COLLABORATIVE
CROP RESEARCH
PROGRAM

THE McKNIGHT FOUNDATION

Phosphorus Efficient Bean Project

Successes, Lessons, and Good Practices in Agroecological Intensification




Background

Legumes, particularly beans *(Phaseolus vulgaris* L.*)*, have an important role for smallholder farmers in Mozambique. Beans have a high nutritional value and contribute to improved diets and food security for resource-poor households. They also promote soil health and increase the yields of cereals in intercropping and rotation systems. Recognizing their economic importance to the economy, the Mozambique government has selected beans as one of its seven value chain priorities. Beans have the potential to provide a source of income for rural households in Mozambique, especially for women who do much of the agricultural work.

According to the Ministry of Agriculture and Food Security (2017), Mozambique has 4,268,585 farming units (including smallholder and commercial farms), 99% of which are managed by smallholders. The majority of the smallholder farming systems are rain fed, with low usage of technologies and limited access to extension services. The average size of farmland is 0.8 to 1 ha, with average productivity of 0.8 tons per hectare of maize and 0.6 tons per hectare of beans (Mwakiwa et al., 2017). This is one of the lowest in the southern Africa region. Increasing agricultural productivity is a key priority for the Mozambican government, and its strategies to achieve this include: (i) supporting research and technology dissemination, (ii) increasing access to inputs, (iii) increasing funding mechanisms, and (iv) carrying out policy reform.

The productivity of smallholder farmers in Mozambique is generally constrained by soils with low levels of nutrients. Major limiting factors in bean production include low availability of phosphorus (P) in the soil and the inability of bean crops to efficiently take up the phosphorus that is available. Moreover, farmers consider beans a secondary crop and thus invest less in their production. The use of improved seeds and fertilizers is limited, which also contributes to low yields. Another key constraint is drought, as most bean varieties do not tolerate long periods without rainfall.

The Research Response

To respond to the low productivity of beans, the Agricultural Research Institute of Mozambique (IIAM) initiated a research project in 2006, which aims to "increase bean production and productivity in soils with low phosphorus availability by developing P-efficient genotypes, with the overall goal of increasing rural household food security and income." The project is supported through The McKnight Foundation's Collaborative Crop Research Program (CCRP), which promotes agroecological intensification (AEI) of smallholder farming through collaborative crop research. AEI means improving the performance of agriculture through integration of ecological principles into farm and system management. The project is now in its third phase and has four major components, namely:

1. Identify and develop legume genotypes with superior yield in low P soils in Mozambique;
2. Determine effects of P-efficient legumes on productivity and sustainability of agroecosystems;
3. Characterize constraints to and impacts of nutrient efficient germplasm on local communities in target region;
4. Strengthen scientific capacity for enhanced legume production and utilization in Mozambique.

The research is being conducted at sites in five districts in the country: Sussundenga, Angonia, Gurue, Lichinga, and Chokwe. Research carried out under each of the main components is summarized below.

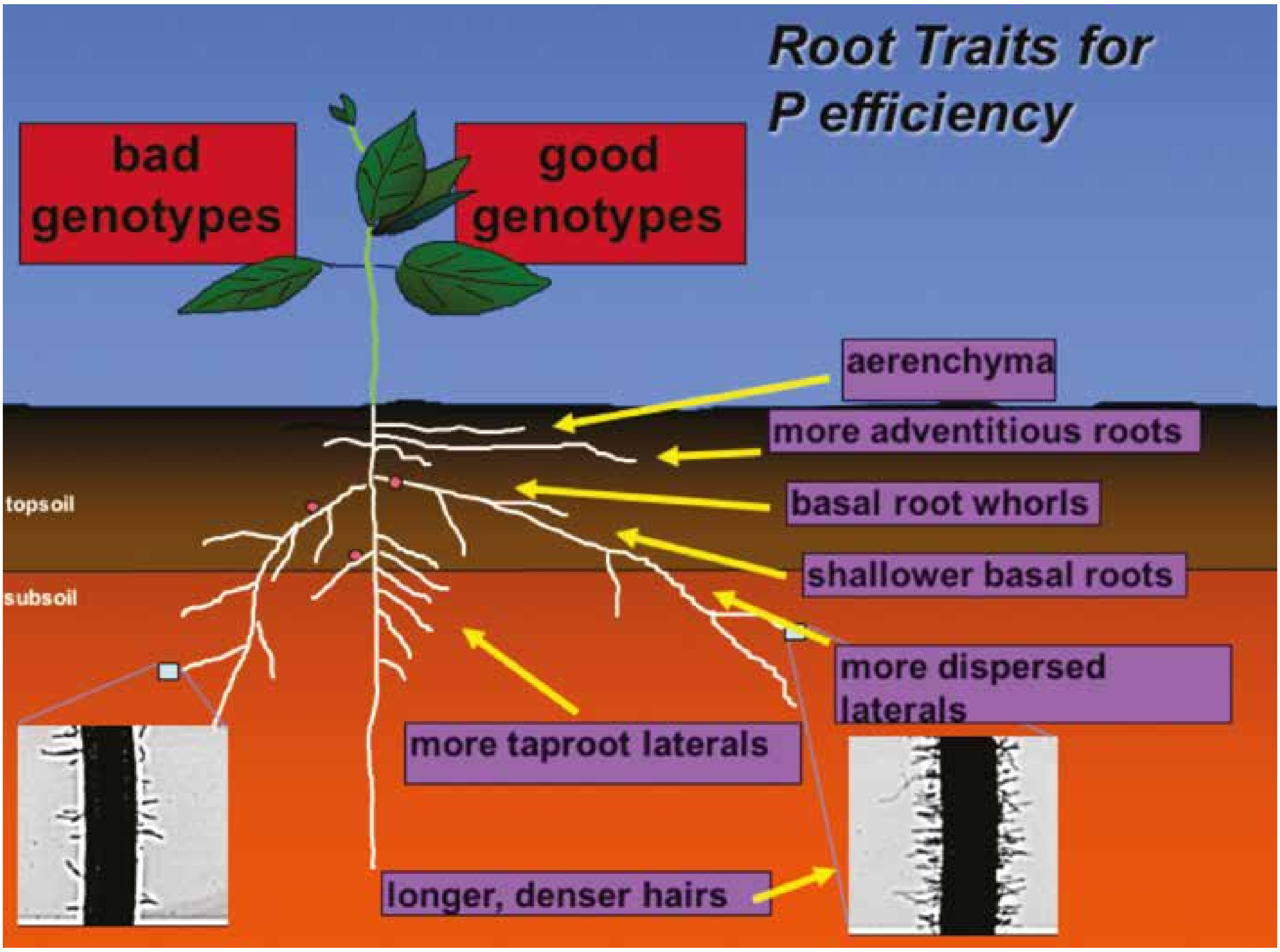
1. Identify and develop legume genotypes with superior yield in low P soils in Mozambique.

- ☐ Investigation of bean root structure for enhanced uptake of P.
- ☐ Evaluation of P-efficient bean varieties with farmers.
- ☐ Development of new bean varieties and how they benefit farmers.

One of the main reasons for the low yields of most current bean varieties grown in Mozambique is that they are not well adapted to the prevailing agroecological conditions. In particular, traditional bean varieties are inefficient in extracting nutrients from soils with low fertility. This is especially true for phosphorus which is an essential element for plant growth. A large proportion of the available phosphorus in low fertility soils is present in the upper layer of the soil profile. The research team hypothesized that certain root traits would allow bean plants to take up phosphorus more efficiently and designed studies to test this. A wide diversity of common bean germplasm is available globally, and the team was able to exploit this to identify lines and varieties that exhibited root traits of interest. More than 200 bean lines, varieties, and wild types from germplasm collections in Mozambique, Honduras, and CIAT (International Center for Tropical Agriculture) were evaluated in on-station trials and in the laboratory.

The root system of the common bean plant consists of a primary root, basal roots emanating from the basal portion of the hypocotyl and lateral roots. The basal roots emerge in distinct tiers or positions, which the root physiologists in the team labeled "basal root whorls". Typically, four roots emerge from each whorl, and the shallow roots arising from the uppermost whorls were thought to acquire the most phosphorus, as they explore the topsoil where the bulk of the phosphorus is present (see diagram). In field experiments carried out in Sussundenga, the researchers found that bean genotypes with three basal root whorls extracted more phosphorus from low soil than bean types with only two basal root whorls. They attributed this to their shallower root systems and a greater range of basal root angles. As a result, genotypes with three whorls had almost twice the shoot biomass, greater root length, and greater leaf area than related bean types with two whorls (Miguel et al., 2013).

In subsequent research, the team found that bean genotypes with shallow basal roots produced significantly more shoot biomass than those with deeper roots. Similarly, genotypes with long root hairs had significantly greater biomass accumulation than short-haired types. When shallow basal roots and long root hairs were present in a single genotype, there was a synergistic effect and the shoot biomass accumulation increased beyond what was expected through combining the two traits (Miguel et al., 2015).



Anica Massas, PhD student at PSU, studying bean roots in the laboratory

Box 1. PhD study

Anica Massas (Ph.D. student at Pennsylvania State University in the USA) explains how her research contributes to the project objectives "Phosphorus is concentrated in the topsoil and does not move readily in the soil, which makes it difficult for roots to absorb it. My research seeks to transfer genes from the Andean family of beans (which have a larger number of basal roots) to the Mesoamerican family, a variety resistant to diseases and with longer root hairs. I want to combine genes for high density basal roots and genes for longer root hairs in one variety. If successful, we will be able to develop varieties that can absorb phosphorus in all soil layers, reducing the need for fertilizer".

Dr. Magalhães Miguel, the principal investigator of the project, sees these results as a major breakthrough. He explains that selection for tolerance of low fertility conditions in Mozambique now focuses on shallow root architecture and increased root hair length and density. These traits are now being incorporated into new advanced bean lines and are being evaluated in field trials on-station and with groups of farmers.

The project team recognized the importance of working with farmers at an early stage of the varietal development process. Farmers have clear preferences for particular characteristics in the beans they grow and consume, and these need to be understood by plant breeders as they develop new varieties. These preferences may vary across locations as do the environmental conditions in which beans are grown. So, farmers in different locations have been involved in selecting new bean lines and evaluating their performance on their own farms. Farmers in multiple villages in Sussundenga, Angonia, Gurue and Lichinga districts have been evaluating lines developed for soils low in phosphorus, the so-called "P-efficient" lines, over several seasons.

Women in Rotanda select their preferred P-efficient bean lines

An example of the varietal evaluation process with farmers is seen in Nhatepe village in Angonia district in the 2014 cropping season. Farmers there received approximately 200 to 250 gm of seed of six P-efficient bean lines. At the end of the season, farmers compared the performance of the lines. They observed that all of the lines are early maturing and have a determinate growing habit, with more uniform grain size and higher yield than the local varieties they had been growing previously. They selected three lines based on yield, marketability, and taste. Both women and men preferred a black colored bean variety called Ica Pijão for household consumption, while men also preferred Catarina and LPA 28 for sale in the market. By contrast, in another village in Sussundenga district, Rotanda, farmers selected only lines which had both high yield and were accepted by traders. Interestingly, Ica Pijão was not selected in Rotanda in spite of its high yield. The reasons for this are not well understood but are currently being explored.

Box 2. Outcomes from the use of low-P bean lines

Ana Bejito is a woman farmer in Nhatepe village, in Angonia District. She is a widow with five children. She received seed of P-efficient bean lines in 2014. After assessing their performance on her farm, she selected two advanced lines: Ica Pijão for household consumption and Catarina for market sale. She reported that the yield is up to 25 kg per kg of seed with these lines, compared with up to 10 kg per kg of seed with the local variety she had grown previously. As a result, her income from the sale of the beans has increased, which has made an important contribution to the overall household income.

Cornelio Sitiverio is a male farmer, married with seven children. He has been a farmer his whole life and also received P-efficient seeds in 2014. Cornelio observed that the seeds are of good quality, with an early and uniform maturity. The advanced lines have good yields and support income generation and household nutrition. Cornelio also believes that the new lines help during famine periods because of their early maturity. People can also consume the leaves and therefore have two sources of nutrients; from the leaves and the grains.

The project team expects that more farmers will soon have access to the best performing P-efficient bean lines. A total of seven improved lines with desirable root traits for the efficient extraction of phosphorus in low-P soils have been evaluated in multiple locations and proposed for varietal release. The lines are early maturing (89-100 days), have large or medium seed size, and yield well under both high and low input systems. Performance data of the seven lines are shown in the table below.

Table. Agronomic data for the seven bean lines proposed for release.

Genotype	Pedigree	Yield (kg/ha) high inputs	Yield (kg/ha) low inputs	Cycle (days)	N⁰ pods/ plant	N⁰ of seeds/ pods	Weight of 100 Seeds (g)	Size of grain	Color
AP 20	AFR 298 x PVA 773	2891.32	1448.02	100	18	5	50	Big	Scratched red
AP 82	AFR 298 x PVA 773	2693.68	1407.46	95	14	6	50	Big	Red
AP 89	AFR 298 x PVA 773	3271.92	1413.53	95	15	5	45	Big	Scratched Red
AP 60	AFR 298 x PVA 773	2629.70	1409.49	100	12	6	50	Big	Red
LPA 26	SUGAR 47 x USA 63	2871.50	1076.00	89	15		31	Medium	Scratched cream
LPA 28	SUGAR 47 x USA 63	2627.90	1070.77	95	20	5	35	Medium	Scratched cream
LPA 31	SUGAR 47 x USA 63	2567.80	1415.24	95	17	5	46	Big	Scratched cream

2. Determine effects of P-efficient legumes on productivity and sustainability of agroecosystems.

- ❑ Examination of soil erosion and nutrient loss.
- ❑ Research on symbiotic nitrogen fixation.
- ❑ How P-efficient lines combine with maize as an intercrop.
- ❑ Conserving moisture through the use of a mulch.

During the development of the new P-efficient bean lines, it was important to understand how they affected soil processes and to identify the most appropriate crop management practices for their growth. The team's agronomists recognized that the cultivation of bean lines with root traits suitable for efficient phosphorus extraction was likely to deplete sources of available phosphorus in the upper layers of the soil more rapidly than other bean types would. But they also considered that bean plants with these root traits would help to preserve the soil and soil nutrients from erosion and other degradation effects. They believed that this would more than compensate for the faster extraction of phosphorus from the soil. To test this hypothesis and generate evidence on other potential agroecological impacts of growing P-efficient beans, they established field experiments in three locations: Lichinga, Sussundenga, and Chokwe. This component of the research was led by Dr. Soares Xerinda as part of a PhD program he completed at Pennsylvania State University in the USA.

Field trials were conducted in 2008 and 2009 on sloping land at the IIAM research station in Lichinga. The aim of the trials was to determine whether there was any difference in soil erosion and removal of nutrients between P-efficient and deep-rooted bean varieties. Results showed that, in both years, there was less runoff water and reduced loss of soil phosphorus in the P-efficient lines. This was attributed to the fact that the P-efficient bean lines had greater above-ground biomass—and more and longer roots in the top 15cm of the soil profile—than the deep-rooted varieties.

In addition, the researchers were interested to know whether P-efficient bean lines would fix more atmospheric nitrogen than deep-rooted bean varieties. On-station field trials were established in 2008 in Lichinga and in 2010 in Ukulima, South Africa to investigate this. On average, the P-efficient bean lines had 39% greater symbiotic N2 fixation than the deep-rooted bean varieties. They also had 41% greater nodulation and 57% greater nodule activity than deep-rooted lines under low-P conditions. These findings suggest that the ability to extract phosphorus efficiently from deficient soils is important for the development of active root nodules.

Beans are often grown as intercrops with maize, so the research team wanted to find out how the P-efficient bean lines and a representative maize variety performed when grown alongside each other. To investigate, they carried out on-station field trials in 2006 and 2010 at Pennsylvania State University in the USA. They discovered that when the shallow-rooted P-efficient bean lines were grown with maize under low-P conditions the average yield was 1.04 Mg ha-1, which was 43.3% greater than the yield of the deep-rooted phenotypes. The average yield of

Field day and evaluation of P-efficient genotypes

maize was reduced by 22.5% when grown with the P-efficient lines, compared to the yield obtained when grown on its own. By contrast, the maize yield was not reduced when grown with the deep-rooted bean types. The researchers concluded that competition between bean and maize roots was greatest with P-efficient lines as they explored a similar layer of the soil profile. The choice of bean plant type to grown in polyculture will depend on a range of factors including the priority farmers attach to each of the crops and, if the harvested seed is to be sold in the market, the relative price they expect to obtain.

Conservation of moisture is critical in bean growing areas which have high temperatures and are prone to drought. P-efficient varieties, being shallow-rooted, are less tolerant of drought than deep-rooted bean types. Therefore, accompanying technologies for moisture conservation such as mulching have proved useful to reduce the risk of losses from increased drought in the main areas where beans are grown. The team recently completed field trials to investigate the effect of mulching on the growth and yield of P-efficient lines of bean. Preliminary findings show that these bean lines grown with mulch were more vigorous and produced more pods than bean varieties grown without mulch. Further studies are being conducted to test this effect.

3. Characterize constraints to and impacts of nutrient efficient germplasm on local communities in target regions.

- ❑ Factors affecting farmer adoption and marketing of P-efficient bean varieties.
- ❑ Formal and informal channels for seed purchase and transfer.
- ❑ Varietal release procedures and bean seed marketing.

Whilst the plant breeders, root physiologists, and agronomists in the research team were developing the P-efficient bean lines and assessing how best to grow them, the socio-economists were exploring how the bean lines could reach the largest number of farmers. Maria da Luz Quinhentos (see Box 3 for her role) set out to identify barriers to diffusion of P-efficient common beans in rural Mozambique villages. She also looked at impacts on household food security and income, with a focus on seed distribution, functioning of markets and supply chains, and intra-household dynamics. She completed the work as part of her Masters program under the supervision of Dr. Jill Findeis at Pennsylvania State University.

Maria's research showed that membership of a social network positively affected farmers' knowledge and willingness to adopt P-efficient varieties. She discovered that farmers acquire seed from two main sources: a formal source (traders, NGOs, and public institutions) and an informal source (friends, acquaintances, and relations in communities). Farmers have strong ties with people in the informal category and weak ties with those in the formal category. Moreover, farmer age, farm size, and non-farm activities influence the adoption of P-efficient varieties. The nature of the technology and the class of adopters would require a variety of diffusion channels from radios, seed trials, demonstrations, field days, extension services, and/or the farmers' social networks.

The socioeconomic studies showed that the adoption of new varieties is fostered if farmers see benefits and have concrete proof that they perform well. Farmers' preferences for the advanced lines of beans are influenced by gender (women tend to look for nutritional traits while men are more concerned about market traits). There are also geographical differences; for example, farmer preferences in Angonia and Sussundenga did not align.

Since they received the first packages of seed, farmers have been able to multiply the seeds and share them among members of their social networks. However, they also report that demand is increasing, and it is not possible to benefit all farmers in the community. Initial results with farmers show that P-efficient lines possess the desired traits for adoption; however, the availability of quality seeds needs to be secured. The availability in local markets is determined by two main factors:

i. The formal procedure for seed release in Mozambique involves several steps, which makes the process bureaucratic and long.
ii. Few seed companies are willing to produce bean seeds. The self-pollinated nature of beans does not attract commercial production since it is believed that farmers will not invest in seeds.

These issues highlight the need to strengthen the common bean seed value chain. First, it is necessary to engage with Mozambique's National Seed Services to jointly develop more simple and flexible processes for seed approval and release. Secondly, there is a need to strengthen the formal seed system and engage seed companies (for basic and certified seed) for bean seed production. The need is critical for seed companies to provide access to seed, especially where social networks are weak.

4. Strengthen scientific capacity for enhanced legume production and utilization in Mozambique

- ☐ Diversity of capacity strengthening activities including English language training.
- ☐ Facilitating research collaboration through networking.
- ☐ Enhancement of infrastructure and research equipment.

Human capital is a key driver of agriculture development in Mozambique. The CCRP-funded project invested in continuous capacity strengthening for improved research, focusing on both long-term (Master and doctoral studies) and short-term training (short courses and training workshops), as well as virtual coaching and support. Within the project's implementation period, four PhD students (three completed and one ongoing) and two Masters students were funded.

Dr. Magalhães says that The McKnight Foundation's willingness to support English training for the candidates was a major benefit, as many researchers in Mozambique have limited English skills. Magalhães also affirms the value of not only training, but also researcher coaching to make them capable of leading major projects. This is illustrated by the fact that Dr. Magalhães himself started as a project collaborative investigator and today is leading the project

Box 3. Maria da Luz Quinhentos

Maria da Luz Quinhentos, a socio-economic researcher in IIAM, was introduced to the project in 2009 as an enumerator. Her commitment, creativity, and the results she had achieved during field work made her an excellent candidate for Masters studies. She earned her Masters degree from Penn State University in Social Science and analyzed the "social networks and farmers' willingness to adopt new agricultural technologies: the case of a new phosphorus efficient bean variety in rural Mozambique". Maria da Luz says that a major benefit was learning English. During and after her Masters program, she developed and strengthened her skills on research design, data analysis, and reporting. Maria da Luz has grown both personally and professionally, developing research and analytical skills and linking to broader research networks and other projects.

As a Lusophone country, language can be a barrier when applying for training programs. Thus, the project introduced the Intensive English Program. All the Mozambican candidates participated in the program and then gained successful admission to Master and doctoral programs in USA universities. The language training has also broadened the professional and research networks of Mozambican researchers from Lusophone to Anglophone countries. This has fostered the exchange of experience, learning, collaboration, and the promotion of other joint research projects.

Samuel Camilo, IIAM researcher in Chokwe, believes that professional development is one of the core components of the CCRP. He says, "McKnight really cares about the professional development of people involved in its projects. I have improved my data analysis skills and other researchers working in CCRP projects have given me timely support." The opportunities to network with researchers from other projects and countries, the research methods platforms, and the short-term training have all been extremely valuable in the development and growth of Mozambican researchers.

Celestina Jochua, IIAM bean breeder, recognizes that the project expanded and strengthened her network and her interaction with similar institutions such as International Center for Tropical Agriculture (CIAT). She says that several training programs held in China, USA, Honduras, and Mozambique benefited not only researchers, but also field and laboratory staff from the National Agriculture Research Institute.

Professor Jonathan Lynch, project collaborator at Pennsylvania State University, agrees that one of the strongest components of the project was the capacity development for staff at IIAM. Moreover, Professor Lynch supports the need "to invest more in agriculture research to help the smallholder farmers and commercial farmers. We need more training and more support for researchers in Mozambique; not only in beans, but in other crops".

Another important component in establishing and strengthening capacity at IIAM was the enhancement of infrastructure and research equipment. The project support rehabilitated and equipped the laboratory in Sussundenga Research Station, which enables basic plant tissue analysis and phenotype screening to be conducted.

Celestina Jochua, one of the PhD graduates evaluating the bean lines

Next Steps

All in all, the project brought new knowledge and state-of-the-art bean breeding in Mozambique. Results are expected to have a significant impact on smallholder farmers' livelihoods through the cultivation of new varieties that can perform better in low P soils without substantial application of fertilizer and still give high yields.

Farmers have seen the benefits of P-efficient bean lines and are willing to adopt them if the seed is available. As a next step, the project has designed a seed promotion and dissemination campaign that involves nutrition components, including bean recipes for households. The campaign, designed in collaboration with the USAID Climate Resilient Beans Project, will be launched in pilot villages as soon as the advanced seed lines are officially released. The team is also conducting research to understand women's empowerment in agriculture in Mozambique, as a leveraged activity with USAID Legume Innovation Laboratory. This is expected to increase understanding on how best to integrate gender aspects in the dissemination strategy. Continued efforts will be made to build and strengthen IIAM partnership networks with seed companies, agro-dealers, and NGOs to facilitate production and distribution of the new P-efficient bean varieties.

New research questions have also emerged that can inform future studies. These include:

- How will the new improved bean lines developed through research affect women and men?
- How can technology reach smallholder farmers using the various dissemination pathways available?
- What is the genetic basis of bean adaptation to stressful environments, and how can this be used to develop more lines for farmers' benefit?

Work remains to be done on the socioeconomic, physiological, and biological aspects in order to sustainably improve bean production systems of smallholder farmers.

Major Lessons

The project design followed an integrated approach where the four components link to and reinforce each other. The research protocols were flexible and allowed for the inclusion of site-specific characteristics and adjustment to local needs. One major lesson to be spread to other projects is the need for early and active involvement of project stakeholders. Farmers need to be involved in the process not only as a recipient of new agricultural technologies but also during the development of these technologies, and in the design of the research and in field evaluations.

The socio-economic studies of the project revealed that farmers will adopt new varieties if they see superior performance in their own fields. However, it became clear during the research that there is a need to influence policy and decision making. In particular, greater clarity is required in the procedures for varietal release, and a faster process would benefit stakeholders.

Dr. Magalhães Miguel believes that the project is an example of the benefits that can be obtained from a long-term commitment by a supporting organization to ensure impact and sustainability. Most funded projects have a lifespan that is too short to sustain the results of the intervention. The long-term support from The McKnight Foundation to IIAM, with a strong component of researcher capacity building, enabled even more powerful achievements so that farmers may continue to benefit well beyond the project's end. This was possible through the CCRP's strategic approach of investing in capacity building, technology development and dissemination, and establishment of strategic partnerships, with farmers playing a central role.

In conclusion, the project showed that investments in agriculture can have a significant impact, but it is necessary to invest in the development of human resources, to have suitable policies in place, and to ensure engagement of government and private institutions and ultimately the integration and collaboration between the various stakeholders.

Project team members

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Maria da Luz Quinhentos, IIAM
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Acknowledgements:
Thanks to Dr Magalhães Miguel and other project team members who provided inputs to the content of this brochure.

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