, land-use efficiency, and value on the market. We evaluated four cropping systems across two environments to identify which systems provided the most quantity and quality of these factors. The environment where the crops were grown affected the results. Over one calendar year at MS, the improved intercropping system (IC) provided the most total grain, protein, kilocalories, land-use efficiency, and value. At RS, results were slightly different in that a monoculture of beans provided more protein, more yield per unit area (LER), and normally returned more profits on the market. On the other hand, the IC at RS provided the highest total grain yield, the most kilocalories, and was the best in terms of the alternative LER. Notably, the farmer system, the traditional intercrop, did not perform as well as the intercrop planted in rows. A beneficial alternative to the strict single crop agricultural policy may be an adjusted intercrop system that still provides the services farmers expect, but maintains higher production encouraged by the government policy.

In modern agriculture, intercropping systems are viewed as backwards and outdated, but decades of research have shown they can be valuable both ecologically and biologically. Farmers analyze their cropping systems from a holistic perspective that accounts for the services they expect from the system. Farmers have intimate knowledge of their local conditions and reality. Combining their knowledge and requirements with agroecological analysis provides additional insight into the potential of intercropping systems and may be a gateway to improved management of natural resources. The integration of different knowledge systems into the evaluation criteria of a cropping system should also extend into the assessment of the impact of changing agricultural policy on farmer livelihoods.

Table 3.1 Altitude and mean soil properties at Musanze Station and Rwerere Station for Seasons 1 and 2, 2011-12.

Location and Season	Elevation	Soil type	Clay	Sand	Total N	Organic C	Bray-p#	pH
	m.a.s.l.		%	%	%	%	ppm	
Musanze Season 1	1861	Loam	18.0	46.1	0.21	2.19	297.0	6.00
Musanze Season 2	1851	Loamy Sand	7.6 (1.6)	75.7 (5.8)	0.13 (0.0)	1.29 (0.06)	111.0 (6.7)	6.00 (0.07)
Rwerere Season 1	2116	Clay	44.1 (5.2)	27.2 (2.3)	0.29 (0.03)	2.46 (0.56)	47.7 (13.7)	5.53 (0.21)
Rwerere Season 2	2109	Clay	45.8 (1.7)	23.3 (0.4)	0.27 (0.01)	2.70 (0.06)	14.5 (1.2)	5.93 (0.18)

Standard errors are in parenthesis
#Bray extractable inorganic phosphorus
+pH in 1:2 soil water ratio

Table 3.2 Total grain yield for each system and crop at Musanze Station and Rwerere Station for Seasons 1 and 2, 2011-12.

Location and Season	Intercrop Systems		Monocrop System	Intercrops Systems		Monocrop System	Total Intercrop (bean + maize)	
	IC	**TC**	**BO**	**IC**	**TC**	**MO**	**IC**	**TC**
	BEAN yield Mt/ha			**MAIZE yield mt/ha**			TOTAL yield mt/ha	
Musanze Season 1	1.7^{A} (0.10)	1.8^{A} (0.18)	3.7^{B} (0.10)	5.8^{a} (0.26)	4.8^{a} (1.00)	6.4^{a}(0.42)	7.5	6.6
Musanze Season 2	1.0^{A} (0.10)	2.3^{B} (0.23)	2.6^{B} (0.18)	7.4^{a} (0.31)	4.5^{b} (0.51)	8.8^{a}(1.25)	8.4	6.8
Rwerere Season 1	1.9^{A} (0.10)	2.4^{A} (0.25)	4.4^{B} (0.20)	1.8^{a} (0.08)	1.4^{b} (0.18)	2.0^{a} (0.30)	3.7	3.8
Rwerere Season 2	1.2^{A} (0.08)	1.4^{A} (0.21)	3.0^{B} (0.18)	3.9^{a} (0.17)	1.9^{b} (0.83)	4.0^{a} (0.61)	5.1	3.3
System Mean	**1.5** (0.06)	**1.9** (0.15)	**3.4** (0.11)	**4.8** (0.24)	**3.1** (0.54)	**5.1** (0.72)	**6.2**	**5.1**
Musanze year total	2.7	4.1	6.3	13.2	9.3	15.2	15.9	13.4
Rwerere year total	3.1	3.8	7.4	5.7	3.3	6	8.8	7.1

Bean and maize yields are added in the last two columns to show total intercrop system yields. The system mean is the average yield across seasons and locations for each system. The total yield for each location over an entire yield is displayed at the bottom of the table. IC is the maize-bean intercrop in rows, TC is the maize-bean traditional intercrop, BO is bean monocrop, MO is maize monocrop. For each season and location (across rows), bean yields with different upper-case letters and maize yields with different lower-case letters were statistically different (<0.01 - <0.0001). Standard errors are in parenthesis.

Table 3.3 Protein content per hectare in each cropping system at Musanze Station and Rwerere Station for Seasons 1 and 2, 2011-12.

Location and Season	INTERCROP SYSTEMS IC	INTERCROP SYSTEMS TC	MONOCROP SYSTEMS BO	MONOCROP SYSTEMS MO
	Protein g/ha			
Musanze S1	950 (40)[a]	870 (110)[a]	870 (30)[a]	610 (40)[b]
Musanze S2	950 (40)[a]	950 (20)[a]	610 (40)[b]	830 (120)[ab]
Rwerere S1	630 (30)[a]	690 (50)[a]	1030 (50)[b]	190 (30)[c]
Rwerere S2	660 (30)[a]	470 (40)[b]	700 (40)[ac]	380 (60)[b]
System mean	800 (20)	750 (60)	800 (30)	480 (70)
Musanze year total	1900	1830	1480	1440
Rwerere year total	1290	1160	1730	560

The protein content for maize and beans are added together in the intercrop systems. Location yields for each system are totaled for the two seasons at the bottom of the table. Standard errors are in parenthesis. Means for each season and location (across rows) with different letters are statistically different (between 0.01-0.001).

Table 3.4 Kilocalories per hectare in each cropping system at Musanze Station and Rwerere Station for Seasons 1 and 2, 2011-12.

Location and Season	INTERCROP SYSTEMS IC	INTERCROP SYSTEMS TC	MONOCROP SYSTEMS BO	MONOCROP SYSTEMS MO
	Megacalories/ha			
Musanze S1	26.9 (1.1)[a]	23.5 (3.8)[ac]	12.3 (0.3)[b]	23.5 (1.5)[a]
Musanze S2	30.6 (1.2)[a]	23.8 (1.2)[c]	8.6 (0.6)[b]	32.2 (4.6)[a]
Rwerere S1	13.2 (0.5)[ac]	12.9 (0.5)[c]	14.6 (0.7)[a]	7.2 (1.1)[b]
Rwerere S2	18.4 (0.7)[a]	10.9 (2.4)[b]	9.9 (0.6)[b]	14.5 (2.2)[ab]
System Mean	22.4 (0.8)	17.8 (2.0)	11.3 (0.4)	18.5 (2.6)
Musanze year total	57.5	47.3	20.9	55.7
Rwerere year total	31.6	23.9	24.4	21.7

The individual kilocalorie content for maize and beans are added together in the intercrop systems. Location yields are added across seasons at the bottom of the table to reflect total yield in a calendar year. Standard errors are in parenthesis. Means for each season and location (across rows) with different letters are statistically different (between 0.01-0.001).

Table 3.5 Land equivalent ratio at Musanze Station and Rwerere Station for Seasons 1 and 2, 2011-12.

Location and Season	INTERCROP SYSTEMS IC	INTERCROP SYSTEMS TC	MONOCROP SYSTEMS BO	MONOCROP SYSTEMS MO
	Land Equivalent Ratio			
Musanze S1	1.65 (.06)	1.48 (.21)	1.09 (.03)	1.27 (.08)
Musanze S2	1.78 (.07)	1.55 (.04)	0.76 (.05)	1.74 (.25)
Rwerere S1	0.94 (.03)	0.98 (.05)	1.29 (.05)	0.39 (.06)
Rwerere S2	1.14 (.04)	0.73 (.11)	0.88 (.05)	0.78 (.12)
Musanze Average	1.72	1.52	0.93	1.51
Rwerere Average	1.04	0.86	1.09	0.59
All factors	1.38	1.19	1.01	1.00

Values larger than 1.0 indicate a greater land use efficiency. Standard errors are in parenthesis. LERs are averaged at the bottom of the table to reflect system response at each location over a calendar year, and averaged across all factors for summary purposes.

Table 3.6 Alternative LER at Musanze Station and Rwerere Station for Seasons 1 and 2, 2011-12.

CROPPING SYSTEMS	ROW INTERCROP			TRADITIONAL INTERCROP			MONOCROP SYSTEM		
LOCATION AND SEASON	total area = 1 ha			total area = 1 ha			total area = 1 ha		
	1 ha beans	1 ha maize	**Total yield**	1 ha beans	1 ha maize	**Total yield**	0.5 ha beans	0.5 ha maize	**Total yield**
	mt/ha								
Musanze S1	1.7	5.8	**7.5**	1.8	4.8	**6.6**	1.8	3.2	**5.1**
Musanze S2	1.0	7.4	**8.4**	2.3	4.5	**6.7**	1.3	4.4	**5.7**
Rwerere S1	1.9	1.9	**3.8**	2.4	1.4	**3.7**	2.2	1.0	**3.2**
Rwerere S2	1.2	3.9	**5.1**	1.4	1.9	**3.2**	1.5	2.0	**3.5**
MS year total	2.7	13.2	**15.9**	4.0	9.3	**13.3**	3.1	7.6	**10.8**
RS year total	3.1	5.8	**8.9**	3.8	3.2	**7.0**	3.7	3.0	**6.7**
Average	1.5	4.8	**6.2**	1.9	3.1	**5.1**	1.7	2.7	**4.4**

Bean and maize yield of an intercrop grown on 1 ha of land compared to bean and maize yield grown in a monocrop on 1 ha of land, split into two half hectares. Location yields are added across seasons at the bottom of the table to reflect total yield in a calendar year, and averaged across all factors for summary purposes.

Table 3.7 Plant populations in 1 ha of intercrops verses half a hectare of monocrops

Cropping Systems	INTERCROP SYSTEMS		MONOCROP SYSTEMS	
Area	**IC** 1 ha	**TC** 1 ha	**BO** 0.5 ha	**MO** 0.5 ha
	Plant Population			
Beans	106700	458300	100000	0
Maize	44400	75000	0	53350
Total	151100	533300	100000	53350

Table 3.8 Price Scenarios of Monocrop and Intercrop at Musanze Station and Rwerere Station for Seasons 1 and 2, 2011-12.

Price Scenarios*		Base	1	2	3	4	5
Output Prices (RWF/kg)							
Beans S1		200	300	200	300	200	200
Beans S2		200	300	200	200	300	300
Maize S1		200	200	300	300	200	300
Maize S2		200	200	300	200	300	200
$ Value/Hectare = Intercrop - Monocrop							
Location and Season	MS S1	$359	$647	$251	$539	$359	$251
	MS S2	-$109	$64	-$337	-$109	-$164	$64
	RS S1	-$194	-$605	$119	$437	-$923	-$610
	RS S2	$391	$439	$380	$391	$587	$599
Year Total	**MS**	**$250**	**$711**	**-$86**	**$430**	**$196**	**$315**
	RS	**$197**	**-$165**	**$499**	**$828**	**-$335**	**-$11**
$ Value/Hectare = Traditional Intercrop - Monocrop							
Location and Season	MS S1	$53	$348	-$217	$79	$53	-$217
	MS S2	-$695	-$319	-$1,419	-$695	-$1,043	-$319
	RS S1	-$207	-$537	$20	$418	-$935	-$708
	RS S2	-$245	-$176	-$595	-$245	-$367	-$17
Year Total	**MS**	**-$643**	**$29**	**-$1,636**	**-$616**	**-$990**	**-$535**
	RS	**-$451**	**-$713**	**-$574**	**$174**	**-$1,302**	**-$725**

Simulation of price scenarios relative to base scenario of equal prices of maize and beans constant across seasons. $ value/hectare represents the difference in economic value between intercrop and monocrop. Positive values indicate the intercrop is more valuable than the monocrop. The highest valued monocrop, either beans or maize, was subtracted from the intercrop.

*At the time of the research, values on the local market in additional to historical retail prices, were most similar to scenario 1.

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