AFRICAN CENTRE FOR CROP IMPROVEMENT

THE NEW BREED

TRAINING THE NEXT GENERATION OF AFRICAN PLANT BREEDERS, IN AFRICA

The African Centre for Crop Improvement (ACCI) is a remarkable and largely unknown African success story. Funded by the Rockefeller Foundation and later Alliance for a Green Revolution in Africa (AGRA), the centre opened its doors at the University of KwaZulu-Natal, South Africa in 2002, with the ambitious goal of becoming a world-class training centre for African plant breeders. Powered by passion and innovative thinking, it has achieved this, and continues to train demand-driven plant breeders.

The ACCI's 109 PhD graduates are part of a new generation of African scientists who are highly trained global experts on African crops, dedicated to working on the continent. They are sought after and have become an elite force in the war against hunger.

Collectively they have released over 140 new crop varieties. Many of these new varieties have been bred to be 'climate-smart', and are drought tolerant and resistant to pests and diseases that plague food security crops.

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The journey and achievements of the African Centre for Crop Improvement would not have been possible without the generous support of The Rockefeller Foundation, the Bill and Melinda Gates Foundation, Alliance for a Green Revolution in Africa (AGRA) and the Generation Challenge Programme (GCP).

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Growing Africa's Agriculture

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Cover photo: ACCI graduate Dr Lameck Nyaligwa from the Agriculture Research Institute in Tanzania looks at inbred lines of maize on a test farm, with Mt Meru in the background on the outskirts of Arusha.

Previous page: Greenhouse facilities at the School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

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DESIGN AND LAYOUT BY LIGHTSHIP STUDIO

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AFRICAN CENTRE FOR CROP IMPROVEMENT

EDITED BY MARK LAING, HUSSEIN SHIMELIS AND SHELAGH MCLOUGHLIN

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Vice-Chancellor and Principal
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PREAMBLE

It gives me great pleasure to endorse this comprehensive history of the African Centre for Crop Improvement—one of the University of KwaZulu-Natal's leading success stories.

The ACCI, as it is more commonly known, has had PhD students in training since 2002. Over a period spanning some 15 years, the centre has successfully graduated a remarkable 109 PhD candidates, with another 29 PhD students currently in training.

The ACCI has been actively involved in plant breeding in 19 African countries, largely in East and southern Africa. Its talented team of committed researchers has worked on 19 crops—largely cereals, legumes and roots and tubers—which are vital for food security in Africa.

When first introduced, the ACCI programme was both innovative and novel, with an initial academic training at UKZN involving a unique curriculum, followed by the field work being done in the student's home country, at his or her home research station, using local farmers' varieties as a basis for breeding better varieties that were fully locally adapted to that environment. PhD supervisors visited the students in situ.

All students had to carry out a Participatory Rural Survey (PRA) so as to ascertain what the farmers considered to be essential traits in each crop and to ensure that the new varieties that were bred were successfully adopted.

Food security and stability in agriculture have been the primary research goals of the ACCI for the past 15 years. They are also the goals of the African Union. UKZN is now a leading brand across Africa in the agricultural sphere, primarily owing to the success of the ACCI's pioneering plant breeder PhD training programme.

Phd student Admire Shayanowako

Strive Masiyiwa

Chairman of the Board for Alliance for a Green Revolution in Africa

FOREWORD

Innovation is a popular buzzword, but to be a genuine innovator isn't easy. They are by definition leaders rather than followers, and usually that entails taking a long, lonely road in pursuit of something risky and new.

In 2001, the Rockefeller Foundation (RF) took a leap of faith, deciding to fund the establishment of the first centre based in Africa to offer world-class training to local plant breeders. The hope was that this venture, the African Centre for Crop Improvement (ACCI), would address several pressing needs at the time: the need for quality agricultural scientists trained in Africa to work on African crops; the need to keep these scientists in Africa; and the need to be able to develop new varieties for each crop adapted to the continent's diversity of agroecologies.

Setting up such a centre, with appropriate programmes and training, required intimate knowledge of local needs and conditions. It required money, energy, insight, creativity and a lot of commitment—a tall order in a resource-poor region of the world. However, dedicated people with the knowledge and passion to drive the project were found, and slowly, over several years, the ACCI matured and produced results that would once have been seen as wildly ambitious.

The brain drain of plant breeders reduced significantly and a growing task force of new graduates was produced to go out and do battle with the effects of climate change, drought, pests, and diseases. The young, upstart centre was so successful that a sister organisation, the West African Centre for Crop Improvement (WACCI), was opened in Ghana in 2007 by the Alliance for a Green Revolution in Africa (AGRA), which took over the funding of these programmes in 2006 through support provided by RF and the Bill and Melinda Gates Foundation.

The two centres have to-date educated over 160 African plant breeders. These scientists have gone on to develop well over 100 new crop varieties that have been released to farmers. Each of these new crop varieties will have a long-term impact, providing improved food security for farm families for perhaps 20-30 years before they are out-performed by new ones.

These achievements are impressive by any standard, but they're not the end of the story. It could be argued that of equal importance has been the symbolic impact of an African institution, staffed by Africans and working for the continent, carving out a space for itself in the global scientific arena. The ACCI has become a world leader in research into Africa's staple food crops, displaying a bold, creative approach to many of the continent's unique challenges. Furthermore, its graduates stand out as self-confident, empowered agricultural scientists who have a plan and skills to match their vision to make an impact in their home countries.

The work of the ACCI is not complete. There is an on-going need for African countries to unite to train PhD-level plant breeders and other agricultural scientists for Africa, in Africa. The ACCI has shown that, given the intellectual space and resources to find solutions to our continent's challenges, Africans are more than capable of succeeding. Now what's needed is for African governments to commit to funding this essential endeavour.

Rufaro M Madakadze
AGRA

WHAT AGRA HAS DONE
TO TRAIN AFRICAN PLANT BREEDERS

Good-quality seed of improved crop varieties is critical to increase smallholder farmers' yields in sub-Saharan Africa. North and South America as well as Asia had significant economic growth when their farmers started using seeds of improved varieties of the staple crops, along with other agricultural inputs.

Producing superior seed is, however, no small task. Improved varieties need to be adapted to the different agroecologies and be resistant to a variety of stresses, including diseases, insect pests, weeds, drought, low fertility and acid soils. They need to mature within the required seasons and produce higher yields. In addition, because across Africa, adoption of newly released varieties is mostly less than 35%, it is extremely important is that they are appealing to farmers, because if farmers like them they are more likely to grow them. And so other traits such as taste, cooking qualities and scent should also be improved.

The challenge doesn't end there. These improved varieties can only be produced by professional plant breeders, and in this regard Africa—along with the rest of the world—faces a huge stumbling block. The global shortage of plant breeders has been widely reported on, and was confirmed by an assessment done by Food and Agriculture Organisation of the United Nations (FAO), in collaboration with several other organisations, which measured national plant breeding and biotechnology capacity worldwide.

The deficit of plant breeders on the continent has been compounded by the lack of programmes in public and private universities that were training plant breeders at MSc and PhD levels. Globally, there is a lack of consistent investment in agricultural capacity building, and a lack of support for professional training in the agricultural sciences.

Morris et al (2006) reported that one reason why capacity building has been weak in many developing countries is that scarce resources tend to be dispersed with no significant numbers of researchers concentrated within a single organisation, or even within a single country.

The formation of the ACCI in 2002 by the Rockefeller Foundation was the first attempt to provide dedicated, relevant smallholder farmer-centered plant breeding training on the continent. At its peak the centre, that was inherited for funding by AGRA from 2006, had nine academic plant breeders managing breeding programmes that were essentially helping to train the next generation from east and southern Africa.

The programmes funded by AGRA have endeavored to develop modern plant breeders with a wide range of skill sets that include genetics, modern quantitative genetics with the use of statistical models, genotype x environmental interactions, physiology, pathology, entomology, soil science and experimental designs. The breeders must also know how to use and exploit DNA-based information for crop improvement, and marker-assisted selection (MAS) (see page 43 for explanation).

In addition to having technical breeding expertise, today's breeders must also possess legal knowledge, business acumen and people skills. They must be able to understand the factors that affect the adoption of new varieties, patterns of adoption and reasons for their eventual success or failure.

The depth and diversity of these skills and the environment that plant breeders must navigate in Africa shaped the education that AGRA funded. It called for a focus on field-based conventional breeding, knowledge in molecular breeding, social science and business skills, as well as knowledge of other disciplines such as crop protection and nutrition.

Most of the breeders trained are from National Agricultural Research Systems (NARS) that have centres scattered all over their countries, including some in remote places with little or no access to molecular breeding tools, and with very little infrastructure or funding to conduct field research.

Before AGRA's funding of plant breeding training there were fewer than 500 plant breeders working in the 13 sub-Saharan African countries surveyed by AGRA's Programme for Africa's Seed Systems (PASS) in 2007. Moreover, many of these scientists had been trained overseas on commodities and approaches not always relevant to Africa, and were therefore unable to make much impact in their home countries.

Since the establishment of the AGRA-funded programmes many others have followed, funding agricultural scientists including plant breeding training. These initiatives include Forum for Agriculture Research in Africa (FARA), the Regional Universities Forum for Capacity Building in Agriculture (RUFORUM) and several sub-Saharan governments, although the numbers are very small.

The success of the ACCI model highlighted the fact that it was possible to train high-level practical plant breeders for NARS on the continent. PASS expanded the regional PhD training to West Africa by funding the West African Centre for Crop Improvement (WACCI), based at the University of Ghana. The quality of these programmes was enhanced by a vibrant funded partnership with Cornell University. WACCI has to date trained 52 plant breeding graduates with 54 more in the pipeline. Fifty percent of the total number have been funded by AGRA. The ACCI has produced 109 graduates (84 funded by AGRA) and has 29 more PhD students currently being trained (16 funded by AGRA).

AGRA has also funded the establishment of MSc training programmes at 13 universities in sub-Saharan Africa. Most of these programmes were regional, admitting students from two to three countries. Each of the universities was funded for full scholarships, curriculum review, and significant infrastructural improvements. The quality of the MSc programmes resulted in the registration of more than 40% additional students who are not funded by AGRA. They are funded by other donors including governments.

AGRA funded trained plant breeding scientists (471, total of PhD and MSc) (Table 2.3) almost doubles the scientists that were in the 13 countries AGRA work in. Graduates of these programmes have released over 135 improved varieties of a wide range of crops, including maize, rice, beans, cowpeas, sorghum, groundnuts, cassava, and finger millet, from most of the countries AGRA works. They have also published over 300 papers in refereed journals worldwide, contributing to the body of knowledge on breeding priority African crops on the continent.

Table 1.1: Plant breeders at PASS inception by country, 2006

Country	Trained MSc scientists	Trained PhD scientists	Total
Burkina Faso	6	12	18
Ethiopia	144	52	196
Ghana	25	12	37
Kenya	30	53	83
Malawi	15	3	18
Mali	15	7	22
Mozambique	9	2	11
Niger	10	3	13
Nigeria	14	25	39
Rwanda	-	15	15
Tanzania	18	14	32
Uganda	10	9	19
Zambia	-	-	No data

Adapted from PASS Country Studies, 2006.

Table 1.2: Total PASS-funded graduates, 2007-2016

Training level	Total funded
PhD	152
MSc	319
Short-term training of seed company personnel and plant breeding technicians	1155

WHAT PLANT BREEDERS DO

It's 3am and still dark outside the glasshouse, where Mohammed Sagir Mohammed is preparing to emasculate a Bambara groundnut flower. It's quiet and he's the only person working at this lonely hour, his intention being to pollinate the flower with pollen from another plant.

Bambara groundnut is self-pollinating, so in order for his cross-pollination to be successful, Mohammed must remove the immature male parts inside the flower, the plant selected to be the female parent. He wears a jeweller's loupe to see the flower parts clearly, and to avoid contamination, he's used 70% alcohol to clean his hands and all the tools for doing the procedures. The entire process requires great delicacy and precision, and must be done in a brief window of one to two hours before sunrise, when the flower of the paternal parent opens to release pollen.

Holding the small, fragile flower of the maternal plant in his left thumb and index finger, he makes a careful cut with sharp scissors, and then uses tweezers to pull out through the slit the sepal, petal, stamens, corolla and standard. Pollen from the paternal parent is then placed on the exposed stigma of the maternal parent with a pollen brush.

Mohammed is a plant breeder, and he's just transferred genetic material from one plant to another, in pursuit of breeding a better variety of Bambara groundnut. Plant breeding is the manipulation of plant species in order to create desired genotypes (genetic makeup of an individual plant) and phenotypes (observable characteristics) for specific purposes. This manipulation involves controlled crosses, genetic engineering, or both, followed by artificial selection of the progeny.

Propagation

At the African Centre for Crop Improvement (ACCI), students are trained to do plant breeding, and most of the crops they work on are propagated by seeds and are self-pollinating. This detail is important because with crops like Bambara groundnut, tef and soybean, the process of circumventing the self-pollination process can be tricky, and determines how many crosses a breeder can make in a day. With tef, it's around three per day, all under a microscope. Compare that with maize, where hundreds of crosses a day can be made.

The rest of the crops that the students work on are either out-crossing, such as maize and pigeonpea, or are propagated vegetatively by roots, tubers and cuttings, such as sweet potato. When breeding cassava, potato or sweet potato, only one perfect individual is needed from which to propagate new clones, and this can be done with cuttings or tubers.

A seed plant like maize, however, is much more time-consuming to breed to the stage of hybrids because a seed production programme is necessary, inbred parents must be maintained, and crosses and hybrid seeds must be produced, with testing at each generation.

Conventional plant breeding

This approach uses various techniques:

- Selectively propagating plants with desirable characteristics and eliminating those offspring with less desirable features;
- Deliberate interbreeding (crossing) of related individuals to introduce traits or genes in order to create new varieties with desirable characteristics;
- Progeny from the cross may then be crossed with one of the parents (backcrossing) to yield a variety with one desirable trait from one parent (the donor parent) in the background of the other parent for all other traits (the recipient parent);
- Hybrids are the outcome of crosses between two completely unrelated parents. Hybrids typically out-yield open-pollinated varieties by 30% due the effect of "hybrid vigour", which occurs when half the genes come from one parent and half from the other parent. To produce hybrids, the parents first have to be self-pollinated for seven generations, to ensure that all their genes are the same, creating an inbred line. The inbred lines are then crossed with unrelated inbreds to create hybrids. Farmers like hybrids for their high yields and uniformity. Seed companies like hybrids because farmers have to buy new seed every season, and cannot reproduce the seed themselves, without a significant yield loss. Hence the runaway success of maize hybrids globally: it's a win-win situation for both the seed company and the farmer.

Sequence showing process of propagating cassava from cuttings taken from parent plants. These cuttings are planted in seedling trays after being dipped in hormone powder to promote the growth of roots. Figure 9 shows a cutting that has grown into a flourishing cassava plant.

Breeding with biotechnology

After the discovery of DNA and RNA in the 1950s and 1960s and the subsequent development of molecular genetics, new breeding tools were developed. Breeders were able to identify discrete nucleotide sequences that could be linked to specific genes or groups of genes, and for the first time, plant performance could be related to variation at the DNA level. For plant breeders this meant that it was possible to breed at the DNA sequence level rather than with the whole plant genotype and phenotype.

ACCI students use some biotechnology techniques, but specifically to enhance their activities using classical plant breeding.

For more on breeding see page 40.

Photo: Borlaug LEAP

Dr Kiddo Mtunda was the first Tanzanian ACCI student to graduate with a PhD in plant breeding, in April 2010. She has released four new varieties of cassava and is also involved in breeding new sweet potato varieties.

INTRODUCTION

Africa's first centre for training plant breeders has been successful because it focuses on finding real solutions for local problems

For the past 15 years, a small university programme based in Africa's deep south has been quietly training a new generation of plant breeders, while scattering seeds of innovation across the continent. Born in a moment of lateral thinking and propelled by the creative energy of its founders, the African Centre for Crop Improvement (ACCI) in South Africa has flourished, becoming known as a centre of academic excellence.

In the manner of all start-ups, its journey has been bumpy at times but also filled with idealism, industry and adventure. Students and staff have travelled to far-flung corners of the continent braving bandits, rough rides and dangerous diseases, all in pursuit of advancing the little-known science of classical plant breeding. The results have been outstanding: over 109 African plant breeders trained, scores of new crop varieties have been released and the programme has changed the way agricultural postgraduates are being trained in Africa.

These developments couldn't be more opportune, for now the global crisis of changing weather is gathering momentum and it's anticipated that Africa is in for a particularly torrid time in the years ahead. The picture of advanced climate change sketched by countless experts depicts dystopian scenes of relentless heat, drought and floods, resulting in mass hunger. It's a grim scenario, but paradoxically it could present the profession of plant breeding—and the ACCI—with their finest hour.

Plant breeding, the systematic manipulation of plant genetic resources to produce improved crop varieties, is one of the most important tools in our response to changing weather. Using specialised knowledge and training, plant breeders are already developing climate-smart "supercrops" that can tolerate drought, heat, waterlogging and poor soils; that are high-yielding, resistant to pests and diseases, and more nutritious.

Importantly, plant breeders are able to circumvent capricious weather patterns that no longer follow the internal schedules of plants. All of this is being done using classical, low-tech methods of breeding, rather than biotechnology alone. In this conventional approach, promising parents are selected and crossed for several generations to produce an improved variety.

These skills are critical. In 2016, the Food and Agricultural Organisation of the United Nations (FAO) reported that by 2050 the world's food demand would be 60% greater than in 2006, driven by population and income growth as well as rapid urbanisation. In sub-Saharan Africa (SSA), these increasing demands will put pressure on an already tottering agricultural system.

The majority of producers in this region farm on a small scale, battling against immense odds and routinely harvesting only five to ten percent of their crops' yield potential. Using unimproved cultivars that are low-yielding and susceptible to drought, diseases and pests, their efforts are hampered by poor soils, an almost total reliance on rain-fed irrigation systems and inadequate post-harvest facilities. On top of all this, climate change is already changing conditions faster than farmers can adapt their traditional crop varieties, otherwise known as landraces.

Enter the plant breeder. Using these landraces as core parental material, a skilled plant breeder can tackle these challenges with wide-ranging results. In Europe, a study that looked at the effect of breeding activities around major crops over 15 years found that they had a substantial impact. Increased yields contributed to stabilising markets, reducing price volatility, increasing food supply and social welfare, and adding more than 70 000 jobs and EUR 14 billion to the European Union's (EU) GDP (Noleppa, 2016).

There were environmental benefits too. By generating higher yields per unit of area, the EU imported less agricultural produce, thereby reducing the need to plough up more than 19 million ha for agriculture elsewhere in the world. This helped to preserve biodiversity and natural habitats, and to reduce greenhouse gas (GHG) emissions.

No such study has been done in SSA, but, even taking into account the huge differences between this region and Europe, there's no reason why employing plant breeders on a large scale in the former couldn't produce significant dividends. However, there is one big impediment—a critical shortage of skilled, experienced plant breeders.

In Africa plant breeding has been affected by a global shortage that's so serious it's been the subject of several international conferences and academic articles. Around the world, fewer scientists are being trained in classical plant breeding because of changing patterns in research funding including a focus on biotechnological approaches, the fact that scientists are moving away from the field and into the laboratory, and wide-scale attrition among field researchers (Morris et al, 2006) and (Gepts and Hancock, 2006).

A survey in 2001 of 12 African countries of plant breeding capacity found a total of 367 plant breeders and 84 biotechnologists, and concluded that those numbers were below the critical level needed to make an impact on major crops, and declining. (Guimarães et al, 2006). No more recent figures are available, a fact that underlines the global decline in interest in the profession of plant breeding. This shortage makes it easy for plant breeders from Africa to find work in developed countries, intensifying the continental crisis. In addition, it's complicated by the huge diversity of agroecological zones, which means that African farmers grow a wide range of crops, requiring more intervention than other regions.

Given the parlous state of facilities for scientific training on the continent, and the tendency for students who graduate in other countries to not return, this is a knotty issue, one that the Rockefeller Foundation (RF) found itself confronting 15 years ago. The foundation was pouring money into training African scientists at American universities, but only 30% of the trained students returned to Africa. Its solution was a gamble at the time; to pour substantial funds into building a centre on the continent that would train African plant breeders to PhD level under local conditions.

The success of this venture, the ACCI, has exceeded all expectations. A 100% retention rate of graduates in Africa, mostly to continue their PhD breeding programmes in their home countries, has meant the addition of 109 new plant breeders to the continents' numbers and has resulted in the release of over 140 novel crop varieties.

Because of its reputation as a world-class centre, a total of 38 students with independent funding have enrolled for the course. Furthermore, based on the success of the ACCI model, the West African Centre for Crop Improvement was started in 2007 in Ghana, and has so far graduated 52 PhD students in plant breeding, bringing the total to 161, with more in the pipeline.

A lot of this can be attributed to the programme's design. Most of the ACCI students' theses are tied directly to their national breeding programmes, with research focused on the needs of their home country, right down to specific genetic traits, so it is highly relevant. There were other unanticipated benefits too. While the intention was to encourage students to carry on working in their home countries after graduation, no one was sure how that would happen.

What's become apparent after 15 years is that students have stayed because while doing their research, they learned the necessary skills for surviving in tough, unpredictable local conditions, and made vital contacts in Africa. All of this has given them a head start, and combined with post-doctoral funding from Alliance for a Green Revolution in Africa (AGRA) to continue with their research, has meant that improved varieties have been more likely to get to market quicker.

Forged in this crucible of customised training and local conditions, the ACCI plant breeder is unique. "The product of the ACCI is not a specialist—it's a person able to go out and solve real problems in the real Africa. That is the real benefit," says Dr Joe DeVries, who as programme officer for the RF in 2001 was one of the founders of the organisation.

The graduates are highly sought after because of their polish, competence and confidence, and several have gone on to high-powered leadership roles in African agriculture.

"I can always tell an ACCI student when I meet them in the field, there's just that extra spark that makes me stand up straighter and put my thinking cap on and stop dreaming and think about really specific ways we might be able to help farmers," says DeVries.

Changing priorities of funders mean that the centre is now contemplating a new way forward. The path is uncertain but the intention is to keep producing plant breeders and helping those farmers. No doubt the spark will light the way. In the meantime, a new mould has been created for producing Africa-based, world-class post-graduate education in the agricultural sciences, and this is a story of how to do it.

African Centre for Crop Improvement

- The ACCI is based in the School of Agricultural, Earth and Environmental Sciences at the University of KwaZulu-Natal, Pietermaritzburg (UKZN), South Africa. It has trained more than 100 PhD students in plant breeding, working in 17 countries in Africa.

  It has excellent resources for training, including biotechnology labs, plant pathology facilities, greenhouses and a farm with 18ha of irrigated lands available.
- Crops: any African food crop
- Breeding approach – conventional breeding, harnessing biotechnology tools such as genomic diversity studies
- Academic staff: Professor Mark Laing (director); Professor Hussein Shimelis (deputy director); Professor Rob Melis; Dr Julia Sibiya; Dr Paul Shanahan; Professor John Derera (Honorary Professor); Professor Pangirayi Tongoona (Honorary Professor) Dr Learnmore Mwadzingeni.
- Administrative staff: Rowelda Donnelly.

Since 2002 the ACCI has had access to funding that has allowed for the training of eight scholarship students per annum. This funding is no longer available and until further large scale funding is secured, the ACCI is training MSc and PhD students who have sourced a bursary from a funder such as:

TWAS: http://twas.org

TWAS-NRF: http://twas.org/opportunity/twas-nrf-doctoral-programme

AWARD: http://awardfellowships org/fellowship/overview/

RUFORUM: http://www.ruforum.org/scholarships

In-service training—for members of the NARS and the CGIAR staff in southern and eastern Africa, where the NARs or CG centre funds the student's training.

Note: UKZN does not charge registration fees for Year 1 for MSc students, or for Years 1-3 for PhD students.

The 2017 cohort of PhD students and ACCI staff. Back row (from left): Dr Julia Sibiya, Andile Mshengu, Chapwa Kasoma, Learnmore Mwadzingeni, Prof Rob Melis, Wilson Nkhata, Prof Mark Laing, Susan van der Merwe. Middle row (from left): Nokulunga Manoko, Esnart Nyirenda, Rowelda Donnelly, Mulu Fetahi. Front (from left): Prof Hussein Shimelis, Nelia Phiri, William Suvi, John Lobulu.

CROPS
FOR AFRICA

Photo: Alliance for a Green Revolution in Africa (AGRA)

Establishing a training facility for plant breeders in Africa was a neat solution to two pressing problems that faced the Rockefeller Foundation in 2001

At the start of the 21st century the Rockefeller Foundation (RF) had reached a turning point in Africa. The American philanthropic organisation had been pouring money into building national agricultural programmes since the 1950s, and two problems had been identified. Plant-breeding programmes were not meeting the needs of the continent's diverse agroecologies, and there were not enough breeders to fix this.

"You had a plant-breeding centre in Harare breeding varieties for the central highlands and that was fine," says Dr Joe DeVries, who was a programme officer in charge of Rockefeller's agricultural division at the time. "But as soon as you travelled away in a car into a different ecology, you needed a new variety."

DeVries is a plant breeder by training who speaks with passion about his involvement with the ACCI and its students. Originally from the US, he began his career in Africa more than 30 years ago, as a volunteer for the United Nations. He's worked in the realm of food security in many countries, including organising agricultural relief and recovery programmes in war-ravaged countries like Angola, Mozambique, Somalia and Sierra Leone.

"We had determined that given Africa's huge, diverse agricultural landscape, one of the main barriers to seeing a green revolution was the lack of improved varieties among each of the many agroecologies where farming takes place." He's referring to the original Green Revolution that took place between the 1930s and 1960s, and saw a huge increase in agricultural production as a result of the transfer of new technologies. While most of the developing world benefited substantially, especially India and China, it missed Africa.

"It dawned on us that Africa's challenge revolved around solving this diversity issue. The breeding function, which was one of the ways farmers could get higher yields, needed to be decentralised."

This meant staffing research stations in all the different agroecologies with people trained in plant breeding, so that they could develop varieties suitable for those areas. A resolution was made to support a new programme for training more breeders, but where would it be based? The RF was already funding PhD training in the US and Europe of young scientists, who were meant to return to their home countries once they graduated. The problem was, most didn't.

TRAINING IN AFRICA

Instead of coming home to join national agricultural programmes, they found jobs, any jobs, outside Africa or with international agencies working on the continent. According to DeVries' manager at the time, Dr Gary Toenniessen, in many cases the universities they attended helped the graduates to obtain better paying positions, rather than encouraging them to return home.

Despite these misgivings, the lure of first-world facilities was strong, and DeVries says his first inclination in looking for a university to host the breeding programme was to choose one in the US. The RF had worked with Cornell most frequently and he had graduated from there.

"Cornell welcomed me and indicated that they would be happy to take on the work of running a new plant breeding programme, but I felt uneasy. I knew the costs and had seen what kind of learning situation winter presented for African breeders. So I decided to cast around to a few other universities. The RF had a real commitment to excellence," he says. "This programme was the successor to a highly respected rice programme in Asia funded by the RF."

"All those people went to do PhD studies in the US or UK and came back with fantastic training, able to do very high-quality work. We had committed to producing the same quality of students for Africa, we didn't want to compromise," says DeVries.

He decided to investigate possibilities in South Africa, because he knew it had excellent educational facilities. However, neither the University of Cape Town nor the University of Pretoria fitted the bill, and he was about to give up when it was suggested that he visit the University of KwaZulu-Natal. There, in mid-2001, he met with Mark Laing, who was a lecturer in plant pathology at the time.

"Within five minutes of talking to Mark I knew my search was over," says DeVries. "He just got it. He understood exactly what I wanted. He understood the diversity issue and that we wanted to train African national crop breeders from humble backgrounds, who probably grew up on rural farms like most of the people they wanted to assist. They had little idea of what it took to create new varieties, but had that irreplaceable contextual knowledge of what farming was about in their home countries, and that's the kind of people he wanted to train."

DeVries had already recognised a weakness in previous RF programmes, which aimed too high in terms of scientific standards, but at same time the RF didn't want to aim too low.

"There needed to be a middle ground which equipped students with all the fundamentals of what it took for them to be an excellent breeder, in terms of the pathology, the theory around crop genetics and methodology, and produced people who would be pioneers in turning out the varieties that were needed in their home countries," he says. DeVries emailed Toenniessen to tell him that they had found the place where they could train large numbers of African scientists, and Laing started writing his proposal.

Laing is a professor of plant pathology whose office walls are covered with colourful artworks. Originally from Zimbabwe, he developed an interest in breeding for resistance to various crop diseases, and says he jumped at the chance to set up a centre devoted to plant breeding, where he could implement the ideas he'd been lecturing on for 25 years. Coincidentally, he had developed a proposal a few years before, for a post-graduate course in pest management at an Iranian university. "The idea was dropped but I had put a proposal together that included the whole concept of block-learning," he says.

He had also gained valuable ideas for his proposal through contact with Dr Walter de Milliano, a Dutch plant pathologist whom he'd met at a conference in 1988. De Milliano had first came to Zambia to breed wheat as an alternative to military service in the Netherlands, and had ended up staying. He had extensive experience working for the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). De Milliano says the seed for the ACCI model came from his own experience of doing a PhD through Wageningen University in the Netherlands, while working at a research station in Zambia.

"Mark liked that I did a PhD in Africa on a crop requested and supported by the government, and he liked the idea that the university had facilitated guidance for research for this kind of PhD. He made it a reality at the ACCI." De Milliano was involved in helping to develop the concept and curriculum of the centre, which was given the go-ahead in October and opened its doors to eight students just four months later, in January 2002.

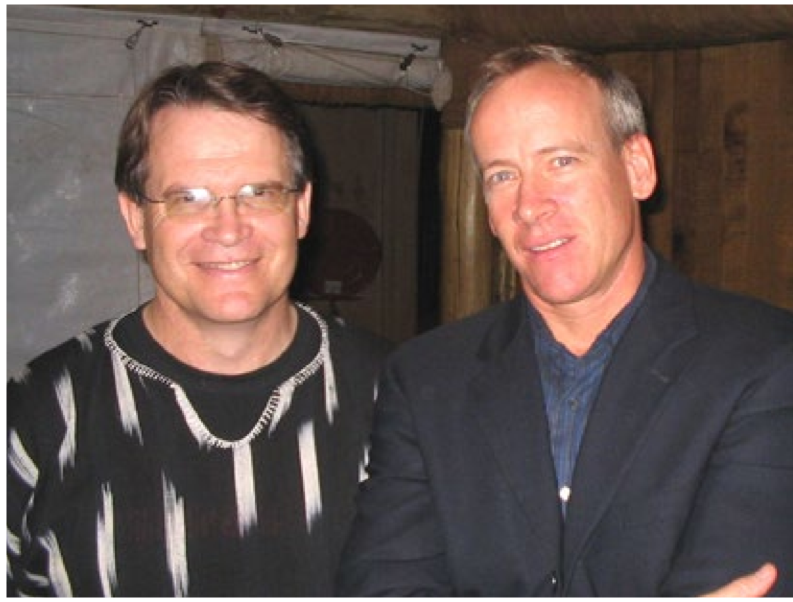
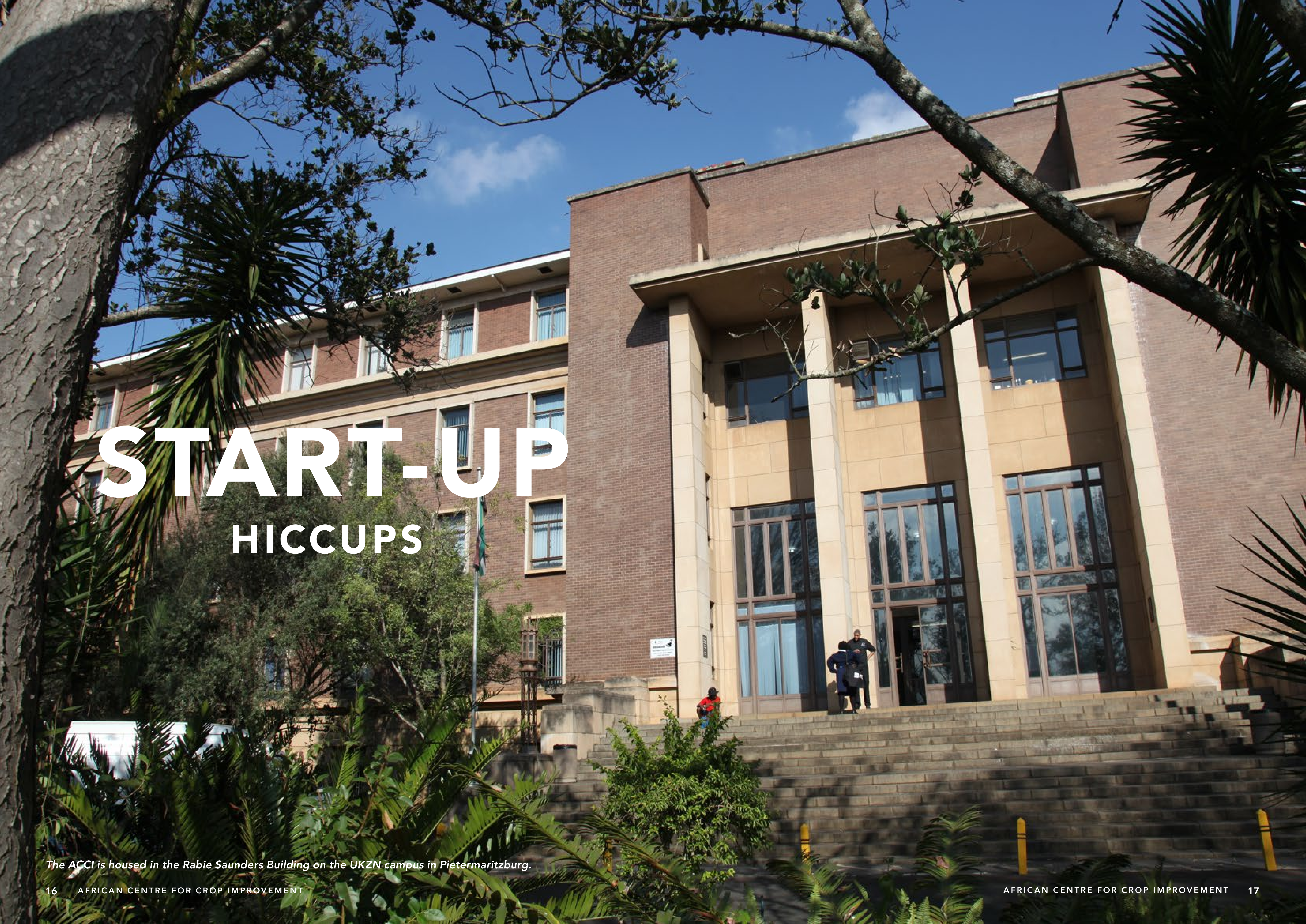


Photo: ACCI

Mark Laing (left) and Dr Joe DeVries at a party for the first cohort of students in 2004, before they left to go and do research in their home countries.



START-UP
HICCUPS

The ACCI is housed in the Rabie Saunders Building on the UKZN campus in Pietermaritzburg.

The ACCI's first cohort with staff in 2002.

Setting up the ACCI was a creative process with a few bumps along the way

The first year was difficult. "There were numerous start-up hiccups," says DeVries. "We called the first cohort 'the guinea pigs'. They discovered when they arrived that they were joining a sort of handmade PhD fellowship programme. Some reacted negatively, they thought it was maybe not a real PhD."

Dr Geoffrey Kananji (graduated 2007), a Malawian who was part of this cohort, says they were "unsure about the programme, what its background was and who the sponsors were. I just received an email from the ministry, saying I'd received a scholarship."

The students had their gripes, which helped shape the programme. Accommodation was one, the amount of their stipends another. For some, just being in a new environment in South Africa was a problem. They had to fit in and it wasn't easy. There was also tension between them and a few university administrators, and some students were not happy that the programme was going to take five years to complete. "We thought it was too long," says Kananji.

Several of the students were relatively old, in their 40s and 50s, and had already done years of studying and working, which contributed to a resistance to being tested. "They didn't want to take exams and be graded," says DeVries. "Mark insisted this was a different kind of PhD. He said, 'we're training you to be a kind of Special Forces. The context you're going back into, there's no breeding going on'.

"He told them, 'You're going to have to develop a lot of your screening facilities with your own bare hands. You're going to have to train your technicians how to plant. You're going to have to set up your own data analysis on your laptop. We'll come out and visit you from time to time but you're going to have to get out all this stuff, and we want you to be tested by fire in an intellectual sense, in a moral fibre sense."

According to DeVries, this tough-love approach was combined with an "unshakeable belief that those students could graduate and go out and be the best plant breeders that Africa had ever seen. That really made a huge difference. It was that confidence building that came with the instruction, and students responded to that as much as to the instruction," he says. Slowly the problems were dealt with and things settled down. Structures were set up so that students had representation at staff meetings, where they could raise issues.

Above: Dr John Derera, who was part of the first cohort of ACCI students, graduated a year early. He's now a honorary professor in the department.

Professor Rob Melis, a plant breeder from the Netherlands who has worked at the centre since the beginning, says this system was introduced after the initial problems, and was "part of the learning curve. Nowadays the opportunity is not really taken up, but it's good to have a forum where they can raise issues like housing and book allowances."

FINDING THE RIGHT STUDENTS

Finding appropriate students for the programme was a big challenge. "There were some students whose basic science wasn't up to the programme, and we declined to fund them after one year," says Laing. "The funders and students were not happy about that."

Candidates had to come from a wide range of countries, but not many in Africa have facilities for training plant breeders at undergraduate and masters level. "The number of universities and how well the students are being trained is important in determining how many students there are to choose from," says Laing. "The next challenge is, how do you evaluate them?"

"Some universities don't train masters students at a practical level. It's also difficult finding the right quality when you don't interview the person. Skype doesn't work without good bandwidth, and if someone is sitting at a research station in Uganda, sometimes the nearest email connection is 20 km away. We just have to gamble and work on word of mouth. However, because there are so few scientists in Africa, each one is known."

Gender is also an issue (see page 20). American funders want at least 50% women, but in many African

AGRA takes over

In 2008 there was a new development that meant significant change for the ACCI. Whereas before funding had come directly from the RF, it would henceforth be paid to an agricultural development organisation called Alliance for a Green Revolution in Africa (AGRA), and disbursed by a sub-unit called Programme for Africa's Seed Systems (PASS), a $150-million programme focused on developing African seed companies.

AGRA was started in 2006 after a call made by then secretary-general of the United Nations, Kofi Annan, for "a green revolution in Africa". Its vision was to help develop African agriculture so that it could feed itself, and RF people on the ground joined it and provided the core staff. Initially funded by RF and the Bill and Melinda Gates Foundation, other donors have since joined the list of benefactors.

For the ACCI, the first phase of funding solely from RF ended in 2007 and the next phase of support by AGRA began in 2008. The biggest change for the PhD programme was that it was reduced from five years to four at the request of the funders. The cut was made in the coursework section, which for some students was preferable, because they got to go home sooner, but for the staff it was a loss.

"Students who came for only four years had less soft skills," says Derera. "That's where the cuts were made. Things I used to do with students I couldn't do in one year." Melis says there wasn't enough time to bring non-plant breeders up to speed, and some undergraduate courses had to be dropped.

There were advantages to the new regime, however. "A lot more staff were hired with the AGRA grant," says Dr Rufaro Madakadze, programme officer, education and training for AGRA. "When we took over, AGRA's main mission was to train plant breeders." Since then, the focus has shifted to other areas of the agricultural value chain, and the ACCI has found itself having to look elsewhere for funding.

The establishment of AGRA also saw DeVries, who had been a regular visitor to the centre in Pietermaritzburg, moving on to a new position as programme director for PASS.

"I went down every year for the first five years and every graduation for four years," he says. "But with my new job I had to step away from oversight of ACCI and I regretted that. It kept me in touch with the coalface of this industry, the new varieties, diseases and training that's required to create a new plant breeder."

Challenges for Women Students

Forty percent of ACCI students have been women. This is below the 50% level preferred by funders, but it's difficult to find enough women who have a master's degree in the agricultural sciences. To accommodate those they do find, the ACCI has had to deal with the issue of students with children.

"We made the decision to make it possible for a mother to have her children in SA," says De Milliano. "It's no longer like it was in the old days, when students would go to study overseas for five to seven years, and leave their family back in Africa."

This issue first came up when Dr Clare Mukankusi (graduated 2008) from Uganda discovered she was pregnant after arriving in Pietermaritzburg. Her child was born in her first year of study. "The ACCI supported me throughout and offered me help when things were difficult, like paying for the services of a nanny when I participated in a plant breeder conference away from Pietermaritzburg," she says. "School schedules were not friendly for a young mother but it toughened me, and support from my classmates was a great help."

Mukankusi had to pay for her child's needs out of her student allowance, but in later years mothers were given financial support for their children. "We don't have a written policy because we didn't want to be tied to anything, we need to be flexible," says Laing. When Dr Julia Sibiya (graduated 2010) arrived with two young children under six, she couldn't afford a nanny. "One of the things we had to fight for and explain to the AGRA director was why we needed support for children," she says.

"Eventually we got an allowance for children that covered their medical aid and school fees. I dropped them off at crèche in the morning and fetched them at 5pm from aftercare. I was grateful that they agreed to support us and allowed us to continue with children. It was challenging but I managed, I was top in the class. My kids really motivated me to work harder and be organised", says Sibiya

Some mothers made the difficult decision to leave their children in their home countries for two years. "I remember very well that I left my daughter who is now six years when she was exactly one year old.

Julia Sibiya: 'My kids really motivated me to work harder and be organised.'

It was a hard decision to make," says Dr Ruth Musila (graduated 2016). "I had to adjust and concentrate on my studies." Dr Hirut Betaw (graduated 2016) says she "felt guilty about leaving my small son for a long time, and at times it distracted my focus".

On being a woman in the male-dominated plant-breeding world, Mukankusi says she has found the science community to be "welcoming as it fascinates them. However, there is always a feeling that people still do not take women seriously and will judge them based on how they carry themselves in their private lives. As such, interaction with colleagues is only at an official level and few friendships develop due to fear of judgment."

"There is also a tendency for men to not take women seriously unless they exude a very serious aura. I am always armed with facts and realities, as I expect to be challenged or ignored during important meetings when men are the majority."

countries fewer women get educated, especially to the MSc level, and trying to find women scientists who want to do plant breeding is not easy.

"Nowadays we have better connections and people get recommended," says Laing. "That's the ideal situation."

STAFFING AND SUPERVISION

Finding people to teach and supervise the curriculum was also difficult. Globally, plant breeders are in short supply, so finding suitable staff to work in Pietermaritzburg was hard.

The course-work component covered a full spectrum of training, and this coupled with the number of students—up to 10 per year—meant that several staff members were needed. At one stage the centre employed seven people who were all lecturing, and on top of that, foreign lecturers were brought in from all over the world to teach in areas where ACCI staff didn't have sufficient expertise. The course work section followed a block system, which allowed for experts to be brought in for short periods of intensive instruction. Here the centre was hampered in being able to pay international-level stipends by foreign exchange rules and tax regulations.

Supervision was tricky to implement and carry out because of distances involved. The ACCI works in up to 12 countries in southern and east Africa, which is more than most programmes, and there could be up to 40 students in the field at one time. "You have to track each student," says Laing. "At our peak we had seven staff members, including me, to help supervise them." That number has declined and the current staff members handle about seven students each—still no small number, entailing at least 14 trips north of South Africa per year for each supervisor.

INFRASTRUCTURE

Generous funding was provided for resourcing and training the students, and each was given a top-of-the-range laptop, and camera to help with their research. The centre, however, operated on a shoestring budget.

This was because of a perception, held by RF and other development agencies, that South Africa, as a relatively wealthy country, should not receive funding. The RF stipulated that, as far as possible, money was to be spent on the students, and in their home countries, rather than investing in South African resources.

Sixty percent of our expenditure goes into research in home countries. That's where the bulk of activity takes place, not in South Africa.'

– Mark Laing

"At UKZN we used existing staff and took over existing resources," says Laing. "Initially there was resentment because suddenly seven offices and two laboratories were gone." Despite this annexation of space, fitting everyone in was still difficult, and Dr John Derera, a Zimbabwean who was part of the first cohort, recalls that the first eight students were "squashed into a tiny office" with the ACCI's financial officer, Lesley Brown. Derera graduated a year early and became a member of staff in 2006. He's now global head of research and development at Seed Co Ltd.

Where expensive facilities were needed, cheaper, innovative solutions were found. For example, a greenhouse facility was needed where students could receive practical training and work on tropical crops through the Pietermaritzburg winter. The estimated cost to build it was R2 million. Instead, one was built for about R250 000, using wooden poles, shade cloth and hoops made from steel pipes that had been bent by the ACCI technician, using a hydraulic car pipe bender.

"We've done everything on the cheap, so capital-wise we've got very little," says Laing. "Sixty percent of our expenditure goes into research in home countries. That's where the bulk of activity takes place, not in South Africa."

Managing budgets was and still is made difficult by the fact that half the money the ACCI receives is held in an overseas account. "It's all in dollars," says Laing. "The problem is that expenses in SA are in Rands. How do you budget for that? What do you set the budget at when the exchange rate is fluctuating? In 2007 over nine months the exchange rate went up to R13.80 and then dropped to R5.30 to the dollar, reducing our rand income by 60%."

A HOME-GROWN WORLD-CLASS CURRICULUM

From left: ACCI graduates Dr Ermias Desta, Dr Batiseba Tembo, Dr Michael Chipeta, Dr Hirut Betaw and Dr Stephan Ngailo at the ACCI premises in Pietermaritzburg.

Students were equipped with an array of hard and soft skills so that they could do their research projects independently in their home countries

"No one had really done anything like it before," says Laing, describing how Africa's first plant-breeding centre was built. When the first students arrived, the ACCI had a home in the School of Agricultural, Earth and Environmental Sciences at UKZN, Pietermaritzburg, but not much else. "A lot of the content of the training programme we offered had to be new," says Laing. "We didn't have staff apart from one plant breeder, so for the first year the students took existing university courses."

The first appointment, in December 2001, was Brown, who had experience in financial management and was hired as an administrator. During 2002 Laing also hired De Milliano, Professor Pangirayi Tongoona and Melis, with whom he designed a curriculum for the second year, and Beulah John who taught scientific English and techniques needed to do a PhD. The curriculum evolved significantly over time, and was constructed by looking at what a plant breeder needed to know. Initially, that included a full background in genetics and plant breeding, with lots of statistics, some plant pathology and entomology, and a range of "soft skills".

The level of knowledge of students entering the programme had to be factored in. "Most students that start here have a masters degree," says Laing. "The assumption is that it equips them to do a PhD, but that's not always the case." For example, courses in population and quantitative genetics, which are seldom taught in Africa, were included in the curriculum, because it is necessary for plant breeders to be able to look at how one or many genes shift in populations, through mutation, selection, migration and genetic drift.

"Most places in Africa, including South Africa, only teach Mendelian genetics, which deals with the laws of inheritance, where genes operate by themselves and have an action or no action," says Laing. "In fact most genes don't work that way, they work by interactions with other genes and the environment. Something like drought tolerance in maize is polygenic, where more than 70 genes are involved, so you can't use the tools that were developed based on Mendelian genetics only."

Another subject that was included was statistics, because the staff wanted students to have an understanding of advanced experimental data analysis and statistical genetics, so that they could do sophisticated genetic analyses of their crops.

Because there weren't enough applicants with plant breeding backgrounds, the programme was opened to people with masters in other areas, such as crop science, entomology and soil science. "We took them and converted them into plant breeders," says Laing. Their PhDs focused on their expertise, so that, for example, a plant pathologist's project would be about disease. "It meant we had to start from scratch. This has evolved over time and now we get more people with a plant breeding background," he says.

Besides, many students in the first cohort were older and had been out of university for several years, so even if they had a plant breeding background, they needed an "update". And if they weren't a plant breeder, they needed full conversion. Biotechnology, or the use of scientific techniques to manipulate plants at a molecular level, was a fairly new area for most scientists, so a full background in that and how it would work to their advantage, also had to be included.

ENGLISH FOR SCIENTISTS

Since many of the students spoke English as their second or third language, support had to be included to enable them to write at PhD level. However, this wasn't as simple as providing English lessons.

"We tried using the English language courses offered on campus, but realised they wouldn't work because they were teaching English for humanities, not scientific English," says Laing. "There's a huge gap between the two, and the way language is constructed is entirely different. The lecturers were talking about ideas, constructs, and "the argument", but in science we don't work that way. We go out and construct evidence by running experiments, which creates outcomes and results that we then analyse, present and discuss.

"We hired a linguist, Beulah John, who was able to make the quantum jump and understand the difference between humanities and scientific communication. She created a course in advanced English communication that revolved around the difference."

The students weren't impressed. "At first we resisted it," recalls Derera. "We thought they were saying we couldn't speak English, and to us it was a waste of time. But later it evolved to be about academic writing and was taught in that light." Derera says the writing class became one of his most important because, apart from teaching him how to write essays and how to argue, as well as about the structure of scientific language, the course also taught soft skills like how to prepare a research grant and how to approach a donor.

PHD TOOLKIT

Successfully completing a doctorate on time is universally a major achievement. In the US the average PhD take seven years to produce, and there's a 50% drop out rate. At UKZN the average time taken is 5.3 years for a PhD in science.

"That's nearly double the length of time it's supposed to take," says Laing. "The common experience is of people taking one or two years longer than scheduled. We didn't have that luxury. There was a guillotine—no further money for the student outside the bursary. If they weren't ready to hand it in on time, they wouldn't finish." With this in mind, the ACCI looked at deconstructing the PhD process into the skills and processes needed to finish on time. What potential bottlenecks could there be? How could they be eliminated? What training could be given?

An important part of the centre's PhD programme is the mini-research project, which students have to do at the ACCI during their academic study year. Although they are visited by supervisors at least twice a year, they spend much of the time working alone and must be equipped with all the essential technical skills before they return home, so that they can function independently.

"There were technical skills that were holding students back," says Laing. "They were plant breeders in name only. Many had never done an artificial pollination before because there was no practical work in their courses at the universities where they had studied."

"We invented what we called the mini-projects, which essentially looked at what technical tools each student would need for their PhD." These were skills such as making cross-pollinations, doing biotech

Top (from left): Fee de Stadler, Lesley Brown, Mark Laing
Below (from left): Professor Pangirayi Tongoona, Dr Walter de Milliano, Beulah John.

studies or inoculating with insects or pathogens. "Some technical skills like successful cross-pollination can be very difficult," says Laing. "For example, with Bambara groundnut, you have to do it between 3am and 5am, because that's when the flowers are fertile. And you have to wear a jeweller's loupe because the male and female flower parts are so small."

Because students would be working on isolated research stations where there would be no one to ask if they got stuck, they had to demonstrate in an experiment any technique that staff felt might be a technical barrier for them, whilst they were still at UKZN. Laing says getting stuck on a technical matter could be a major logjam for many students. "When you're insecure you procrastinate. If you're confident you're freed up to do things fast and efficiently."

For some students, learning these skills changed the direction of their careers. For example, two students who came from Kenya—one, the head of a cassava programme, and the other, the head of a sorghum programme,—had never bred their own varieties, they had only tested varieties from an international breeding programme. None of these was suitable because they had been bred in other countries, with different agroecologies. The ACCI works on the premise that there has to be a programme for every agroecology in every country. One variety won't suit an entire region.

"The real breakthrough in cassava breeding in Kenya only happened when our student started making his own controlled crosses, producing his own seed and screening it in Kenyan conditions," says Laing. "Then he got really good quality stuff that could be used. The same story with the sorghum breeder—he had to make his own crosses to make progress with the crop."

SOFT SKILLS

Each student received a total of $30 000 to pay for the three years of field research for their PhD. They were taught how to use Excel and, once they'd defined their research pathway, they had to identify cost components such as transport, labour, planting, weeding, irrigation and fertiliser, and budget for them on an annual basis. They were also taught other soft skills such as how to apply for grants, and give successful conference and Power Point presentations, which all helped to ensure long-term sustainability. "The soft skills component was unique," says Derera. "I don't think there were other PhD programmes that taught this."

PhD students from the 2017 cohort at the ACCI in Pietermaritzburg. From left: Chapwa Kasoma, John Lobulu, Wilson Nkhata, Nelia Phiri, Mulu Fatahi, Esnart Nyirenda, William Suvi.

How to write a PhD without getting paralysed

The ACCI has an impressive record for students completing their degrees on time—75% in four years. To help with the final writing process, it produced a guide for students that outlines what is needed and why, every step of the way.

This helps them to know from the beginning what their thesis is going to look like, and they have an intellectual framework in which to place their information. Students are required to:

1. Identify the endpoint of the thesis so that they can pace themselves.
2. Produce a full proposal at the beginning of the research stage, in which they include the draft contents page of their thesis, plus a timetable for experiments in each chapter, so that when they leave Pietermaritzburg to go home they have a season-by-season timetable of what they will be doing.
3. Write up their research as they go, starting with doing a Participatory Rural Appraisal (PRA) in the field (see page 33). They have to write that chapter after their first year and publish it.
4. Follow the prescribed format for the thesis, i.e. abstract, introduction, materials and methods, results and discussion, references.
5. Follow the prescribed method for writing the Discussion of each chapter, which is seen as a the most difficult section in the writing process. This is because students often get contradictory results, and trying to process them all simultaneously can be overwhelming. The solution is to first capture all the key discoveries in the results section in point form.
6. Next, take these points from the Results section into the Discussion section and use them as the basis for a paragraph on each. Add what other people have found (references), then connect the paragraphs. Breaking the process down like this clears the intellectual bottleneck and avoids paralysis.

IN THE FIELD

With most of their research done in their home countries, students gain valuable experience and knowledge about farmers' problems and local agroecologies

A unique feature of the programme is that the ACCI students do their research in Africa, on local crops. The benefits of this are twofold: the time taken to get improved crop varieties to farmers is reduced, and the retention rate is strengthened, since students get a head start in establishing themselves in their countries.

In most cases the fieldwork done as part of the PhD feeds directly into the national breeding programme in the student's own country. Some already have advanced research projects, and the supervisor's goal is to teach them how to do this with best practice in research methods.

"We assume that there are long-term national projects, and not just for the thesis," says ACCI deputy-director Professor Hussein Shimelis, a genial plant breeder from Ethiopia who joined as associate professor in 2008. "The project should be sustainable. Breeding projects by their nature take a long time, sometimes 10 to 15 years."

The focus of most projects is on food security and drought-tolerant crops. Shimelis says the centre also emphasises the needs of small-scale farmers, and tries to align with the research strategies of the national agricultural system of each country. The breeding work is done in the relevant agroecology, with all the attendant challenges of working in a third-world context, and the students gain valuable experience.

"Africa has its own dynamics," says Derera. "To survive you have to have an understanding of the landscape; it is one that is highly dynamic. It's a place where you have to sort out logistics 80% of the time, and you have to be smart enough to deal with things when they don't work out.

"The ACCI trains you for that environment. Students are taught to be self-sufficient, working at a distance. For example, you are the one with money. Because of your grant you will be earning more than what the director at the government research station earns. You have to deal with the politics of the station."

These politics can be petty or serious. At one station in northern Zambia the director and the financial officer "abused" the student's money, and it took a top-level intervention to sort things out. At another station, in Kenya, two students were due to get their PhDs before the director, so he made them share a small room with other students, and then removed the lighting for the office. Again, an intervention had to be made, and the jealous director was sent off to an even more remote station.

There are other, more mundane challenges, such as limited access to quality scientific literature and laboratory facilities for analysis, and communication problems due to poor internet connectivity.

"By the time the students are finished, they are hardened," says Derera. "Working in Africa is very difficult for someone coming from the US. It takes two to three years learning to deal with all the issues of the Third World, but the ACCI guys have already gone through the mill. They've learned how to deal with all those politics, the economics, the Third-World challenges, like having no electricity or no fuel."

For many graduates the space provided by being supervised from a distance had its benefits. Betaw says doing research in her home country, Ethiopia, gave her the opportunity to be left to her own devices. "I developed my skills in research and financial management, teamwork, problem solving and decision making, and became more confident and familiar with the problems I face in my breeding work at home."

Dr Justus Chintu (graduated 2013), a Malawian, says working away from supervisors gave him "independence to learn to run my own project and sort out challenges which cropped up". Working in their home countries also provided the opportunity for building relationships that would benefit students in their careers. "The student was in touch with his employers, which made it easier to continue in the job effectively after studies," says Dr Francisco Miti (graduated 2008), a Zambian maize breeder.

SUPERVISION

In negotiating this environment students are given plenty of support. They have their own funds that make them relatively independent of local systems. They are equipped with a road map of how to proceed in their research, written in their first year, and technical skills they will need to do it. Each also has a primary supervisor and one or two co-supervisors from the ACCI.

Hussein Shimelis (centre) in the field in Rwanda with ACCI graduates Dr Placide Rukundo (left) and Dr Jean-Baptiste Muhinyiza.

The supervisor goes into the field with the student and checks trial designs, harvesting, and whether they are doing things correctly. Sometimes supervisors also meet with administrators. This hands-on supervision is important, says Melis, because distance learning can be a challenge. "We're not always there and things can go wrong. Often you have to intervene. For example, I visited one student in Kenya, who was having a problem with an insect and spraying without success. When I went there I just had to recommend a different chemical, which worked."

De Milliano describes an instance where a student was struggling with his research, and he helped him build a greenhouse for breeding insects. "For the first time in the bush, he managed to do the experiment," says De Milliano. "Julius Nyerere said research stations should be with the farmers. There's a limit to that idea, but what is strong about the ACCI is that it's doing this."

De Milliano adds that the psychological benefit of these visits by supervisors should not be underestimated. Recalling the effect on a student who was working on an isolated station in Serere, Uganda, he says, "when a foreign professor came all the way from SA, the leading country in Africa, to visit him, his colleagues were very impressed. It's a huge boost."

Students may also have an in-country co-supervisor. This is a senior staff member at the research station who mentors the student and fights political battles for them in terms of allocation of resources like land, staff and transport. "If you're a young scientist, you need a heavyweight, someone who understands how things work and can help you with allocation of resources and getting things done," says Laing. "In some cases these mentors were fantastic support. Initially we were able to pay them, and then not, but we still got great support from some in country-co-supervisors, even then."

MANAGING SUCCESS OF STUDENTS

Each student is given $30 000 over three years. This has to pay for about three years of field trials and necessities like subsistence, transport and petrol, which in many countries are expensive. The students have to budget for all these resources, and are taught how to know what each experiment will cost, and how to track expenditure against projected expenses. "This is a standard in project management, but scientists often don't do that, so it's a powerful tool that we teach our students," says Laing.

Students are taught how to use software for mind mapping, where a diagram is created to visually organise thoughts, so that they can capture ideas for what they are doing. They are also taught to use Microsoft Project as a tool for viewing their own resources, in terms of project management.

"That led us to the realisation that each student was a project, and to see the PhD as a project with a timeline and an action path, where you could do critical path analysis," says Laing. "That was a huge breakthrough. In the past, with no timeline and no research pathway, things drifted. In IT project terms this is called "slippage"—the gap between how you're doing things and when you said you'd do them by."

Managing slippage with the students was crucial. They needed timetables and, as with any project, there were time, money and milestones involved. "How do you keep a timetable in a creative process?" asks Laing. "When we first started, colleagues criticised this idea, but you have to be creative within the time available."

WHEN THINGS DON'T WORK OUT

Sometimes students don't live up to expectations, or their progress is hampered by an external factor. Supervisor visits and quarterly reports by the students and their in-country supervisors are used to monitor progress, and often pick up problems.

"If you're going to have students in distant places you must have a mechanism for tracking them," says Laing. "The reports work well. They're done very thoroughly, and we go through the financials as well." In the case of the student whose money was being siphoned off, no progress had been made and his funds had disappeared. When he was questioned, the real story came out.

"You must also see things for yourself," says Laing. "Supervisors can be conned. You must see plants in the ground." He tells how in Mozambique, it was discovered that a student had crops growing but had given the job to someone else, and didn't know what was actually happening. "It's tricky to sort out problems like that. The funder has invested money and everyone blames you if you want to sort it out. But if a student is not up to it, you have to pull the plug."

Laing has come under enormous political pressure to keep students the ACCI considers unsuitable, from funders who have spent money and UKZN, which stands to lose considerable revenue, but he's unrepentant about his tough stance. "A doctorate is not just an academic and intellectual challenge. A lot of drive, personality and social skills are involved. It's a very challenging experience and is about how tough you are. A lot of people are not up to it."

Travel in the rough

Dangerous air travel, dysentery, burglary and bad roads. For ACCI supervisors, travelling to visit their students has been exciting, enriching and at times terrifying.

On a trip to visit a student at Manza research station in northern Zambia, Melis, Dr Paul Shanahan and Laing had to charter a small plane to fly over Katanga, the war-torn finger of the Democratic Republic of the Congo (DRC) that pokes into Zambia. The three passengers lost consciousness in the air because the plane wasn't pressurised. "The pilot said he wasn't affected because he was used to it," says Laing, adding that the huge, Cold-War-era airstrip at Manza had no control tower.

On another trip to Ethiopia, he got dysentery and nearly died, but he also remembers the magic of seeing Christian Orthodox churches cut into volcanic rock in Lalibele, in the north of the country, and that it took eight hours to drive 300km on a good tarred road, because of the plethora of livestock wandering about, including camels.

Shimelis says his eight years of travelling extensively in SSA have taught him valuable lessons about the diverse cultures, agroecological and farming systems that he's seen, but he's also had to contend with vehicle breakdowns, car accidents and the theft of all his valuables from a hotel room in Tanzania.

"The travelling has been good," says Melis, who's Dutch, and generally understated, although he uses words like "pioneering" and "hectic" in the next few sentences. "You don't go as a tourist; you meet the students and their families, and you sometimes stay in villages. It's been an eye-opener."

Laing in Benin

Breeding what farmers want

In West Africa dwarf varieties of rice were bred but rejected by women farmers. When local women were eventually interviewed by an ACCI student, they explained that they harvested the rice while carrying children on their backs. Harvesting was by hand and they wanted tall varieties that reached chest height, because they were easier to cut without bending.

In Ethiopia a new dwarf variety of sorghum was bred that took 25 years to develop at great expense, but it was rejected by farmers because they had multiple uses for long-stemmed sorghum plants, valuing the stem as much as the grain-bearing head. Farmers have been criticised for being "anti-progress", when the real issue is that the plant breeders do not always match improvements to local needs, because they failed to ask what key traits the farmers wanted in new crop varieties.

The ACCI believes that this approach is fundamentally flawed, and in some cases has resulted in years of expensive research going to waste. To avoid this, the centre incorporated a tool called Participatory Rural Appraisal (PRA) into the methodology used by students in their PhD. PRAs are used in development work to collect and consider the opinions and knowledge of local people, when planning projects that affect them. The breeder does a survey and farmers are asked, for example, if they want tall or short stems, big or small grains, the colour of grain they prefer, and what the crop will be used for. This information is then used to do the breeding, with the breeder choosing the best varieties according to their criteria and the defined farmer-preferred traits.

In the West African case, the information about the need to develop tall rice varieties came to light when Dr Andrew Efisue (graduated 2007) did his PRA. For other students the PRA uncovered unexpected preferences on the part of the farmers. Musila found that good baking quality is highly prized in rice varieties in the area of Kenya where she worked, because rice bread is a staple, used in traditional ceremonies and as a cheap, convenient breakfast. Jimmy Lamo (graduated 2010), working in Uganda, found that rice aroma is very important to consumers.

In addition to the PRA, some students have gone a step further and used the Participatory Breeding approach, where farmers' opinions are canvassed after cross-pollinations have been done between parent plants, the resulting seed has been planted and a range of progeny need to be selected. Farmers are invited to the field to choose the varieties they like the most. Crops may even be cooked there and then in the field, to taste the different options.

However, participatory breeding can be a slow and resource-demanding process, because farmers have to be brought to the fields every time selections need to be made, so it's not often done. "It's good to do both. From a rigorous academic point of view, it's important to do the PRA so that you can be sure that you've met most of the farmers' criteria for traits they think are important. You can apply statistics to it and get a clearer picture," says Laing. "But you also need to get farmers' input on judgment calls that must be made about which varieties to keep. Many quality traits are not easily measureable, for example, taste."

Derera says soliciting farmers' opinions is a "unique" aspect of the ACCI thesis and valuable because "you get a product that will go places. ACCI varieties are more likely to be adopted by farmers because of that, because you aim to deliver what your end users want."

"Our research areas were problem-driven," says Kananji, who did breeding on common bean. "You interacted with the farmers in your own country, got to understand what their problems were, and analysed and validated them. This process is important because it drives ownership of the problem."

Smallholder farmers

Account for 80% of all farms in SSA and provide 80% of food in Africa.

Depend almost entirely on rain-fed agriculture.

Labour shortages are a major constraint, especially for planting, weeding and harvesting.

Directly employ about 175 million people, of which 70% are women.

Farmland is often degraded with poor soils.

No irrigation and limited fertilization is applied.

Yields of most crops are typically 10-20% of yield potential, and are well below global averages.

Lack labour, inputs, credit and don't participate in commercial markets.

Crop varieties are usually landraces developed by farmers over hundreds of years, with some good traits such as drought tolerance but usually a low yield.

Yields are typically 5-10 % of potential.

Labour productivity and incomes lower than global average (about $2 per day).

Photos: Alliance for a Green Revolution in Africa (AGRA)

UNCHAINING
MINDS

Dr Cousin Musvosvi, a post-doctoral student in the MSc plant breeding programme, in the library at UKZN.

An important aspect of the ACCI programme is producing empowered scientists who are able to think and act independently

Academic libraries in most SSA countries are severely lacking in contemporary content, and one of the difficulties for ACCI students is how to keep up to date with cutting edge research, once they leave South Africa.

Although big strides have been made in the last decade, internet access in most African countries is still not widespread and fast enough to make using it for research a viable option. For a start, electricity provision in SSA is poor and often unstable, with South Africa using 60% of the power generated, and the rest of the region's 860 million people using substantially less power than Spain.

Africa has one of the lowest internet connectivity rates in the world, with only about 200 million people, or 20% of the population, able to access the internet, largely through mobile broadband using smartphones. This is changing rapidly. The installation of half a dozen deep-sea cables along the eastern and western seaboards since the turn of the century has been a major boost for the continent's digital revolution and the number of internet users is expected to double by 2020.

Data charges, however, are very high and remain a significant barrier. Another obstacle is access to quality research. The cost of subscribing to the most prestigious, peer-reviewed international journals—that account for publishing approximately half the world's academic research—is beyond the reach of most African universities, and the publishers are not prepared to make their content available at affordable prices.

"Students do a good literature review here while they have access to the library resources," says Laing. "But even UKZN can no longer afford to subscribe to all the important overseas journals, so our resources are getting worse. We've had to go back to the old days of writing to an author and asking for a copy of their article. That's what we're reduced to. In the past we had access to fantastic journals, but now we don't have access to key publications anymore."

The book budget at UKZN is also contracting because of the exchange rate, which has made it difficult to keep up in complex subjects. In the early years the ACCI partnered with Cornell University to provide literature, but it was very expensive and AGRA was not prepared to continue funding it.

The growth of open access journal sites, where research is shared, mostly without restrictions, is making a difference. "There's always a way of accessing databases," says Shimelis. "Nowadays students can use social media sites like ResearchGate, which is not completely comprehensive, but they can often find what they are looking for."

The bottom line, however, is that students lose out. "They just don't read the literature. There's very little reading. One of the problems we have as a university is that the literacy of our students is going down," says Laing.

"When students arrive, some have never had access to journals. They're suddenly faced with thousands of references to maize, and to be able to pull out one is a huge task. They're also coming from schools and homes where reading was not the norm."

INDEPENDENT THINKING

Part of the training of a Doctor of Philosophy includes being able to think independently and analytically. Graduates must be able to look at literature critically and disagree with the current paradigm if necessary.

Shimelis says independent thinking is encouraged by the design of the ACCI PhD, where students work alone on their own research projects when they return to their home countries.

"In Europe, most (African) PhD students don't work independently. They take a portion of an existing project of their supervisor, and do their PhD on that," he says. "You're not on your own. Then, when you go back to your home country you start from scratch."

In terms of challenging beliefs, Laing cites an example of cassava breeding, where "the paradigm international scientists were trying to sell was that it was such a difficult crop, only they could breed it". They believed there wasn't expertise at any national research stations to do it.

He believes that paradigm was being pushed in order to hold on to research funding. "We had to challenge that and point out that what they were doing was inappropriate and inadequate, and that there were better alternatives. And secondly, that it was relatively easy, quick and cheap to do that. Cassava is probably the easiest crop to breed." ACCI students are now breeding and releasing new cassava varieties in Rwanda, Uganda, Zambia, Kenya, Malawi and Mozambique.

It's difficult for many African scientists to challenge the existing paradigm because there's a hierarchy of respect, even in universities. The environment is not egalitarian and this is a problem even in first world countries. Those who do challenge existing paradigms are seen as mavericks and troublemakers.

"Someone who's really grasped the philosophy of science needs to be free to challenge any paradigm. They need to have the ability, understanding and authority so that they can do that," says Laing.

The philosophy of science says that people present hypotheses which are tested, and if they seem to work, then they become the prevailing paradigm. This paradigm is then meant to be challenged by new paradigms. The problem is if you get a body of people invested in an old paradigm who don't want to change, and who will do anything to kill the new paradigm because it will undermine their status as a guru of the old paradigm, even if it's outdated.

"In an authoritarian system all you do is squash the junior who comes up with a fresh idea," says Laing. "For our students to have the courage to take on the existing paradigms takes huge bravery, and we need to train them to become gurus in their own right, to set up new paradigms and hopefully not to become dictators, but to embrace newer paradigms."

Part of the ACCI's goal is to show what plant breeders can do using conventional breeding techniques, because there's a desperate poverty of imagination amongst government breeders. "They're always in the situation where they can't take risks because they tend to struggle to secure funding. So they choose established topics with low risks, where they can make small incremental gains," says Laing.

Bold steps are especially relevant in the face of climate change. According to some of the latest research, breeding gains are not moving fast enough to keep pace with changing weather patterns. Laing believes that if everybody adopted conventional breeding and went about it in a systematic way, the world could easily beat climate change. "The problem is the politics and funding of research in Africa, plus the psychology of breeders, is such that they don't have faith in themselves and their approach, and so the breeding gains are limited.

"Also, when you're a young scientist at a remote research station, you don't have senior guys to mentor you because they've all been promoted to administration in the capital city. The revolution that the ACCI brings is that we're constantly mentoring our students so that they have people to turn to who say, 'go for it'. We don't have to accept current paradigms, we have the freedom to break them and we give our students the freedom to do that. And having got the experience, they're now free.

"What strikes people when they meet our students is that they have the confidence to go out and be Star Trek scientists, to go out and do what others haven't done. That's the transformation we need in African science. It applies to many subjects but especially to plant breeding. You have to have faith, to believe in the power of plant breeding, and to be sure that in the next three to five years you'll have crop varieties that will be much better than the current varieties."

Laing is emphatic that the ACCI's number one goal with its students is transformation of them as people, and it appears to have been successful. "The ACCI PhD really unchained the minds of people," says Derera. "They became considered in all spheres of life, whether social, political, or financial. Working with donors and even international universities made an impact on their world view."

He described an initiative—that ceased for a variety of reasons—during his time as a student, when they would present project proposals by live video to Cornell University plant breeding staff, who would then comment and advise on them from their perspective.

What was a huge boost to the African students was realising that they knew as much or more than Cornell students about local crops and conditions, and that they had a whole range of experience and skills that should not be underestimated. "The ACCI PhD was done here in Africa but it was a global PhD. It opened up everything," says Derera.

BREEDING

Photo: Alliance for a Green Revolution in Africa (AGRA)

In a world where biotechnology dominates, the ACCI has focused on a conventional breeding approach because it's more appropriate in Africa.

One of the surprising features of the ACCI is that it focuses more on classical plant breeding methods than biotechnology. In the 21st century this might seem anachronistic, but there are sound reasons.

In conventional breeding, parent plants are selected for desired characteristics, and crosses are made and then screened to see which are best. The biotechnology approach largely involves finding the DNA fingerprint of a gene associated with a desired trait in one plant and transferring it to another plant, which is then used to propagate a new variety.

The first reason why the ACCI has stuck mainly with the conventional breeding approach is that most crops in Africa are still at a relatively early stage of development, compared to, for example, America, where plant breeding is at a very mature stage. In the US, plant breeders in the 1950s started taking farmers' landraces and breeding and developing inbred lines and making hybrids. Out of that came three giant companies that now dominate maize breeding: Syngenta, Monsanto and Du Pont/Pioneer.

According to Laing, US plant breeders have run out of diversity in their germplasm and the only way they can bring about change now is to do genetic manipulation. "In Africa we are at the 1950s stage with most of our crops, apart from maize. Most importantly, plant varieties are not well defined and won't be for a long time. You have to go through the process of conventional breeding."

This involves collecting farmers' landraces, seeing what potential there is, taking out the best material and combining it. "There's a failure to recognise that agriculture evolves and has to go through processes," says Laing. "From farmer landraces to hybrids, you have to go through steps, and Africa hasn't gone through those steps in each of its countries."

He argues that because of the continent's enormous genetic diversity, there's a lot of work that needs to be done gathering information, and at this stage biotech is not appropriate. "We can take and use some of the biotech tools but definitely not everything that is considered mandatory for plant breeding in the US."

The second reason the conventional approach is preferred is that most African countries lack the infrastructure and budget to do biotech. "Marker-assisted selection (MAS) is used by Monsanto, Syngenta and Du Pont/Pioneer, but they're huge multinationals and can afford it, they've got lots of staff to do it and they've got plant varieties that are extremely well defined, so it works there and it's worth their while. But in our situation none of those criteria is met," says Laing.

"MAS has limited application in Africa. There are relatively few places here where one can undertake it, whatever the advantages are reported to be. And therefore we focus on conventional breeding because we know that this can take place at any research station where they can grow crops."

BIOTECH YES, GMO NO

Another significant feature of the ACCI approach is that it does not use genetic modification. "When we talk biotech to the general public, they immediately think genetically modified organisms (GMOs), but biotech is a much bigger genetic toolbox," says Laing. "GMO is just one small component."

"We don't use GMOs in our research—for pragmatic rather than ideological reasons. It's slow, expensive and tends to deliver one trait, whereas most African crops need improvement in a whole range of traits.

"And even in countries with enabling legislation, you have to do punitive biosafety studies and then face people with green agendas in committees who just want to say no to their release. So the chance of the work being wasted is high, and it's therefore risky. Also, a lot of countries in Africa don't even have legislation that allows them to evaluate GMOs—so we can't go there either," says Laing.

Time is also a big issue. It typically takes 10 years to make any progress, but ACCI students only have three to four years for fieldwork. Also, most countries where the students are working don't have those facilities. "So from the beginning we said we're not going down that road and our mantra has been to release the power of classical plant breeding," says Laing.

"People underestimate the gains that can be made, particularly where plants haven't been bred much. In Africa, working with material we are using, you can triple the yield of lots of crops, really quickly."

Dr Learnmore Mwadzingeni, a post-doctoral fellow at the ACCI, works on a UV 1800 spectrophotometer, used for analytical assessment of organic acids.

BIOTECH TOOLS USED BY ACCI

DNA fingerprinting

The biotech the ACCI does use is essentially fingerprinting the DNA of crops. One application of this is in diversity studies—for example, if there are 100 different varieties of Bambara groundnut, DNA fingerprinting makes it possible to find out what the origins are and how much movement of seed there has been.

One ACCI student collected samples from around Africa and found that there had been extensive movement of Bambara groundnut around the continent with, for example, seeds from Nigeria being found in Zimbabwe. Tracing a seed's origins is important because breeding programmes require the broadest range of diversity possible in the germplasm that is used. "That way we ensure when we do breeding that we will get the greatest diversity of genes and have the greatest chance of getting novel gene combinations and good traits that the farmers haven't had before," says Laing.

Marker-assisted selection

ACCI students are taught MAS, despite its limitations in Africa. If a plant breeder knows what genes are associated with particular characteristics, it can be used to test progeny for the genes that are wanted. Some genes, like the one associated with Vitamin A, have a visual marker like orange flesh, so testing to see if it's present is not needed. But a characteristic like protein content can't be seen, and the test for protein is expensive, so MAS is a useful way of finding it.

However, MAS is not always the answer, as shown in ACCI attempts to track resistance to maize streak virus in Uganda and Mozambique. In the Ugandan study MAS was used in one project and field-testing in another. The results showed that neither was faster. MAS didn't make bigger gains and the varieties bred using it were not better. “Overall the conventional selection project did better because we could select for other traits at the same time, whereas MAS only selected one thing,” says Laing.

The results of a Mozambican project were alarming because there were multiple errors. The ACCI found that markers may sit on either side of a gene and sometimes break off. Sometimes a marker was present but the valued gene broke off, so the DNA test said that the marker was present but the plant was not resistant. Alternatively, there was resistance expressed even though the marker had broken off. Either way, the marker’s presence or absence failed to reflect the presence or absence of the important gene in about 20% of the test plants.

“The false positives and negatives were significant. We were testing in the field because we didn’t trust the DNA markers. They mostly worked but there were errors. It’s a big problem if you keep a plant because it has a marker for resistance but it isn’t resistant. You’re breeding susceptibility back into your population.

“There are a few situations where MAS is extremely valuable but they are rare. For us it’s a minor technique and should be a minor approach,” he says.

Recessive and multiple genes

One good case where MAS is really useful is to track recessive genes. If a plant has a useful but recessive allele (the two halves of a gene) for a trait, the recessive trait won’t be visible if the dominant allele is present and the plant may be thrown out. This is a problem because there are many cases where disease resistance and other useful traits are carried by recessive genes. The breeder may even have a case where three or four useful genes are all recessive, but without being able to look at what’s present in the plant, they cannot know if they are all present or only some of them. MAS allows the breeder to track each of the good genes, even in a mixture of recessive and dominant alleles.

To complicate things further, most of the traits of greatest interest, such as yield and disease resistance, are quantitative traits. This means that these genes are not just present or absent, but they are expressed over a range. In most cases, these are controlled by a large number of additive genes, with each gene contributing to the overall outcome, “how much yield”.

“The difficulty is that you can’t track these additive genes using DNA tools because they might be sitting on different chromosomes,” says Laing. “And sometimes, there are so many, you can’t afford to track them all.”

The International Maize and Wheat Improvement Centre (CIMMYT) did a five-year study on genes for drought tolerance in maize. Costing over $15 million, the study showed that 35 gene complexes contributed to 40% of drought tolerance in maize.

“That meant there were well over 70 genes actually controlling drought tolerance,” says Laing. “In that case your approach has to be different. Even in classical breeding you have to adopt a different approach to accumulating additive genes.”

In the case of transferring a simple trait into a good parent variety, the breeder does a backcross. This entails finding a parent with the desired trait, crossing it with a high-yielding parent and then crossing the offspring repeatedly with the high-yielding parent, but checking that each generation keeps the desired trait from the donor parent. After seven generations, the result is a plant with 94% of what the agronomic parent had, and one trait of the donor parent, usually involving one or two genes.

A complex situation involving hundreds of genes requires a different approach. Recurrent selection involves taking many parents with some level of the desired trait. Instead of looking for a plant with a high level of the desired trait, the plant breeder assumes that all plants have some additive genes to contribute to overall population.

“If you’re putting a choir together you don’t need established singers, you just assume most people can sing,” says Laing, explaining this approach. “The problem with plant breeders is that they are always looking for an opera star, but it’s not necessary. You just have to have faith that the additive genes are there, and that recurrent selection will collect them.”

The plants are crossed and planted, several times, each time keeping the best three to ten percent of the progeny.

“Each time you look for the maximum numbers of crosses. You want randomisation of crossing because you don’t know what will be the best set of gene combinations,” says Laing.

“By applying selection pressure you move the whole population in the direction you want it to go—for example, with drought tolerance or disease resistance. In two to three cycles of selection, the parent population of plants can move from fully susceptible to highly resistant,” he says.

“That’s the approach we’ve taken with some disease and pest resistance that people said we couldn’t succeed with, such as stalk borer resistance in maize. People said we couldn’t succeed, because there was no “good source of resistance”. We said we would just use what’s available in Africa, in local landraces. And within three years, we had significant resistance.”

Tracking proteins in plants

In cases where DNA can’t be tracked, gene products can be useful indicators. If, for example, a plant breeder wants to measure the difference between a variety that is frost tolerant and another that gets killed by it, they can expose them to cold and measure the biochemicals in each.

Instead of trying to measure it in genes, because there may be 100 genes involved, the breeder can try to measure proteins. “When you see a gene is present in a DNA fingerprint, it doesn’t tell you how active it is,” says Laing. “But if you measure proteins you can measure how much is produced – i.e. it’s a quantitative measure.” When polygenes come together, they only make a few proteins, which is easier to track than genes.

Drought tolerance, cold tolerance, salt tolerance etc. are all quantitative traits that are polygenic. You can’t track them using DNA but you can track them using proteins, so the ACCI is now starting to study the proteomics (the study of proteomes, or sets of proteins produced in an organism) of quantitative traits.

“In some cases the research we have tried to do is difficult,” says Laing. “For example, with insects and diseases, do you inoculate or let nature take its course? In most cases, you need to inoculate to get statistically valid results. Drought is one of the most important things we study because it’s a big problem across Africa. It’s also one of the most difficult things to measure because drought is sporadic and unreliable. In a wet year, how do you measure drought tolerance?”

It’s difficult to do good phenotyping for drought tolerance unless you have a “rainout” facility to control unintended rainfall. The ACCI has now created a novel technology to get consistent drought screening results every season. This customised technology involves putting down plastic sheeting and drip irrigation, and then using known quantities of water. (see page 159) This technology is transferrable to any research station in Africa and means that researchers can reliably create an artificial drought when they need to, in order to screen for drought tolerance.

ACCI inventions

ACCI students have invented other equipment. Jimmy Lamo (graduated 2010) invented a machine to measure how easily rice grains fall off the head of a rice plant. This trait, known as “shattering”, is a problem because rice can’t be harvested once it falls on the ground. In nature, wild rice plants have evolved to lose grains as soon as possible, but one of the first things plant breeders do when domesticating a wild plant is look for mutants that don’t shed the seed.

Lamo did research on rice, looking at how to eliminate the shattering gene because it causes huge losses in East Africa. He invented a device to measure the strength it takes to pull a rice seed off the head, so that he could quantitatively evaluate one variety against another for this trait.

Lamo also enhanced a prior invention, for removing male flowering parts from rice, to speed up the process of crossing rice parents. The alternative is to do it with tweezers, plucking off the male parts one by one. His invention uses a domestic vacuum cleaner attached to a long hosepipe with a fine nozzle on the end, that allows a technician to suck off the male parts quickly and efficiently. One vacuum cleaner can be linked to four suction hoses for four technicians to work in parallel, speeding up the process greatly.

Another of his innovations was a hand-held single grain tester, that was efficient, cheaper and more suitable to field studies than a commercial laboratory testing unit.

Another student, Theresia Munga (graduated 2008), came up with an innovative technique while doing research on cassava. She wanted to inoculate two viruses onto cassava plants to see how resistant they were. One, the brown streak virus, doesn’t transfer very easily because it’s not clear what the insect vector is.

Munga had to come up with a technique for guaranteeing that the virus was present in the plants she was working on. The technique that worked was grafting a diseased bud onto a branch of the test cassava plant.

By transferring the virus into test plants, she was able to select four varieties that were tolerant to the virus and one that was fully resistant.

Timescales for breeding

One of the difficulties of conventional breeding is the time it takes to develop new varieties of some crops. Laing says timescales aren't always understood by people who aren't plant breeders.

"We've been asked to take farmers' landraces, which have been bred for hundreds of years by farmers, but are completely heterogenous and have had no development done on them, and produce a hybrid in three years," he says. "We tried to explain that it's not possible, but the people making the request couldn't understand what the problem was."

Some crops are open pollinated, other self-pollinated and a few are grown as hybrids. The fastest to develop are cassava and sweet potato, where timescales vary from five to six years from start to release of a new variety. This is because they are vegetatively propagated. Crosses are made and selections done. If one perfect individual can be found, then it can be propagated from tubers or stem cuttings.

With maize, however, it takes roughly 10 years to do the pre-breeding phase in which crosses are made between selected parents, followed by inbreeding for seven generations to generate homozygous inbred lines. This is necessary to ensure that all the alleles of each genes are the same. The breeder must then cross the A inbred parents with the Bs to create a hybrid that carries 50% A alleles and 50% B alleles. So each parent contributed exactly half of the genetic content to the plant. That gives hybrid vigour and boosted yields, but it takes about 10 years to go from creating inbred parent lines to having a hybrid variety ready for release. At its fastest, the whole process takes 20 years.

Sorghum takes longer and is even more complicated, because to make a hybrid, the plant breeder has to use genetic male sterility, because the plant wants to pollinate itself and this has to be stopped. The only way to do that is to introduce a gene into it to stop it making pollen, which is complicated because the breeder must still be able to make seed. They must therefore have an A line, a B line and a restorer line, i.e., breed three different populations concurrently to produce a single hybrid sorghum. This whole process, from working with farmers' landraces to releasing a new variety, takes at least 25 years, almost a breeder's career.

"Once you've got there, you can churn out new varieties every year, but funders just throw their hands up," says Laing. "It's too long. It's a challenge for people to accept that it takes so long. But it's not like making carpets or shoes. You can't make a maize plant grow any faster."

There are two technical tricks that can speed up the process: using double haploids and male gametocides. The first is using a trick of tissue culture to create 100% inbred lines in a single step, instead of having to inbreed plants for seven generations. This can cut six years off a breeding programme.

The other trick is to use a special chemical to sterilise the pollen in the female parent of an inbreeding crop such as sorghum. If the row of plants next door are not sprayed, then they can contribute pollen to their neighbouring female rows, creating hybrid seed relatively easily. This avoids the cost and time it takes to develop male sterile lines and can save 5 to 10 years in a breeding programme of sorghum, for example. The ACCI and its students are investigating both these technologies, to be used on a range of crops.

Left: ACCI field assistant Margaret Hambule, planting a new variety of cassava shoots.

CROPS

ROOTS AND TUBERS

Photo: Alliance for a Green Revolution in Africa (AGRA)

Photo: Alliance for a Green Revolution in Africa (AGRA)

CASSAVA

SPECIES INFORMATION

Botanical name: *Manihot esculenta*
Family: Euphorbiaceae
Common names: manioc, tapioca, yuca

INTRODUCTION

Cassava is a lifesaver and a potential killer. And now, thanks to climate change, (see page 156) cassava, already Africa's number one root crop and a major source of cheap calories for more than 500 million Africans, is set to become even more important.

First brought to West Africa by Portuguese traders from Brazil in the 16th century, archaeologists have found possible evidence of this crop's cultivation as far back as 8500 BCE in the Zana Valley, Northern Peru. From West Africa, its cultivation spread east and south, and today it's important in Nigeria, Zambia, Zimbabwe, Mozambique, Kenya, Uganda and the DRC.

During lean times like the annual Hunger Gap (see page 61), this crop, along with sweet potato, keeps starvation at bay. Its low fertilizer requirements, tolerance for drought, locusts and marginal soils, and the long-term storability of the roots in the ground, make it a crucial food security crop.

If not processed properly, however, it can be deadly. There are two types of cassava, bitter and sweet. Sweet cassava has low levels of cyanogenic glucosides, so it can be boiled and eaten without processing. The bitter variety, however, has high levels of two cyanogenic glucosides known as linamarin and lotaustralin, which release toxic hydrogen cyanide in the gut when consumed.

If it doesn't kill the consumer, it can cause permanent damage to nerves, a condition called Konzo, which causes victims' arms and legs to wobble like they're made of rubber. In order to make it safe to eat, bitter cassava must be processed by soaking in water, rinsing and cooking. There are less toxic varieties available but these are not popular because they are more liable to be eaten by animals such as porcupines, bushpig and baboons.

Processing of bitter cassava in Africa

There are three main ways to remove the cyanide component from cassava: washing, drying in the sun or fermentation.

- With washing, the tubers are chopped and soaked in fresh water for 24 hours, which can remove 50% of the cyanide content.
- With drying, the tubers are chipped or grated into threads, which are left on racks to air dry. An enzyme in the tuber breaks down the glucoside, releasing cyanide into the air over a period of 14-21 days.
- Finally, the tubers can be mashed and a beneficial bacterial culture added to the mash. The bacteria feed on some starch and the cyanogenic glucoside, making the fermented mash safe to eat after three to four days.

Cassava has been seen as a poor person's crop, but its status is likely to change dramatically in the future. Several studies have indicated that what's been dubbed the "Rambo root" is the only staple crop likely to benefit from climate change. While others are projected to produce lower yields, scientists say cassava will flourish in the predicted higher temperatures and yields could increase by up to 10%.

DESCRIPTION

Cassava is a perennial woody shrub with large hand-shaped leaves and edible cylindrical roots that may be up to one metre long and several centimetres thick. The male and female flowers appear on the same plant, although some cultivars seldom flower.

USES

In Africa five different cassava food products are consumed: fresh roots, dried roots, pastes, granulated products and leaves. It is also used to make biofuel, animal fodder and alcohol, and the roots are an important source of industrial starch, used in the production of paper and textiles, and by the food industry.

NUTRITION

Roots contain 65% water and about 30% starch, plus vitamins B and C, magnesium, calcium, iron, thiamine, riboflavin and nicotinic acid. Protein content is low at one to two percent but it does contain essential amino acids methionine, cysteine and cysteine.

Leaves are similar to other dark green leaves in nutritional values, containing vitamins A (carotene) and C, iron and calcium, and are a good source of protein. However, they can contain high levels of cyanogens, so the leaves need to be cooked carefully to remove the toxic component (see page 51).

AGRONOMIC REQUIREMENTS

Tolerant of frequent droughts, cassava can grow in leached, acidic soil with nutrient levels too low and aluminium levels too high for other staple crops.

Plants are propagated from cuttings from woody stems, and require a warm tropical climate with a pronounced dry season. Roots can be harvested within one to three years after planting or stored in the ground for 24-36 months, depending on the variety, so harvesting and processing can be delayed.

The plant survives long drought periods by dropping leaves and then rapidly growing new shoots when rain comes. Without irrigation it needs a good rainy season. Yields are usually five to fifteen tonnes/ha, although cassava can produce over 80 tonnes in optimal conditions

PROBLEMS AND BREEDING

Viruses: Two main viruses attack cassava in Africa—*cassava mosaic disease*, which is a conglomerate of viruses, and *Cassava brown streak disease*. Susceptible varieties usually suffer 100% crop loss if infected as young plants.

Laing says despite being told that ACCI students would not be able to breed for resistance to viruses, because it was "too complicated" and they didn't have the resources, they have been successful. "It's actually easy. You just make lots of crosses, plant thousands of seeds, keep irrigating, and they keep flowering.

"You plant in areas where they have a bad virus problem, select for resistance and breed them, put them back again, and their progeny keep getting better and better. You do that for two or three cycles and you can get very resistant varieties with high yields that taste good."

Flavour: Because cooking quality of cassava is important, students have held cooking days in the field with farmers, where different varieties were cooked and tasted. High dry matter (flouriness) is also considered important for cooking and Dr Kiddo Mtunda (graduated 2010) from Tanzania bred cassava with this trait. Mtunda, who currently holds the position of principal agricultural research officer at the Sugarcane Research Institute in Kibaha, has done subsequent cassava research in Tanzania, focusing on the breeding, evaluation and selection of cassava for virus resistance (both *cassava mosaic disease* and *Cassava brown streak virus*), high starch content and yield. In 2015, four new cassava varieties that she had bred were released.

Drought tolerance: Dr Joseph Kamau's (graduated 2007) PhD research focused on breeding cassava that was drought-tolerant and early maturing, with the participation of farmers. He achieved a big breakthrough with the development of a variety that was both resistant to *Cassava mosaic virus* and ready to harvest in less than half the time it usually took, thereby giving farmers an additional harvest.

"I was already a cassava breeder so I knew what I was looking for," says Kamau. "Most cassava only matures after 18 months to two years. To produce the early maturing variety I used farmers' materials." Like many ACCI students, Kamau came from a farming background and has released 12 new varieties of cassava and four of sweet potato.

In Zambia Dr Martin Chiona (graduated 2009) heads the Root and Tuber Research Team at the Zambia Agriculture Research Institute (ZARI) and under his guidance the team has developed four new varieties of cassava, which mature early and are high-yielding, producing up to four times more than local varieties. ZARI cassava varieties are also bred to be drought-tolerant and to thrive in poor soil without pesticides.

SOME REMAINING BREEDING OBJECTIVES FOR CASSAVA

Low vitamin A: Orange varieties of cassava with increased beta-carotene are found in Brazil, so creating orange-fleshed African varieties is a real possibility, as has been done with sweet potato. However, Brazil has a restriction on the export of all plant germplasm, so getting hold of orange parent material has so far been difficult.

High Protein: Most African cassava varieties only have about 2% protein. This is seriously inadequate when so many people subsist largely on cassava for three months every year. However, some South American varieties have up to eight percent protein so it should be possible to improve this by backcrossing a high protein South American variety with some excellent African varieties, and then selecting for progeny with high-protein and good performance under local conditions. Several back-crosses into the African parent would be needed to stabilise the high-protein variety in an African genetic background.

Insects: a range of insects such as green mite, mealie bug and white fly attack cassava. Breeding for resistance to these pests would enhance productivity and food security.

Post-harvest: Cassava self-destructs three days after harvest, a process called post-harvest physiological deterioration (PPD). The white flesh of the tuber turns brown as the plant attacks itself. This problem presents difficulties for small farmers in getting their crop to market. It's also a barrier to what could be a lucrative market for commercial cassava—industrial starch, which is used in the production of clothes, food, paper etc. If a plot of tubers are harvested on Friday but are only processed on the following Monday, the tubers will have started to degrade already, and the starches will have turned brown.

Currently, the world's industrial starch is made from roughly equal proportions of maize and cassava, but with growing demand for maize in the production of ethanol, there's an opportunity for cassava producers to increase their market share. Laing is optimistic that this PPD problem can be solved if breeding is done in a systematic way.

Low yields: The average African farmer is only getting about five to ten percent of yield potential.

Propagating from cuttings: The standard way of growing cassava, where 750mm-long sticks cut from mature cassava trees are planted, is very inefficient because trees don't yield many sticks, maybe eight per tree. The ACCI has been working on techniques to get 800 cuttings from one tree, by propagating from each node and shoot. The centre is currently working on a project in KwaZulu-Natal to produce industrial starch for SA, where they have to produce a quarter of a million cuttings from 12 parent plants. Each generation must be multiplied from the previous generation as fast as possible.

Laing says that vegetatively propagating cassava is a logistical challenge and they are "discovering how to do it. It's not written down. Every successful cassava breeder faces the same challenge: how to convert one exceptional parent into a million offspring?"

Photo: Alliance for a Green Revolution in Africa (AGRA)

IRISH POTATO

SPECIES INFORMATION

Botanical name: *Solanum tuberosum*
Family: Solanaceae
Common names: potato, Irish potato

INTRODUCTION

The Irish potato is part of the 4 000-strong family of native potatoes that has been sustaining people in the Andes for an estimated 8 000 years. Taken to Europe by the Spanish in 16th century, it was probably brought to Africa in the 17th century by ships carrying it to China via the Cape of Good Hope, and by European missionaries during the colonial period.

Highly palatable, easy to cultivate and rich in carbohydrates, the potato has become the most important non-cereal crop in the world, eaten by more than a billion people. One hectare of potatoes can produce two to four times the food yield of grain crops. The potato also produces more food per unit of water than any other major crop, and is up to seven times more efficient in using water than cereals.

It has become an important cash and food security crop in the developing world, which now produces more than half of the global harvest of about 368 million tonnes. Africa produces only four percent of the global harvest, presenting an opportunity for farmers in areas with suitable growing conditions. The continent's top producers are Malawi (16%), Rwanda (8%) and Uganda (4%).

DESCRIPTION

The plant is a herbaceous perennial with white, pink, red, blue, or purple flowers with yellow stamens. Cross-pollination with other potato plants is mostly done by insects, although self-fertilisation also occurs. Tubers form in response to decreasing day length.

After flowering small green fruits are produced, each containing 100-400 seeds. All parts of the plant except the tubers contain the toxic alkaloid solanine and should not be eaten.

USES

Potatoes are cooked in a variety of ways, including boiling, baking, roasting and frying in oil. They are also used to feed animals and to brew alcohols such as vodka, potcheen or akvavit. Potato starch is used in the food and textile industries and in the manufacture of paper and cardboard.

NUTRITION

Potatoes are rich in carbohydrates, and have the highest protein content (around 2.1%) of root and tuber crops. This protein is good quality, with an amino-acid pattern that is well matched to human requirements. They are also high in vitamin C—a medium-sized potato contains about half the recommended daily intake—and contain nearly a quarter of the recommended daily dose of Vitamin B6.

AGRONOMIC REQUIREMENTS

Potatoes are native to high altitudes and in Africa are mostly grown in the highland parts of Ethiopia, Rwanda, Kenya, Uganda and South Africa. They grow very well in subtropical regions during the cool season and at moderate elevations in tropics. In the lowlands a bacterial disease kills it.

The plant is vegetatively propagated, with a new plant grown from a tuber or piece of tuber, called a "seed". The new plant can produce 5-20 new tubers, which will be genetic clones of the mother plant. True seeds of potato can also be planted to produce new tubers, but these will be genetically different from the mother plant.

PROBLEMS AND BREEDING

Pests and diseases: Potatoes in Africa are vulnerable to diseases caused by viruses and bacteria. In Rwanda, Dr Jean-Baptiste Mukinyuza (graduated 2015) successfully bred for resistance to late blight (the cause of the Irish Potato Famine between 1845 and 1852 that killed over 1 million people), and Dr Jane Muthoni (graduated 2015) achieved resistance to bacterial wilt in the Kenyan Highlands.

Betaw is currently working as a research associate in a potato breeding programme at the International Potato Centre (CIP) in Ethiopia. For her research project on potato, she identified disease-resistant, drought-tolerant and high-yielding materials from the germplasm she evaluated that outperformed the currently grown cultivars. These new varieties were handed over to the national potato research programme for further evaluation and distribution to farmers.

Photo: Alliance for a Green Revolution in Africa (AGRA)

SWEET POTATO

SPECIES INFORMATION

Botanical name: *Ipomoea batatas*
Family: Convolvulaceae, the morning glory family
Common name: Sweet potato

INTRODUCTION

Sweet potato didn't originate in Africa, but it has become a critical crop for a continent plagued by hunger, disease and social turbulence. Grown in Latin America from at least 8000 BCE, the plant was carried over the Atlantic Ocean by Portuguese ships in the 16th century, and later to East Africa by the British.

Sweet potato has been described as "starvation food", because of its value in the Hunger Gap (see page 61). The International Potato Centre (CIP), based in Lima Peru, goes a step further, stating that that sweet potato—because of its ability to produce good yields in poor conditions with little labour—is "particularly suitable as a crop for households threatened by civil disorder, migration, or diseases".

CIP points out that the crop requires "fewer inputs and less labour than other staple crops. It tolerates marginal growing conditions, such as dry spells or poor soil, and provides more edible energy per hectare per day than wheat, rice, or cassava".

Sweet potato is also a valuable weapon in Africa's bid to alleviate vitamin A deficiency, which affects an estimated 43 million children under the age of five. This condition can cause blindness, disease and premature death. Consumption of the orange-fleshed sweet potato (OFSP) varieties known to be high in beta-Carotene (a precursor to vitamin A) is seen as a viable strategy to combat vitamin A deficiency, and ACCI students have focused on developing this trait. The leaves are harvested and cooked to make a high protein "spinach", which also provide vitamins, minerals, antioxidants, dietary fibre, and essential fatty acids. In some countries, especially Rwanda, the above ground vines and leaves are harvested for cattle feed.

Because average yields in sub-Saharan Africa are 10 times lower among small-scale farmers than commercial growers, breeding has also focused on improving yields by producing varieties that are more resistant to disease, pests and drought, and produce storage roots full of starch that are dry and floury when cooked. Varieties that produce watery roots are rejected by farmers, irrespective of the variety's yields.

Production of sweet potato is expanding faster than any other major crop in SSA. CIP attributes its rapid expansion over the past decade to a variety of factors, including changes in cropping patterns driven by major disease problems with Africa's cassava and banana crops. Other contributing factors include declining farm size, economic volatility, and growth in commercial production.

DESCRIPTION

Sweet potato is a trailing leafy vine that spreads along the ground by rooting at the nodes. Its leaves are heart-shaped and flowers are purple, pink or white. The tuberous roots are white, orange, purple or yellow.

USES

Roots are fried, boiled, baked or cooked in sweet or savoury dishes. Leaves are cooked as a green "spinach" dish.

NUTRITION

Exceptionally nutritious, containing high-quality protein and substantial quantities of vitamins A, B and C. Energy value high, 110kcal per 100g.

AGRONOMIC REQUIREMENTS

The plant needs subtropical heat and is propagated by planting pieces of tuber or stem cuttings.

Roots and stems will die if exposed to temperatures lower than 10°C for a few days, and tuberisation is inhibited if day length exceeds 14 hours. The roots are ready for harvesting 60-90 days after planting.

PROBLEMS AND BREEDING

Pests and diseases: Breeding is done for resistance to viruses and drought, and for increased yield. Leaf spot, weevils, swollen storage roots, and millipedes are also a problem.

Propagation: Propagation is a logistical challenge. It's also difficult to make money out of breeding sweet potato, because once a new variety is made available to farmers, the farmers propagate the crop vegetatively for their own uses. Hence the need for government scientists to breed this crop. No commercial seed company could afford to breed sweet potato to sell a new cultivar only once.

Low protein content: Because of its importance as a survival crop, one of the main goals for sweet potato breeders is to increase the protein content from a low average of two percent. The ACCI has a student in Pretoria working on this, who has so far tested about 600-700 varieties from all over the world. CIP has supplied many different varieties for this research.

Vitamin A: ACCI students have worked on breeding orange sweet potatoes with higher beta-Carotene, which has entailed trying to strike a balance between palatability and nutrient density. If a variety has too much vitamin A it becomes slimy and unpleasant to eat, so a compromise has been to retreat and breed a variety that's floury, because that's what tastes good when roasted, with a moderate level of vitamin A. In Kenya Kamau has bred four varieties with high beta-Carotene that have been released, while Damien Shumbusha, due to graduate in 2018, has bred and released three varieties with this trait, and Chiona has released novel varieties of which four have been commercialised.

Yield: Shumbusha has also released eight varieties in Rwanda that are high-yielding.

Chiona did his research project on enhancing beta-Carotene content in high dry matter varieties. Since graduating he has bred five varieties, of which four have been commercialised.

Breeding challenges: Breeding sweet potato is difficult because variety A and variety B may be incompatible, making cross-pollination impossible. The breeder has to do many crosses to be successful. Laing says this is bad for an academic study, "because when you do breeding you try to cross variety A, B, C, and D with each other. When they don't cross, you don't have a nice matrix of results. It makes a mess out of your statistics. That's been a big problem. You have to do big numbers of crosses with a lot of parents to find some that are compatible."

Photo: CSIRO/Wikimedia Commons

Cowpea infested with weevils. When post-harvest pests like weevils, rats and moulds destroy food stores, millions of people are left hungry while they wait for the next harvest of staple grains and legumes. During this 'Hunger Gap' crops like sweet potato and cassava are lifesavers.

Hungry in a sea of crops

The Hunger Gap or the Hungry Gap. It's a global phenomenon as old as humans, referring to the time faced by all farmers when the staple crops from the main growing season are finished or starting to spoil, and those from the next aren't yet ready to eat. In most of the northern hemisphere the Hunger Gap is no longer a problem, but in Africa this time is a predictable, annual period of starvation for millions of people, because of poverty, lack of alternative food sources and post-harvest problems.

It goes like this: the staple foods are cereals—maize, sorghum, rice, tef or wheat—that take three months to grow, a month for drying and another for harvesting and processing. Most farmers in SSA plant in November/December, which means the first food of the new season is only ready in April.

Ideally, that food store should last for 12 months, but because of moulds, weevils and rats, nine months of storage is more common. In Africa these post-harvest losses, caused by a lack of effective storage technologies and warm winters that are no obstacle to pests, account for the loss of 40%-70% of harvests, versus five to ten percent in Europe. Even when the previous season was a bumper one, the rats and weevils can decimate the crop in storage.

That three-month gap in available food means that late summer/early autumn is often a time when people are hungry while surrounded by seemingly abundant fields, that aren't yet ready for harvesting.

In places like Niger, where the Hunger Gap can last six months, people resort to eating once a day, or when they can find food. Parents go hungry so their children can eat, and men often leave home to go and work elsewhere to earn money for food, while their wives stay at home and struggle to make ends meet.

"The Hunger Gap is a perspective-changing concept," says Laing. "There's a period where food is short, and if you live in an environment where there are no shops, no safety net, it's scary. Every year you face hunger, and starvation is a real possibility in most years."

CROPS

CEREALS

Photo: Alliance for a Green Revolution in Africa (AGRA)

Photo: Alliance for a Green Revolution in Africa (AGRA)

ACCI graduate Dr Pedro Chauque covers pollinated female maize flowers with brown paper bags at a research station in Mozambique.

MAIZE

SPECIES INFORMATION

Botanical name: *Zea mays*
Family: Poaceae
Common names: Maize, corn, mielie

INTRODUCTION

All the many types of maize came from a single domestication of a grass in southwestern Mexico, more than 8 000 years ago. Although the difference between the two plants is largely controlled by differences in just two genes, teosinte (*Zea mexicana*), with its squat stature and small cobs, bears no resemblance to its tall cousin, *Zea mays*, which has gone on to rule the world of domesticated cereals.

Indigenous people bred selectively for thousands of years to produce modern maize, with bigger kernels and retention of ripe grain on the ear. The staple crop spread across Latin America and was taken to the rest of the world by the Spanish and Portuguese. It may have been taken from the Mediterranean to Africa by Arabs, but was also introduced directly from the New World in the 16th and 17th centuries, where it spread rapidly, replacing sorghum in many areas.

The biggest advantage of growing maize in Africa is that it can produce a higher yield than any other cereal, given the right conditions. With fertilizer and enough rain, maize can yield 10 tonnes per hectare, versus sorghum's four to six tonnes and pearl millet's two to three tonnes.

Other advantages of maize are its large kernels, which make it less attractive to birds, and better storage life—because of fewer losses to weevils—than crops likes sorghum and pearl millet.

However, maize is less drought-tolerant than these crops, and with less rainfall predicted in coming decades due to climate change, production will fall. About 90% of the areas currently used to grow the crop are projected to experience major climate changes, which will result in yield reductions of 12-40%, with West African countries the worst hit.

With eastern and Southern Africa consuming 85% of their maize production and Africa as a whole using 95%, the effects of climate change on food security could be dire (see page 161), and demand urgent attention from governments, scientists and agriculturalists.

DESCRIPTION

Maize is a tall plant of three to twelve metres, with large leaves growing from nodes on the stem. Ears of 18-60cm grow above some of the leaves in the mid-section of the plant. These are female inflorescences (groups of flowers) tightly wrapped by husks.

The apex of the stem ends in the tassel or male flowers, which release pollen.

Elongated pale yellow, hair-like stigmas, called silks, grow from the ends of these ears. At the end of each is a carpal, which, if fertilised, can grow into a pea-sized kernel fused to the cob. Kernels come in various colours, including blackish, blue-grey, purple, green, red, white and yellow.

Apart from colour, differing kernel sizes and the presence of soft floury tissue at their centres determine the type of maize.

- Dent corn has a central core of soft endosperm that causes shrinking, creating a dent at the end of each mature kernel;
- Flint maize has soft floury endosperm plus a hard outer endosperm; (check)
- Popcorn has a hard endosperm;
- Soft maize (flour maize) has a large soft centre surrounded by hard endosperm, but does not shrink;
- Sweetcorn has more free sugars and less starch than other types.

USES

Maize is eaten raw or processed, and is cooked in a variety of ways, as wraps, porridge, bread and cakes. It's also used as animal feed, and to make high fructose corn syrup, corn starch for cooking and alcohol such as bourbon whiskey and beer. The starch is made into plastics, adhesives, fabrics and other chemical products. The cobs are used for bio-fuel and bio-plastics, and the kernels to make ethanol. Another major use of maize, especially in the Northern Hemisphere, is as silage, used to feed cattle in winter. Silage is maize harvested at a green stage, which is then placed in anaerobic conditions, under which a yoghurt-type fermentation takes place, enhancing the protein content of the silage.

NUTRITION

Maize has a similar energy value to other grains but is slightly less nutritious because of lower levels of two amino acids, lysine and tryptophan. It is rich in vitamins A, C and E, carbohydrates, and essential minerals, and contains 9% protein. The kernels are also rich in fibre.

AGRONOMIC REQUIREMENTS

Maize flourishes in warm weather and well-drained, moist soils. Optimal soil temperature for germination is 16-18°C, and it does not tolerate frost at any stage of its development. It requires 450mm-600mm of water per season.

PROBLEMS AND BREEDING

Pests and diseases: Maize is affected by many disease and insect problems, so breeding for resistance is a priority.

- **Diseases:** in SSA these include downy mildew, rust, leaf blights and spots, stalk and ear rots and maize streak virus (MSV).
- **Insects:** various species of stem borers cause 20-40% losses during cultivation and 30-90% losses post-harvest and during storage. Other insects feed on the grain in storage.
- **Other pests:** in SSA these include ear borers, armyworms, cutworms, grain moths, beetles, weevils, grain borers, rootworms, and white grubs. The ACCI has successfully bred maize that's resistant to several of these pests.
- **Parasitic weeds:** across Africa two species of a plant genus called *Striga* attack maize crops. The parasites put out roots that tunnel into the roots of maize and other cereal plants, like a creature from *Alien*. They stunt the host plants, and cause crop losses of up to 90%. They only attack poorly fertilized plants, so this really is a problem for small scale farmers across Africa, especially in the drier areas with low fertility.

Lodging: Maize plants can be blown over if they are bred to be too tall for their stem thickness or root structure.

Drought: Maize is the most sensitive cereal to drought. Tassels and silks may not come out when the plant is stressed, and if the gap between tasselling and silking is too big, then no pollination happens, so no seed forms.

Poor soils: A large amount of fertilizer is needed to produce 10 ton/ha, which most African farmers can't afford. Maize is also sensitive to aluminium in the soil that is dissolved in acid soils, which are common across Africa. Either the soils need to be limed, or the varieties need to be aluminium-tolerant. ACCI students have bred varieties that can grow in poor soils.

Breeding maize: The genetics of maize is complicated because it has a very big genome, but making hybrids is relatively easy.

Desirable parents are chosen. This might take up to five years. The parents sit in groups that are cross compatible to produce hybrid vigour. Assume that two parents sit in the A and B groups. Inbreeding must be done with parents so they are self-pollinated to produce pure As and pure Bs.

Maize plants have evolved to cross-pollinate, so self-pollination or "selfing" is a cumbersome process where the ears of selected plants are covered with bags to prevent pollination by another plant.

When the silks have emerged, pollen from the same plant is transferred to the silks.

Selfing is done for six generations, which takes about six years, so it takes about 11 years to get inbred lines of the A and B parents.

The inbred lines are then crossed with each other, A x B, because hybrid vigour is the goal. This will result in greater yield of perhaps 30%. These hybrids have to be tested at different sites, to make sure that they always perform well. This stage takes another 10 years, so to release a hybrid takes about 20 years when starting from scratch.

For farmers, one consequence of choosing to grow hybrid seed is that they have to buy fresh seed the next season because allowing hybrids to cross-pollinate will result in lower yields again, since the hybrid vigour is being lost with each generation.

Of all the crops that the ACCI works with, maize has received the most attention, with students researching many different traits, ranging from drought tolerance, early maturation and protein quality to resistance to *Striga*, Maize streak virus, Gray leaf spot, nematodes, Northern corn leaf blight and stem borer.

After 10 years of research at UKZN, Derera has developed 121 maize inbred lines (parents of hybrids) which were shared with breeders in Ghana, Zambia, Malawi, Mozambique and Kenya, to make hybrids.

He's also developed 10 Vitamin A-rich orange maize inbred lines, 21 popcorn inbred lines and 15 popcorn varieties.

Dr Arnold Mushongi (graduated 2011) worked on breeding maize in Tanzania for the traits of early maturity, stay-green (the leaves stay green for longer) and dry-down (quick drying of the grain on the cobs) for his PhD thesis. Since graduation he's developed varieties that are drought tolerant, pest-resistant and can grow in less fertile soil.

However, only one of his varieties has been released, in 2015. This is because although seed companies want his inbred lines, the Tanzanian government will not release them as inbreds. "They want to control the seed trade so they try to produce the hybrid seeds themselves, but they do not have the skills sets in-house to do this," says Laing

Miti, who hails from Zambia, had a background in seed quality control, testing and certification before joining the ACCI programme in 2003. He went into plant breeding because while working on developing a seed delivery system in the rural areas of Zambia, he realised that the majority of farmers growing maize, the country's staple crop, were battling with drought and fertilizer acquisition.

"I was convinced that what mattered was not only developing a system for seed provision in rural areas but also delivering the right type of seed and fertilizer," he said. Miti did his research project on breeding maize that was tolerant of drought and low soil nitrogen and still produced good yields. Six varieties bred by him have been registered, of which five were commercialised.

Fellow-Zambian Dr Mweshi Mukanga (graduated 2009) worked in crop protection before starting a PhD with the ACCI in 2004. His project involved breeding maize varieties with resistance to maize ear rots, an indirect method of selecting for reduced levels of mycotoxins (mycotoxins being deadly chemicals released by fungi into food crops).

Because of his knowledge of mycotoxins, he has also participated in studies aimed at mitigating the effects of mycotoxins in maize and food legumes, and promoting a better understanding of mycotoxins.

In Mozambique Dr Pedro Fato (graduated 2010) looked at maize improvement for resistance to major tropical foliar diseases, especially downy mildew. A maize breeder at the Agricultural Research Institute (IIAM) in Mozambique for more than 20 years, he has bred six new varieties that have been released and commercialised. He has also contributed to the release of 17 new varieties. Most of these lines combine drought tolerance with resistance to downy mildew or field and storage insects.

In South Africa Dr Sharmane Naidoo (graduated 2010) researched a molecular marker for a gene associated with the trait for phytic acid. This is a compound in the seed that helps with germination vigour but has a detrimental effect when eaten, because it binds with essential minerals in the gut and passes through the system. People subsisting on maize can develop a mineral deficiency because of this. Naidoo created a hybrid with local maize and adapted material in plants from America, and when she finished her PhD she handed her germplasm over as part of the ongoing ACCI maize research programme.

Another South African, Dr Kirthee Pillay (graduated 2011, non-AGRA) researched nutritional quality and consumer acceptability of vitamin A-fortified maize, which is orange. She found that although the fortified maize was better for people with vitamin-A deficiency, all age groups apart from pre-schoolers preferred the white varieties, indicating an attitudinal obstacle to overcoming this deficiency in consumers.

In Kenya Dr Philip Leley (graduated 2008) has released five new varieties of maize, of which four have been commercialised, and Dr Philip Kwena (graduated 2003) has released one new variety of maize.

Photo: Alliance for a Green Revolution in Africa (AGRA)

Gerald Nakhungu on his finger millet farm in Matungo, Kenya. Switching from farming sugar cane to a variety of millet developed by an ACCI-trained plant breeder has brought higher returns with every harvest. Gerald's three children are now in private schools, he has opened a mobile phone and motorcycle taxi business, and grows trees for sale as building materials.

FINGER MILLET

SPECIES INFORMATION

Botanical name: *Eleusine coracana*
Family: Poaceae
Common name: finger millet

INTRODUCTION

Finger millet is a tasty, high-status, extremely nutritious crop that's on the wane, mainly because of the drudgery involved in producing it. This contradiction may explain why it can fetch higher prices in some regions of Africa than sorghum and maize.

Consumption of this indigenous crop, believed to have originated 5000 years ago in the highlands of Uganda and Ethiopia, has declined considerably in places like southern Africa, Burundi, Rwanda and Zaire, and it is largely kept for festivals and ceremonies.

The other reason it is grown is as a security crop for small farmers, because of a unique feature—weevils don't eat its seeds because they are too small to climb into. Its long storage time—up to 10 years—means it can be kept for the end of the season when these pests have eaten everything else. According to anecdote, it is even used as money for trading, because of its long life.

Hardier and less susceptible to diseases and pests than other cereals, finger millet can be grown in most soils, as long as there's 800mm of rain per year.

With its many virtues, it seems like a crop worth promoting. Noel D. Vietmeyer writes in "Lost Crops of Africa" that finger millet, in its genetic development as a crop, is "about where wheat was in the 1890s", with huge scope for improvement in its untapped gene pool. With improved farming methods and plant breeding, farming finger millet wouldn't be so laborious, and it could take its place as one of the continent's most valuable crops.

DESCRIPTION

A small tufted grass that is under one metre. The stems end in "fingers" with little round seeds at the end.

USES

Finger millet grains are ground into a flour to be used in porridge or to make bread and cakes, which are wrapped in banana leaves or maize husks, and roasted. It has high social value in places like Uganda, where it is served as a status food in celebrations. The grain can also be popped.

Finger millet also provides malt to make beer and other alcoholic and non-alcoholic beverages, such as "areki", a popular Ethiopian liquor. The straw is used as fodder for animals, and in Uganda the by-products of beer are used to feed chickens and other animals.

Medicinally, the seed is used as a prophylaxis for dysentery, and in southern Africa the juice of leaves are taken as an internal remedy for leprosy. The straw is also used for thatching and plaiting, and in China for making paper. In Sudan the leaves are made into string.

Finger millet has one of the largest root systems, and is used in Brazil as a fertilizer pump. The roots go down 10m and suck up fertilizer that has gone below the roots of soybeans and is lost to them. The plant is planted between soybean crops and chopped up with rollers after about six weeks, when the mulch is left to rot. Soybeans are then planted into the mulch.

NUTRITION

Finger millet is especially valuable as it contains the amino acids methionine, tryptophan and cysteine, which are lacking in the diets of people who live on starchy foods like cassava, polished rice, or maize meal.

Research done by a dietetics PhD student working with the ACCI found that the grain also has the highest measured levels of antioxidants of any plant food. This supports anecdotal accounts in Kenya of greater longevity of humans in areas where people eat a lot of the crop. It's high in calcium, iron, manganese and fibre, and has a better energy content than other cereals. It is ideal for feeding to infants and the elderly.

AGRONOMIC REQUIREMENTS

Finger millet uses more water than pearl millet, and is grown in higher rainfall areas—the wetter parts of Mozambique, Zimbabwe, Tanzania, Kenya, Uganda and parts of Ethiopia—although it does not thrive in heavy rainfall. It grows best in warm temperatures of 18-27°C and fertile, well-drained soils. It is usually harvested three to five months after sowing.

PROBLEMS AND BREEDING

Labour intensive: The small size of the seeds makes finger millet difficult to handle. Weeding is a problem in Africa because the dominant weed, a wild relative, looks very similar to the crop, especially in the early stages, so close attention on hands and knees is inevitable. It's also quite a short crop, so it is easily shaded out by taller weeds. The small grain size is a disadvantage in harvesting and processing into flour.

Pests and diseases: Birds are a big problem because they love the seeds. Finger millet is also affected by a fungal disease called "blast" or Gray leaf spot (*Pyricularia grisea*), which looks like there's been an explosion when it strikes. This disease attacks the stem, causing the plant to wilt and die.

Kenyan Dr Chrispus Oduori (graduated 2008) has released four new varieties of finger millet, including one that's early maturing and resistant to blast and *Striga*. In Uganda Dr Lawrence Owere (graduated 2014) also worked on resistance to blast. The crop is also troubled by *Striga*, but not as badly as sorghum, pearl millet or maize. Breeding for disease resistance is one of the main areas of focus.

Low yield: Another area of focus for plant breeders is low yield, one of the crop's main deficiencies because it has never been bred by scientists. Oduori was the first to first to try to improve this and in his area he managed to increase yields from 600kg per hectare to 3.5 tonnes per hectare.

Self-pollination: Finger millet is strongly self-pollinating, which can make breeding difficult, but some plants with male sterility have been found in Uganda, which could help to ease this problem.

Right: Dr Chrispus Oduori at the Kenya Agricultural and Livestock Research Organisation's finger millet farm in Kakamega, Kenya. AGRA funded Oduori's PhD training at UKZN and later gave him a grant to advance his PhD products to the point of release to farmers. One of these products is 'maridadi' finger millet, which in comparison to traditional varieties has higher yield, matures earlier, is adaptable to the environment, and resistant to biotic stresses and drought. Farmers planting 'maridadi' finger millet have recorded up to 500% increases in yield in comparison to traditional varieties.

Photo: Alliance for a Green Revolution in Africa (AGRA)

Photo: ACCI

PEARL MILLET

SPECIES INFORMATION

Botanical name: *Pennisetum glaucum*
Family: Poaceae
Common name: pearl millet

INTRODUCTION

Pearl millet is a crop that could—and should—rocket to prominence as the effects of climate change accelerate around the world. It's already on the move; globally production has increased in the last 15 years, due mainly to higher yields in India and expanded areas of cultivation in West and Central Africa. It is a staple food to about 500 million people globally.

It's not hard to see why. Pearl millet is very nutritious and the hardiest of all the cereal crops. The most heat-tolerant and drought-tolerant cereal, it also grows in soils with high acidity and salinity, and is more resistant to insects and diseases than sorghum, maize and other grains. According to ICRISAT, an estimated 90 million people in some of the harshest environments in the world rely on it for food and income.

Pearl millet is an indigenous African domesticate of *Pannicum violaceum*, and in Africa it is found from the Atlantic to the Nile, including the dry zone of the savannah belt between the Sahara and Sudan. The earliest archaeological remains of the plant were found in Mauritania, dated about 900BC, but domestication probably happened much earlier, 40 000 years ago, after which it spread through the Near East to India, reaching Pakistan before 1500BC.

As a grain with a mean protein content of 16%—versus a paltry eight percent in maize and wheat—there is a huge potential market for including pearl millet in animal feed, baby food and protein-fortified breakfast cereals. For example, where a ton of maize fed to chickens requires the addition of 220kg of imported soya protein to boost the protein level, using pearl millet instead would require far less additional soy protein and would bring down the cost of feed.

With this impressive array of attributes, pearl millet is well placed to expand into areas where it's not yet cultivated and can be grown as a cash crop.

DESCRIPTION

Pearl millet is a large grass, one to five metres tall, with several culms each ending in a bristly spike or bulrush, covered with seeds. The grains, which are about the same size as barley and resemble pearls, can be white, red, yellow or brown.

USES

The tall stalks are good for thatching, animal feed, building, poles and fuel.

The grains are used whole, cracked or ground into flour, and made into porridge, bread or roti. In Nigeria the grains are fermented and used to make a traditional weaning food.

Mature ears are cut off, dried and stored on heads. They are also an important source of malt for traditional beers.

NUTRITION

Pearl millet contains a mean of 16% protein, more than any other cereal, with a better amino acid profile. In feeding trials, it has been shown to be nutritionally superior to rice and wheat, and across Africa it's known as a weaning food for babies. It has a high iron content and the amount of Vitamin A and minerals are good. Pearl-millet-based foods also have a high fibre content which gives them a low glycaemic index—better for maintaining blood sugar levels.

AGRONOMIC REQUIREMENTS

Pearl millet flourishes in well-drained, loamy to sandy soils. It is heat and drought-tolerant, with yields of 250-3 000kg/ha when rain-fed, although rainfall must be evenly distributed throughout the growing season. It is sensitive to low temperatures at seedling and flowering stages. High day-time temperatures are needed for the plant to mature. Its rainfall requirements are lower than those of maize and sorghum, being 200-600mm of rain. The heads ripen over several weeks and have to be protected from birds.

PROBLEMS AND BREEDING

Lodging: Pearl millet's tall stalks can fall down in windy conditions.

Pests and diseases:

- **Weeds:** it is vulnerable to attack by the parasitic weed *Striga*;
- **Bacterial diseases:** bacterial spot (*Pseudomonas syringae*) and bacterial leaf streak (*Xanthomonas campestris* pv. *pennamericanum*) attack the leaves;
- **Fungal diseases:** these include downy mildew (caused by *Sclerospora graminicola* and *Plasmopara penniseti*); blast (caused by *Pyricularia grisea*) and rust (caused by *Puccinia substriata* var. *penicillariae*);
- **Insects:** including millet head miner and stem borers;
- **Parasitic nematodes:** these attack the roots;
- **Birds:** these are a huge problem because pearl millet is their first choice of cereal to eat. A flock of birds can strip a crop in days. This is less of a problem for commercial farmers, who grow large areas and can sacrifice some to birds, but small-scale farmers can't afford to do that.

Dr Geoffrey Lubadde (graduated 2015) did research into breeding for yield, drought tolerance and disease resistance.

Photo: ACCI

Photo: Alliance for a Green Revolution in Africa (AGRA)

RICE

SPECIES INFORMATION – AFRICAN RICE

Botanical name: *Oryza glaberrima*
Family: Poaceae
Common name: African rice

INTRODUCTION

Rice consumption, once confined to West Africa, where an indigenous variety has been cultivated for centuries, has soared with increasing urbanisation. It's now the fastest-growing staple food on the continent, and while consumption of traditional crops like sorghum and millet has been falling for decades, per capita consumption of rice has increased by more than three percent every year since the late 1990s.

This is largely due to the changing role of women in families. With more women joining the paid workforce and their time becoming more valuable, foods like rice, which take less time to prepare, have become the preferred choice, and rising incomes have meant that consumers can afford their preference.

African rice, however, has not benefited from this trend. A bit of a Cinderella crop, it has an image problem, being low-yielding and less attractive in appearance than the more popular Asian rice. What most of the world and even many Africans don't know, is that it is African rice, a descendent of the wild *Oryza barthii*, that provided the genetic material that gives Asian rices like basmati and jasmine their scent.

This link was discovered by an ACCI student, Dr Honoré Kam (non-AGRA, graduated 2012) of Burkina Faso, who, after collecting 330 African and Asian rice varieties in his country, undertook a study that looked at the DNA of African and Asian rice. He found a close relationship between indigenous African rice and scented varieties such as Basmati.

African rice has been cultivated for at least 1500 years on the continent, and was probably domesticated some 2 000-3 000 years ago in the inland delta of the Upper Niger River in Mali. Grown mainly on the floodplains of northern Nigeria, the inland delta of the Niger River, parts of Sierra Leone and Ghana, African rice is still an important crop in those areas, prized by locals for its nutty flavour. It's also cultivated in parts of Brazil, Guyana, El Salvador and Panama as a result of the slave trade.

African rice produces smaller yields than Asian rice—600kg-1.5 tonnes/ha versus four to six tonnes/ha, and scatters seed on the ground (called "shattering"). The grain is brittle and more difficult to mill. It is, however, better suited to African conditions, being more tolerant of fluctuations in water depth, iron toxicity, infertile soils and severe climatic conditions, and it exhibits better resistance to various pests and diseases. There are also a few ultra-quick-growing varieties that farmers in northern Sierra Leone, for example, reportedly keep as "hunger-breakers", to be used in emergencies. For these reasons, many small-scale farmers still prefer it to its more popular cousin.

The gap between demand for rice and supply presents an opportunity for farmers growing the more resilient local rice, but breeding will have to be done so that higher-yielding varieties that are more appealing to consumers can be produced.

DESCRIPTION

African rice is an annual with erect stems up to 90-150 cm long. The sheaths, which enclose the stems, are smooth and hairless.

USES

African rice is a staple starch for humans, being boiled or ground into flour to be used in bread. It is also used to brew beer and in traditional ceremonies, and in the Central African Republic the root is eaten as a remedy for diarrhoea. It is fed to chickens and other animals.

NUTRITION

The crop has a similar nutritional value to Asian rice, i.e. it's an excellent source of carbohydrates, protein, fat and vitamins if not overly milled and polished.

Because African rice is more difficult to polish, it tends to have a higher nutritional value than Asian rice, which tends to be highly processed.

AGRONOMIC REQUIREMENTS

African rice grows best on fertile alluvial soils, although it tolerates low soil fertility and can produce higher yields than Asian rice on alkaline and phosphorus-deficient soils. Floating rice is planted on loam or clay soils.

Two different methods of cultivation are used:

Dryland: a small percentage of African rice is grown using rain as the only source of water. This rice thrives in light soils where there is a rainy season of at least four months and minimum rainfall of 760 mm. It is often interplanted with other crops like millets, maize and sorghum.

Floating: in the River Niger's inland delta in Mali, farmers grow different varieties of floating African rice. These plants can grow in water more than 3m deep and are often harvested from canoes.

PROBLEMS AND BREEDING

Pests and diseases: nematodes, African rice gall midge, rice stripe necrosis virus, rice yellow mottle virus, and the parasitic plant *Striga*.

Lodging: The plants can have weak stalks, and may topple during windstorms.

Shattering: Plants drop the seed as it matures.

Splitting: The seed often breaks during handling.

Colour: Although the grain itself is always white, most types have red husks.

Processing: To remove the husk is laborious.

Weeds: caused by genetic interaction between African rice's wild and cultivated races.

Three students from West Africa who studied at the ACCI with funding from USAID via AfricaRice in Benin, have done research on African rice. Kam, Dr Mounirou El-Hassimi Sow (graduated 2012) from Niger and Dr Kouadio Nasser Yao (graduated 2012) of Côte d'Ivoire all worked on a project on the application of MAS for improving African rice.

For their research projects, Sow and Kam travelled extensively in Niger and Burkina Faso, respectively, to interview farmers and collect hundreds of local rice varieties (see opposite). These ancient varieties were then characterised in field trials and using DNA profiles, and novel genes for resistance to Rice yellow mottle virus were found. This virus is the most destructive rice disease in Africa.

In Yao's research project he made significant advances in combatting the effects of the African rice gall midge, which wreaks havoc on rice crops. After investigating the best way to screen rice varieties for genetic resistance to the midge, he identified SSR markers for the midge resistance gene that will be used for marker-assisted selection for midge resistance.

Yao currently works as a biotechnologist at the BECA centre in Nairobi, as well as teaching in the ACCI MSc and PhD programmes as a visiting lecturer.

Incredible journeys to save ancient rice

In 2008 two intrepid students undertook journeys for their research projects that entailed travelling thousands of kilometres through some of the most inhospitable terrain in the world.

Dr Mounirou El-Hassimi Sow from Niger and Dr Honoré Kam of Burkina Faso were both studying African rice, and undertook to travel extensively in their homelands to interview farmers and collect germplasm of landraces. This is now being stored for safekeeping with AfricaRice.

Sow, who now works for AfricaRice as a biotechnologist in Ibadan, Nigeria, travelled across Niger for more than 2000 km by boat, motorbike and public transport. His journey included navigating the Komadougou and Niger rivers, as well as many of the main waterways and marshes. Along the way he conducted a PRA with farmers and collected about 270 rice varieties, many of which are threatened with extinction and have never been gathered before.

Sow recalls a "very cold, dark and scary night" in the Sahel where he and two colleagues pushed a broken-down car for hours in a sandstorm while trying not to get lost. He says his trip would be impossible now because of the prevalence in the area of the Nigerian extremist group Boko Haram.

Laing says Sow's doctoral research was "a fascinating study of what DNA fingerprinting can tell us of the history of rice cultivation in Africa over several thousand years".

Kam, now working as a government plant breeder in his homeland, spent three months travelling about 4000 km, mostly by motorbike, through Burkina Faso, collecting 330 African and Asian rice varieties. He stayed in villages along the way.

Laing says Sow and Kam undertook their journeys just before a wave of adoption of Asian rice that ushered in the extinction of many ancient African rice landraces. Varieties that had been around for thousands of years were dropped in favour of high-yielding Asian varieties, despite their vulnerability to African pests and diseases.

One of the reasons for them travelling so extensively was to gather a definitive collection of very old varieties, which has since been deposited in a collection held by AfricaRice. In the recent civil war in Côte d'Ivoire, a lot of valuable germplasm was lost from the AfricaRice collection.

"The two collections of indigenous varieties from Niger and Burkina Faso are literally priceless treasures, as a source of ancient rice genes," says Laing.

Photo: ACCI

RICE

SPECIES INFORMATION – ASIAN RICE

Botanical name: *Oryza sativa*
Family: Poaceae
Common name: Asian rice

INTRODUCTION

Although most of the Asian rice consumed in Africa is imported from the east, the species is widely cultivated on the continent, especially in East and southern Africa, with more recently in West Africa too.

The wild ancestor of Asian rice is *Oryza rufipogon*, which grows throughout south and Southeast Asia. The earliest records of domesticated rice are probably those from the Lower Yangtze River valley of southern China, dating from about 6000 BC. The first African country to come into contact with Asian rice was Madagascar, via East Indian voyagers from Sumatra in the first millennium AD.

DESCRIPTION

Asian rice is a grass one to five metres high with an upright stem. Leaves grow from nodes on the stem and the grain grows from spikes that droop.

USES

Whole grains are boiled or steamed and consumed whole, or are ground into flour while uncooked and used to make baked goods, noodles or crackers.

It is also used in traditional medicine to treat skin conditions, indigestion, diarrhoea and nausea. Starch and oil extracts are also used in cosmetic and hygiene products. Rice straw is used for animal feed and bedding.

NUTRITION

Rice is an excellent source of carbohydrates, and also protein, fat and vitamins, if not overly milled and polished.

AGRONOMIC REQUIREMENTS

Asian rice is normally grown in a paddy or field that is kept wet. Africa doesn't have enough suitable marshlands, so it's mostly grown in marshlands next to large lakes or big rivers. In those areas both Asian and African rice are grown in paddies. However, it is also grown as "upland rice" which means that it is grown as a dryland crop, just like wheat or sorghum. Upland rice is very dependent upon an even summer rainfall, so drought tolerance is a key trait.

PROBLEMS AND BREEDING

Pests and diseases: Asian rice is highly susceptible to local pests and diseases, including a fungal disease called blast, which attacks the stem, Rice yellow mottle virus (RYMV, which produces a stunted crop covered with yellow spots and stripes, and a fly called the African rice gall midge, which lays eggs on the outside of stem. When the larvae hatch, they crawl into and eat the stem, stopping seed development completely.

Soil problems: particularly a very high iron content in soil, which is common in West Africa, which can poison a crop; salinity is a problem for paddy rice production because salt levels can build up over time if there is no leaching by heavy rains.

Dr Tenyson Mzengeza (graduated 2009), who manages a research station in Malawi and also co-ordinates the National Cereals Crops Research Programme, focused on grain quality in his research project. Since graduation, he has released three new rice varieties that have high, stable yields, are resistant to environmental stresses and respond well to nutrient inputs.

In Nigeria Efisue has released four new varieties that have a number of superior traits, including early maturity, high-yield, long slender grains and tolerance to iron toxicity. Efisue is a government breeder and university lecturer in Nigeria, as well as being one of the ACCI's visiting lecturers in the MSc programme.

Lamo tackled rice in his research project in Uganda, looking at drought tolerance and grain shattering. Shattering is the process in which plants disperse their seeds, and his research required that he was able to determine how likely different varieties were to shed rice grains, using a suction device. Since graduating Lamo has bred nine new varieties of rice, of which eight have been commercialised.

After graduating with PhD that focused on maize for Zambia, Mukanga switched to post-doctoral research that was also funded by AGRA, and which involved him implementing a rice breeding programme. This targeted increased yield, and resistance to blast and soil acidity in upland rice varieties. As result of this work, three new rice varieties were released in 2011.

He is currently working on a southern African programme that is evaluating rice varieties that have been bred for greater productivity in Malawi, Mozambique and Zambia. He is also involved in several studies focusing on aflatoxin control and storage insect pest management.

Dr Sophia Kashenge-Killenga (graduated 2011) bred rice for the coastal region of Kenya, aiming to include the traits of tolerance to drought, salinity and low fertility upland rice (*Oryza sativa* L.) varieties.

In Liberia Dr Quaqua Mulbah (non-AGRA , graduated 2015) is the primary government rice breeder for the whole country. He's worked on upland rice varieties, breeding for resistance to drought and blast, and also did research on the combination of a biological control agent with partial resistance to provide integrated control of blast.

Photo: Chen Che.

ACCI graduate Dr Jimmy Lamo is the main rice breeder in Uganda, where he has released nine varieties of high-yielding rice that are resistant to blast and are drought tolerant.

Photos: Top: Rasbak, Wikimedia Commons. Bottom: A.Davey/Wikimedia Commons.

TEF

SPECIES INFORMATION

Botanical name: *Eragrostis tef*
Family: Poaceae
Common name: Tef

INTRODUCTION

Virtually unknown in most parts of the world, tef is a superstar crop in its country of origin, Ethiopia. Although it's also grown in Yemen, Malawi, India and the US as a cereal, and as pasture in South Africa and Australia, in Ethiopia its grain fetches a higher price than all other cereals and it is prized by millions of Ethiopians. Tef is favoured over other cereals and is eaten daily, supplying about two-thirds of the protein in a typical diet.

This object of devotion has a tiny grain, used to produce injera, a chewy, sour-tasting bread that looks like a giant pancake. Tef is also eaten as a porridge or gruel, and its straw is valued by farmers.

Although the size of its seeds makes production laborious, tef holds great promise as a crop in other African countries, because it grows well in dry, difficult conditions, across a wide range of altitudes, and is very nutritious.

It has a high protein content of nine to fifteen percent and is gluten-free, making it an increasingly popular choice in western countries as a substitute for wheat.

DESCRIPTION

Tef is a short grass with narrow leaves and open, branched inflorescences with numerous small spikes. The grains are small (about one millimetre in diameter) and vary in colour from reddish brown to white.

USES

In Ethiopia tef flour is used to make injera, gruel, cakes, dry, unleavened bread called kita and homemade beverages, including a traditional beer called tella. In the US, where consumption is growing, it's used as a thickener for soups, stews and gravies.

Tef is also used as a cheap, nutritious, palatable fodder for animals, and the soft, pliable straw is a preferred binding material for walls, bricks and household containers.

Injera

Injera is a large, round, flat, spongy bread with a sour taste. Sieved flour is mixed with a large volume of water and allowed to ferment for two to three days. Then leavening is added and the dough is left to rise. A clay pan (mitad) is heated on the fire, greased with oil seeds and the dough is poured in a thin layer in concentric circles. It is eaten with various savoury dishes placed in the centre of the bread.

NUTRITION

Protein content ranges from nine to fifteen percent and has a good balance of amino acids. Mineral content is good with notable iron and calcium content, and absence of anaemia in Ethiopia seems to correlate with areas of tef consumption (National Research Council, 1996). Also worth mentioning, is that because seeds are so small, they have a greater proportion of bran and germ, the outer portions where nutrients are most concentrated, and are often consumed as a whole-grain flour because of their size.

Seeds are rich in energy (353-367kcal per 100g) and fat content averages about 2,6%.

AGRONOMIC REQUIREMENTS

In Ethiopia tef is grown either as a staple or standby crop. As a staple it's usually sown late and harvested in the dry season. As a stand-by, a fast-maturing variety is sown if the main crop shows signs of failing. Once established, tef requires little attention. Since its rapid growth deters weeds, it withstands most pests and diseases and it produces without extra fertilizers.

PROBLEMS AND BREEDING

The smallness of the seed: This is the biggest problem. The tiny seedlings can be damaged by wind and rain, and threshing, winnowing and grinding the small seeds by hand requires extra time and labour. Yields are also comparatively low, but since not much breeding work has been done on tef, this could be improved.

Drought, and soil acidity and aluminium toxicity: These are major production constraints for this crop. This led Dr Ermias Desta (graduated 2016) to investigate tolerance to aluminium toxicity and Dr Mizan Tesfay (graduated 2017) to breed tef genotypes for drought tolerance, for their research projects. Laing and a post-doctoral fellow, Dr Habteab Ghebriowot (non-AGRA), have an ongoing project to increase the size of tef seed by increasing the numbers of chromosomes in novel tef varieties.

Photograph: Bernard Gagnon/Wikimedia Commons

Photo: Alliance for a Green Revolution in Africa (AGRA)

SORGHUM

SPECIES INFORMATION

Botanical name: *Sorghum bicolor*
Family: Poaceae
Common name: sorghum

INTRODUCTION

Sorghum is Africa's most important contribution to the global food basket, yet, compared to rice, wheat and maize, it is a Cinderella crop, relatively neglected by researchers.

An indigenous African plant, *S. bicolor* was domesticated from *S. arundinaceum*, possibly in the Ethiopian Lowlands or the Sudan more than 3 000 years ago, and has over centuries spread across the globe, becoming especially valuable in countries like Mexico, India and China.

Described as a physiological marvel, sorghum thrives in a range of climates and can withstand high rainfall and extreme drought. It grows in marginal places where few other crops can survive, because of features like deep, powerful roots of three to five metres, and the ability to conserve moisture by reducing transpiration when stressed. It also has the unusual characteristic of being able to slow down its metabolic processes and become dormant during a drought, springing back to life when rains return.

Sorghum has many uses, including huge potential as a biofuel source. Because of its adaptability, it could be a better source of biofuel than maize or sugarcane in marginal agricultural lands.

There are, however, a few obstacles holding back this useful all-rounder. Apart from an image problem—it's seen as food for "peasants" and animals—the grain's food value is compromised by its poor-quality, indigestible protein. In addition, sorghum is more difficult to process than wheat, rice or maize.

These are serious drawbacks but many believe that given more research support, sorghum could make an even bigger contribution than it does already as the world's fifth biggest cereal crop.

DESCRIPTION

A robust cane-like grass with erect stems (culms) that are up to six metres high. The stems may be hollow, dry or juicy, and have large multi-branch clusters of small grains at the ends. The plant may have multiple stems, or a single main stem.

USES

Rural households make extensive use of sorghum. As food it's boiled, popped and baked. It's fed to cattle, and used as hay or silage. The stems are used for building, thatching, fencing, weaving, broom-making and firewood. Living plants are windbreaks and in an industrial context sorghum can also be used to make alcohol, vegetable oil, adhesives, waxes, dyes and starches.

In addition, the grain is malted and used to brew beer. (see box)

NUTRITION

The main component of sorghum grain is carbohydrate, up to 79% of its weight, and levels of B vitamins, found mainly in the germ, are high. Its protein content is high at 9-15%. However, protein quality, is poor, with deficiencies in critical amino acids, especially lysine and threonine, and only about two percent of the protein found in most commonly cultivated varieties is digestible by humans.

AGRONOMIC REQUIREMENTS

Sorghum is a short-day species, with some varieties becoming very tall when days are long and only flowering when the days become shorter. It can withstand drought but is killed by frost, and grows best at about 30° Celsius. It tolerates a wide array of soils.

The crop is grown from seed but will also regrow after being cut, so that a second crop can be harvested. Sorghum can also be propagated from stem cuttings. There are nodes along the stem that have tissue that can produce roots, and sprouts that grow into new plants.

PROBLEMS AND BREEDING

Protein: Although the edible portion of the grain contains a similar amount of protein to maize and wheat—about 8-15%—this protein contains prolamine, which is not easily digestible. In addition, tannins in the seed coats of dark sorghum grains block the body's ability to absorb and use proteins and other nutritional elements.

This indigestibility could explain why in Africa sorghum is often fermented before being eaten, and why ruminants, which have bacteria in their rumen that break the protein down and make it digestible, can eat it, but monogastric animals like pigs and chickens can't.

This indigestibility problem means that feed for these animals must be supplemented. If it could be solved it would have huge implications, not only for human nutrition on the continent but also the cost of raising these animals, which are currently fed maize supplemented with lysine, since sorghum is cheaper than maize.

Dr Amele Assefa (graduated 2013) is currently working as a post-doctoral student at the ACCI in South Africa. One of the areas she's investigating is how to improve digestibility and protein content, using chemical mutagenesis. This is reproduction characterised by the alternation of a sexual generation and a generation that reproduces asexually. So far, she has developed 12 varieties, four of which had high lysine that she obtained in Ethiopia. These have been planted and are being evaluated for use.

Breeding difficulties: Another big problem with sorghum is that it's a very hard crop to breed as it is strongly self-pollinating. If breeding for Africa, tall plants are preferred, three to five metres high, which means having to stand on a very tall ladder to do pollination. Since sorghum is self-pollinating, the plant breeder has to stand on a ladder to do the cross pollination, which entails emasculating the plant and introducing new pollen to the female parts.

Because of these practicalities, producing hybrids on a large scale is difficult. One technology that offers possibilities is a chemical hybridising agent that kills the male gamete. This is sprayed onto the A line (the female parents) to kill off pollen it produces. Pollen from B line plants (male parents) is then collected and dusted on to the A line, so that only cross-pollination takes place. This approach can cut the breeding time from 25 years to 10 years.

Assefa is currently working on breeding sorghum hybrids using this method, which Laing says will be a game changer if it works.

Pests and diseases:

- In wet parts of Africa sorghum is affected by a fungal disease called downy mildew, that gets carried in seed, and is very difficult to control. Leaf spot is also a problem.
- Birds love sorghum and are very problematic because they can decimate a field. Varieties with seed coats that contain tannin are bird-resistant because the seeds are bitter and difficult to digest, but these are also indigestible for humans.
- The parasitic weed *Striga* is a big problem for sorghum farmers and several students have focused on breeding for resistance to it. The ACCI currently has a PhD student, Emmanuel Mrema, working in Tanzania on a strategy to breed for resistance to *Striga*, combined with the use of a biological control agent, *Fusarium oxysporum* f.sp. *strigae*. (commonly called "Foxy") that is applied onto the sorghum seed. This fungus colonises the roots of the sorghum plant, and when the parasite attacks these roots, Foxy emerges and kills the *Striga* plants.
- Insects—stalk borer is a massive problem with different species found down the length of sub-Saharan Africa. As a moth, stalk borer lays eggs on the outside of the stem, and when the caterpillar hatches, it climbs into the stem and eats it. Breeding for resistance is an option, as is the use of an endophytic fungus that grows up the stem and is a parasite of insects. If a stem borer eats the stem, it will be killed by the fungus, a solution currently being developed by a PhD student, Bernice Bancole.

Post-harvest:
Post-harvest pests are another serious problem, with 50-70% of harvested sorghum grain eaten by weevils, beetles and moths in storage. Breeding for resistance is an option, and the ACCI also has a graduate, Dr Mohamed Saeed, who is looking for fungi that kill the insects and can be applied to grains after harvest.

These post-harvest grain pests eat more than half of the cereal and legume grains harvested in Africa every year, so the quickest, simplest way to double the food supply of Africa would be to control these pests effectively.

SWEET SORGHUM

Some varieties of sweet-stemmed sorghum contain up to 22% sugar and are grown across Africa to be eaten as a snack.

This is twice as much sugar as that produced by sugarcane (6-14%) and in South Africa this has implications for producing bioethanol. Unlike sugarcane, sorghum is not limited to being grown in the coastal zone and it doesn't need to be irrigated. It wouldn't make sense to produce ethanol for Johannesburg on the coast from sugarcane, because with transportation it would be too costly. But sweet sorghum could be grown across most of southern Africa, where summer rainfall is reliable.

Sorghum also releases natural herbicides that suppress weeds, and chemicals that kill eelworm, a pest that is a huge problem when growing sugarbeet and other crops. Since sorghum is a summer crop and sugar beet is harvested in winter, rotating the two means that sugar can be produced year-round without the nematode problem affecting the latter.

Dr Clement Karari (graduated 2007) has bred and released a high-yielding variety in Kenya. Dr Itai Makanda (graduated 2010) bred high yielding sweet sorghum varieties for his PhD. Other students have bred for resistance in sorghum to *Striga*, sorghum midge and drought.

Deadly brew

Sorghum is also an important brewing species, and in Africa it's been used for thousands of years to make traditional beer. This beer has huge cultural significance, and among the Zulus in South Africa, only sorghum beer is acceptable to use in ceremonies, because that's familiar for the ancestors.

In most parts of the world, barley is used when making beer or whisky, using natural enzymes in germinating barley grains (malted grain) to break down the starch into sugar. First, malt is made by germinating the barley, which releases amylase. This is then put in the oven and gently toasted to stop germination, then ground to produce malt. The malt is added to the starch and the amylase converts the starch to sugar. Yeast then converts the sugar to ethanol and CO_2.

In Xhosa culture, a form of "noble" sorghum beer with a musky, smoky flavour is made by deliberately using mouldy grain, a practice that probably developed because traditionally, mouldy grain was used to make beer instead of being eaten.

However, the fungus produces several deadly toxins, called aflatoxins, and among the highest levels of throat cancer in the world occur in South African people in the Eastern Cape province, where this tradition of brewing "noble" beer occurs.

'Ukhamba' – a Zulu sorghum beer pot crafted by Zanele Nala

Photo: Alliance for a Green Revolution in Africa (AGRA)

WHEAT

SPECIES INFORMATION

Botanical name: *Triticum aestivum*
Family: Poaceae
Common names: bread wheat, ordinary wheat

INTRODUCTION

For decades wheat, like rice, has been riding a wave of popularity driven by urbanisation, a swelling middle class and changing lifestyles.

One of the current top three cereal crops along with maize and rice, this modern favourite has ancient origins. According to genetic and archaeological research, *Triticum aestivum* (bread wheat) originated about 9 000 years ago in the Caspian region of Iran, and was the result of a cross between a wild grass, *Aegilops tauschii*, and a cultivated wheat, probably *Triticum durum*. (*T. durum* is still used today as the preferred wheat species for making firm pasta like spaghetti, because of its large, hard, low-gluten grain.)

Bread wheat's popularity can be ascribed to its sticky gluten, that traps CO2 bubbles released by yeast or bacterial fermentation in rising dough, producing lighter baked goods.

The taste and convenience of wheat products has led to growing numbers of African consumers switching their preferences to bread from traditional staples (maize, sorghum, millet, sweet potato, cassava and yam), and consumption of wheat on the continent has soared with demand outstripping production. Millions of tonnes of wheat must be imported, and according to Consultative Group on International Agricultural Research (CGIAR), consuming countries spend precious foreign reserves to import at least US $12 billion worth of grain each year.

Experts believe the continent could increase yields by up to four times in areas where conditions favour wheat growing—including SA, Ethiopia, Egypt, Kenya, Zambia, Zimbabwe—although this would entail infrastructural and value chain improvements. A crop needs roads to reach the market, and the market must be accessible to the farmer.

DESCRIPTION

Bread wheat is an annual grass of up to 85cm with a spike (flowering and fruiting part) on each of its one to five stems. Each spike, which is up to 15cm long, contains two to five rudimentary spikelets (clustered units of flowers and bracts) at the base of 10-25 fertile spikelets.

USES

Food: Wheat grain can be ground into flour; germinated and dried creating malt; crushed or cut into cracked wheat; and parboiled (or steamed), dried, crushed and de-branned to create bulgur. Couscous is also usually made from wheat.

The nutrient-rich bran is used to enrich breads, breakfast cereals and other foods. Wheat flour is used to make a wide range of baked goods, from bread to crackers, sauces and breakfast cereals.

Drink: Used to make beer, boza (a fermented drink found in Turkey and the Balkans), vodka and other spirits.

Textiles:

Building materials:

Straw: feed for livestock, a fibre for mud for making of bricks

NUTRITION

Whole wheat contains high levels—relative to the RDA—of fibre, Zinc, Copper, Manganese, Selenium, Niacin (Vitamin B3) and Vitamin E. It's also a good source of energy and contains about 12% protein.

AGRONOMIC REQUIREMENTS

Wheat can be grown in summer or winter, and with irrigation or dryland agriculture, depending on the variety. Generally it needs cool temperatures with sufficient rainfall.

It's relatively fast-growing and can mature in four to five months.

PROBLEMS AND BREEDING

Pests and diseases: Rust is the main disease affecting wheat, with Fusarium head blight a close second. Rust fungi mutate rapidly, so it is necessary to keep breeding new varieties. Historically, this has entailed looking for new resistant genes and then backcrossing these into good agronomic parents. However, with the repeated failure of this approach since 1901, the ACCI staff and students have been breeding for durable resistance, using landraces that contain additive genes for rust resistance that can be accumulated in parent populations.

In Ethiopia Dr Netsanet Hei (graduated 2015) made significant progress in her research project breeding for durable resistance to stem rust, one of the most destructive diseases faced by farmers in that country. The student is advancing her breeding work to release promising varieties.

Drought tolerance: At the ACCI the focus under Shimelis has been on breeding for drought tolerance. Work is done first on screening suitable varieties under stressed and non-stressed conditions, before selection and crossbreeding is done.

The centre also has PhD students working on wheat in Ethiopia. One of them has graduated and is a research co-ordinator for the wheat pathology programme in that country. Dr Batiseba Tembo (graduated 2016) from Zambia developed wheat genotypes resistant to spot blotch disease, that badly affects wheat production in warm and humid environments.

Photo: Alliance for a Green Revolution in Africa (AGRA)

CROPS
LEGUMES

BAMBARA GROUNDNUT

SPECIES INFORMATION

Botanical name: *Vigna subterranea*
Family: Fabaceae
Common names: Bambara groundnut

INTRODUCTION

Bambara groundnut could be described as a diamond hiding in plain sight, given its low profile among establishment agriculturalists and support agencies, compared to its importance to African small-scale farmers. The invisibility of this legume whose seeds grow underground is puzzling, given its potential as a low-input, sustainable crop in drought-prone areas, and as a nutritional booster for poor communities.

It's a popular staple for millions of rural people, although this is difficult to measure because it's mostly grown for home consumption, and production and consumption figures are estimated. According to FAO an estimated 287 793 tonnes of Bambara groundnut was produced in Africa in 2014, which is considerably less than the 11,401,228 tonnes of peanuts produced in 2013. But their figures do not take into account crops produced for home. This can lead to serious miscalculation of real production levels, which Laing estimates at 20 times the FAO figure, close to 6 million tonnes.

Eaten as a meal or a snack, it is a popular take-away lunch for workers in the fields, and an important source of protein for families, especially during the Hunger Gap. The crop's positive attributes are multiple. It has been hailed by scientists as a "complete food" with a good balance of carbohydrate, protein and fat content. It tolerates poor soils and drought, and it grows where peanut (an alien groundnut that has reached loftier heights in Africa) often fails.

Bambara groundnut's nitrogen-fixing roots help to replenish soils, therefore making it good for intercropping with maize, millet, sorghum, cassava, etc. It is also a good animal feed because its leaves are rich in nitrogen and potassium.

Although it's not grown on a large scale as a cash crop, there is potential for growth here, especially if work is done on building markets and developing a commercial food processing stream. In Zimbabwe it's successfully sold as a canned product.

DESCRIPTION

Bambara groundnut grows to a height of about 35cm, with divided leaves on slender stalks. Pale yellow flowers flower and self-pollinate, then develop white spikes that grow downwards into the ground. Round, single-seeded or two-seeded pods develop in the soil, underground and out of sight. The seeds are very hard when dried, and, depending on the variety, are a range of different colours, including black, red, spotted, yellow-brown and cream. They look stunning in a large basket at a market.

USES

Immature beans are eaten raw or cooked, while mature seeds are pounded into flour or soaked, then boiled or roasted in oil.

A vegetarian milk is also produced by processing the bean in the same way that soy milk is made, and is used as a weaning milk in some African countries. According to some reports, its nutritional quality is better than other legume-based milks. The seeds have been used to feed chickens and fish, and the leaves are suitable for animal grazing.

NUTRITION

Bambara groundnut is a compact source of good nutrition, containing about 60% carbohydrate, 20% protein and six percent fat, plus a range of vitamins and minerals. The seeds have been found to be richer than peanuts (groundnuts) in essential amino acids such as isoleucine, leucine, lysine, methionine, phenylalanine, threonine and valine. The fatty acid content is predominantly linoleic and palmitic acids.

AGRONOMIC REQUIREMENTS

The crop flourishes in average temperatures of 20 to 28°C and annual rainfall of 500 to 600mm. It fixes nitrogen easily and prefers sandy soils because the spikes can penetrate the soil surface easily, although it has a termite problem because of that.

It is usually planted early in the rainy season and seeds are well spaced, often inter-cropped with maize and pumpkin and mounded to prevent attacks by insects. Farmers can expect yields four months after planting, of about 1 000kg/ha.

PROBLEMS AND BREEDING

Bambara groundnut has relatively few problems: termites, leaf spot and sometimes viruses.

Yields can be low and breeding this crop is exceptionally difficult. The ACCI has produced a manual on making successful crosses, and selection protocols.

Dr Mohammed Sagir Mohammed (non-AGRA, graducated 2014), did a survey of the crop's production in northern Nigeria that Laing describes as "incredibly important, documenting its real importance to rural communities in its centre of origin, West Africa".

In his PhD thesis he investigated the genetic origins and diversity of Bambara groundnut and found that varieties had been shared far and wide across Africa. In Kano State he identified 27 landraces being used by farmers, and he also characterised diverse collections from seven different geographic regions. The study generated valuable, novel Bambara groundnut genetic material that will be useful in breeding new, improved varieties. This was the first documented case of cross-pollination and breeding of Bambara groundnut.

Mohammed now works at Ahmadu Bello University, Zaria in Nigeria as a legume breeder.

Photo: Ton Rulkens/flickr

Photo: Jamain/Wikimedia Commons

COMMON BEAN

SPECIES INFORMATION

Botanical name: *Phaseolus vulgaris*
Family: Fabaceae
Common name: bean

INTRODUCTION

The common bean is one of the mainstays of food security in SSA, and is estimated to meet more than 50% of household dietary protein requirements. In countries like Rwanda, Kenya and Uganda, each person eats an average of 50-60kg of beans in a year, and the continent is the second biggest bean-producing region in the world, growing about 2.5 million tonnes.

That's not bad for a crop that came from Latin America, where it was domesticated in Mexico and the Andes before 5000 BC. By the time Portuguese explorers arrived in America in 1492, it had become the staple over most of the New World. Ships then carried multiple varieties to far-flung places around the globe, including Africa, where about 80% of varieties are of Andean origin and 20% Mexican.

Researchers believe levels of bean production could be far higher if not constrained by low levels of potassium and moisture in soil, as well as pests and diseases, and here the role of plant breeders is crucial.

DESCRIPTION

The common bean is a highly variable species. Some varieties form bushes of 20-60 cm while others are climbers, forming vines growing on wooden stakes two to three metres high. All varieties have green or purple leaves divided into three oval, smooth-edged leaflets and white, pink or purple flowers. The flowers become pods of 8-20cm, which may be green, yellow, black or purple and each enclosing four to six beans. The kidney-shaped beans, up to 1,5cm long, are varied in colour and often mottled.

USES

An important food for millions of people around the world, the common bean is a good substitute for meat. The mature seeds are mostly boiled and eaten whole, mashed, mixed with cereals, or in soups, while the immature pods and seeds are consumed as a vegetable.

The crop is also used as fodder for animals, and in folk remedies for a range of ailments, from acne and diabetes to diarrhoea, eczema and hiccups.

NUTRITION

On average, a cup of cooked common beans supplies 15g of protein, which is about 30% of the recommended daily amount. Beans are high in fibre and the B vitamin folate, which is essential for the production of red blood cells. They also contain carbohydrate and a variety of vitamins, minerals and other nutrients. They are gluten-free and have a low glycaemic index.

AGRONOMIC REQUIREMENTS

The crop flourishes in a warm climate, growing best at temperatures of between 18-24° Celsius. Seeds should be planted in warm soil (over 13°C) that is at least 90cm deep, and not too sandy, as this will lead to low fertility or nematode damage. Soil should be well drained, loose and have a pH of 5,8 to 6,5.

PROBLEMS AND BREEDING

Beans in Africa are under constant attack by pests such as root knot nematodes, bean flies, and post-harvest weevils, as well as diseases caused by viruses, bacteria and fungi. Because of these enemies, the bean can be difficult to grow, and there's a real need to breed better varieties with a comprehensive resistance to the many problems.

Most PhD students at the ACCI working on beans have focused on an aspect of disease or pest resistance.

These breeding projects have not been easy. Beans are self-pollinating, and can only be cross-pollinated in the early hours of the morning, by hand, when each plant must be emasculated before the bud opens.

In Malawi Kananji has produced six new varieties of common bean. For his research project he worked on storage pest resistance to two weevils (bruchids) that focus on eating bean seed. "This was very relevant; I was able to come up with a solution and the farmers were very happy," he says. "Some of those varieties have been taken up by seed companies and are being commercialised."

After graduation he continued doing bean research with the help of a grant from AGRA, breeding several climate-smart varieties that were early maturing.

In Uganda Dr Stanley Nkalubo (graduated 2007) has released nine varieties that are early maturing and high yielding, two of which are anthracnose-resistant and three CABMV-resistant.

Left: Dr Clare Mukankusi, who was in the second cohort of ACCI students, is now a bean breeder for CIAT at Kawanda, part of Uganda's National Agricultural Research Organisation, and one of only two bean breeders monitoring the flow of beans in and out of the continent's biggest bean genebank.

Photo: Georgina Smith/CIAT

Photo: Alliance for a Green Revolution in Africa (AGRA)

COWPEA

SPECIES INFORMATION

Botanical name: *Vigna unguiculata*
Family: Fabaceae
Common names: cowpea, black eyed pea

INTRODUCTION

For an estimated 200 million people living in SSA, a small indigenous legume, the cowpea, is probably all that stands between them and malnutrition. For most, one or other cereal crop is their main staple food, none of which supplies adequate daily protein, with the amino acids that are essential for building and repairing the body.

Cowpea, which scientists believe probably originated in the Sahel region some 5 000-10 000 years ago, has been called 'a near-perfect match for the African soil, weather and people' (Lost Crops of Africa: Vol 1) Apart from being drought-tolerant, it's also exceptionally nutritious, supplying the protein and amino acids that help balance the diets of people living on minimalist diets.

Cowpea feeds both animals and people, and some varieties cook fast, which is a huge plus, especially when fuel is scarce or expensive. It also helps to control erosion and fixes nitrogen. It's been adopted by other countries, most notably India, Brazil, the Caribbean and US, where it was taken by slaves, but the biggest producers and consumers are African, with an estimated 38 million households (194 million people) cultivating it in SSA.

Farmers intercrop it with maize, sorghum, millet and cassava, and in rice farming it is used before or after a crop – where it enriches the soil with nitrogen, helping to break the cycle of continuous cropping of cereals, and to provide extra income.

Despite its many attributes and obvious importance to marginal communities, however, cowpea's growth over the last two decades has been slow. Like sorghum and Bambara groundnut, cowpea is languishing in the wilderness and its huge potential will remain largely untapped until money is spent on developing it.

DESCRIPTION

Cowpea flowers are white, blue or purple in the morning, yellow at noon and withered by evening. Stems are thicker than the common bean and never become woody. Varieties can be bush types, or creepers with long stem that can creep 10m across the ground. Pods are variable lengths, cylindrical and end with a rounded tip.

Variation in bean colours: the seed can be uniform ivory, cream, red, brown or black; ivory or cream with brown, black or brown and black eye, two coloured with the eye having two wings on a light background or spotted grey or black. Seeds are usually ovoid or rounded and sizes vary.

USES

Cowpea can be eaten at different stages of growth—as fresh green leaves, dry leaves, green pods, green beans or dry grain. Immature green pods are boiled and eaten as a vegetable. The seeds are boiled in soup or ground into flour to make cakes that are deep-fried or steamed. Flour is also used to make porridge, puddings and soup.

Canned cowpea is popular in Zimbabwe. The seeds are sometimes roasted, ground and used as a coffee substitute.

It is a dual-purpose crop, and hay, which can be kept for months and fed to livestock when there's no other food, is also an important product.

It is a green fertilizer. It fixes nitrogen, adding up to 70kg per hectare to soil, and can be used as mulch to fix depleted soil.

NUTRITION

The dried seed is very nutritious, containing up to 24% good-quality protein with plenty of lysine. This makes it a very good partner for lysine-poor cereals and roots such as maize or cassava. However, as with other grain legumes it is deficient in methionine, cysteine and tryptophan.

It also contains about 63% carbohydrate, oil, minerals and other nutrients.

AGRONOMIC REQUIREMENTS

Cowpea grows best in summer at temperatures around 30°C, and time taken to flower can vary from 30-100 days, depending on how photosensitive the variety is. It can grow adequately in 400-700mm of rain and prefers sandy, well-drained soils, although it can tolerate a variety of different soils as long as they are not cold.

PROBLEMS AND BREEDING

Cowpea offers big opportunities for breeding improved varieties because of its extensive genetic diversity. It's much more drought tolerant than other legumes and a lot of work is being done on extending and improving this attribute. Dr Rogerio Chiulele (graduated 2011) has bred drought-tolerant cowpea in Mozambique. Chiulele, who is currently an assistant professor at Eduardo Mondlane University in Maputo, helped set up a cowpea breeding programme run by UEM that screened 300 Mozambican cowpea lines for drought tolerance and yield and, after several seasons, identified six varieties that had both traits and were adapted to different agroecologies.

The UEM team has also collaborated with the University of California, Riverside, who shared germplasm that contributed to the development of three drought-tolerant, high yielding varieties that were released in 2015. Local varieties were also crossed with black-eyed peas, which fetch a higher price, thereby increasing marketability.

Insects are a major problem, with at least 15 major and 100 minor insect pests attacking the plant in Africa. It also has some viruses, a bacterial blight and charcoal rot of the stem and roots, caused by *Macrophomina phaseolina*, that are problematic. In Uganda Orawu has released three varieties that are resistant to Cowpea aphid-borne mosaic virus (CABMV) and are high-yielding.

Post-harvest pests include weevils and bruchid beetle, which begin infecting the plant in the field and then really go to town when it's in storage. It's been estimated that in Nigeria, some 30 000 tonnes of cowpea grain are lost annually, most of it during storage.

Another devastating pest is a parasitic weed, *Striga gesnerioides*. In Burkina Faso Dr Jean Baptiste De la Salle Tinegre (2010) has successfully bred for resistance to this pest in four different varieties.

Striga

Striga, also known as witchweed, is a daintily flowered botanical plague that attacks multiple crops, leaving devastation in its wake. Affecting rice, maize, sorghum, millet and cowpea, it is estimated to infest about 50 million hectares in SSA, causing crippling production losses for small-scale farmers, and seriously threatening food security.

The worst offenders are *Striga hermonthica*, which has pink flowers, and *Striga asiatica*, which has red, with the former estimated to have overrun 2.4-4 million hectares of land under maize and cereal production, causing losses of 30-80%. *Striga gesnerioides* specifically attacks cowpea.

A parasitic weed, each *Striga* plant produces 90-500,000 small, light seeds that are easily dispersed and can lie dormant in soil for 10 years. They grow into the host's roots and absorb water, nutrients and minerals.

The use of herbicides and fertilisers can curb *Striga* but most small-scale farmers can't afford these inputs, making plant breeding and seed-based technologies the best bets for overcoming the evil genius.

Shimelis (left) and Solomon Assefa, a student from the 2014 cohort, in Ethiopia, standing in a field of sorghum that has been invaded by colourful Striga plants. Photo: ACCI

Photo: Alliance for a Green Revolution in Africa (AGRA)

PIGEONPEA

SPECIES INFORMATION

Botanical name: *Cajanus cajan*
Family: Fabaceae
Common name: pigeonpea

INTRODUCTION

If there was a contest to name a crop worthy of the term "super food", pigeonpea would be a strong contender. Containing high levels of protein, amino acids, minerals and vitamins B1, 2, 3, 5 and 6, C and K, this drought-tolerant legume would seem to be made for people whose diets are nutritionally poor.

In its motherland, India, where it was domesticated thousands of years ago, pigeonpea is a staple for millions of people. Curiously, in Africa, where a second centre of diversity was established at around 2000BC, it is not as popular, and most of what is grown is sold as a cash crop to the Middle East.

Pigeonpea grows extremely well in Africa and at present about 21% of global production (1.05 million tonnes) is produced here, mainly in Malawi, Tanzania, Kenya, Mozambique and Uganda.

Given its climate-smart and nutritional attributes, it would seem worthy of a major marketing drive in drought-prone areas, along with breeding programmes to improve varieties in these places.

DESCRIPTION

Pigeonpea is a shrub that grows to about two metres high. Its main stem is erect with many branches, and leaves composed of three leaflets alternate along the stem. The flowers are yellow and seed pods are two to thirteen centimetres long, containing up to nine seeds that are white, brown, purplish or mottled.

USES

The plant is eaten as a green vegetable, while the dried peas are eaten whole or as flour. The seeds can be sprouted and then cooked as a vegetable, with the sprouting improving digestibility. Seeds are also eaten with rice or in stews, and in Colombia, Dominican Republic, Panama and Hawaii they are canned.

In addition, the seedpods and leaves can be fed to livestock, stems are used for fuel and construction, and the plant can be used as a living fence or to provide 'green manure' in vegetable gardens. The stems are also used for thatching and making baskets.

NUTRITION

Pigeonpea is an important addition to subsistence diets, with mature peas containing a high percentage of protein (22%), as well as high levels of important amino acids (methionine, lysine and tryptophan), minerals (iron, magnesium, manganese, phosphorus, potassium and zinc) and vitamins (B1, Folate, C and K). Carbohydrate makes up 62% of the grain.

AGRONOMIC REQUIREMENTS

Pigeonpea is one of the most drought-tolerant legumes, although it prefers hot, moist conditions. It does not tolerate frost. It is a short-day plant, taking 60-235 days to reach pollination depending on cultivar and latitude. It tolerates a wide range of soils and pH but prefers pH 5.0-7.0.

PROBLEMS AND BREEDING

Quality: Because it is mainly a cash crop in Africa, quality issues are especially important, and the size and colour of grain determines the price that's obtained.

It has one very serious disease, *Fusarium* wilt, that attacks the root and then the stem. Kananji has successfully bred for resistance to this disease in Malawi, with one variety released. He has also bred two other varieties and contributed to new early maturing varieties that could be taken to areas where the crop was not traditionally grown because of the climate. These varieties are now grown in Malawi, Mozambique and Zambia. Dr Didas Kimaro (graduated 2017) from Tanzania initiated a pre-breeding of pigeonpea for *Fusarium* wilt resistance. His breeding project is being supported by AGRA to release promising varieties for Tanzania conditions.

Photo: Alliance for a Green Revolution in Africa (AGRA)

Photo: Alliance for a Green Revolution in Africa (AGRA)

GROUNDNUT

SPECIES INFORMATION

Botanical name: *Arachis hypogaea*
Family: Fabaceae
Common name: peanut

INTRODUCTION

The groundnut, another Andean native hailing from northwest Argentina and southern Bolivia, has been cultivated since before 2000 BC. In Africa it's an important crop for commercial and small-scale farmers, because of its high edible oil and protein content, and the continent accounts for 28% of global production. Like other legumes, groundnut fixes nitrogen in soil, making it especially valuable to farmers who can't afford fertilisers.

DESCRIPTION

Groundnut is a small, usually erect annual that can reach 60cm in height. It's thin-stemmed with oval leaves arranged in alternate pairs. The plant produces flowers that are orange, yellow, cream or white and have 'pegs' that grow down into the ground as soon as they've been pollinated.

The pods can reach 10cm in length and contain one to five seeds. Fruits form below the ground, out of reach of birds and other seed eaters, but they are vulnerable to termites.

USES

Seeds are eaten raw or roasted, chopped up in confectionaries and ground into peanut butter. Young pods, leaves and tips can be eaten as a cooked vegetable.

Oil is extracted from the seeds and used in cooking, margarines, salads, canning, deep-frying, shortening in pastry and breads, in pharmaceuticals, soap, cold creams, lubricants and fuel for diesel engines. The oil cake is high in protein and can be eaten by animals or people.

The leaves are used as fodder for animals.

NUTRITION

Groundnut is a rich source of oil (up to 26%), protein (up to 36%), minerals (calcium, magnesium, potassium and iron) and vitamins E, K and B1). It also has a good amino acid makeup.

AGRONOMIC REQUIREMENTS

The groundnut grows very well in tropical and sub-tropical climates, favouring temperatures of 30-34°C, although it can tolerate a range of 15-45°C, and a long growing season. It prefers well-drained, sandy soils and is drought-tolerant, although rainfall of 500-600mm is best for optimal growth.

The groundnut is grown from seed, which should be planted in loose crumbly soil with no weeds. It can be grown alone or intercropped with crops such as maize, cassava or soya bean. The groundnut is ready for harvest after 85-130 days, depending on the variety. After harvest, pods should be dried in the sun for two to ten days.

PROBLEMS AND BREEDING

Groundnut is difficult to breed because artificial pollination is complicated. There are relatively few varieties because the plant generally self-pollinates, but the advantage of self-pollinating plants is that once a variety has been bred for resistance and quality traits, the individual plant seeds itself.

Although there's not much genetic diversity to work with, ACCI students have made excellent progress. In Malawi and Mozambique, Chintu and Dr Amade Muitia respectively have both bred for resistance to Groundnut rosette disease and Leaf blight, producing varieties that are strongly resistant to both diseases. This is a formidable achievement, because in Africa, the Groundnut rosette virus complex (a mixture of several viruses working together) devastates entire crops, while leaf blight is a serious fungal disease that can defoliate a crop in days.

Chintu is currently employed as a groundnut breeder in the Ministry of Agriculture in Malawi. Plants that he evaluated for his PhD and found to be resistant to rosette disease have been incorporated in the national groundnut breeding programme, and, in conjunction with an ICRISAT team, he has released seven groundnut varieties that are currently being promoted for use by farmers in Malawi.

Muitia did work for his thesis on breeding early-maturing groundnut with resistance to aflatoxin contamination, reduced susceptibility to Rosette disease and leaf blight, and for quality traits. In 2013 an early maturing variety bred by him was released and commercialised.

The ACCI is also breeding for resistance to a fungus called *Aspergillus flavus*, which infects the nuts underground and produces several highly toxic mycotoxins,called aflatoxins. Although the crop is highly susceptible to contamination by some 20 different mycotoxins, Aflatoxin B1 is particularly dangerous for humans and can cause liver cancer. Whereas the limit for safe consumption is four parts per 1 000 million, in Africa groundnuts often contain a level of hundreds of parts per million.

If groundnut plants are exposed to any stress in the last two to three weeks before harvest, the fungus can attack and release these toxic compounda, making the groundnuts dangerous to birds and mammals. This is a huge problem across Africa, for health and economic reasons, since many countries such as those in the European Union will not permit imports of the crop from affected areas. Exports of groundnut to the EU from Mozambique have dropped at least 90% due to this fungus.

Apart from breeding for resistance, the ACCI has also been looking at biological control agents to control this fungus, and so far these trials have been very successful, reducing aflatoxin contamination by more than 70%, and increasing yields by 40-50%.

Termites are another hazard, eating the seeds underground, and *Aspergillus flavus* often goes in and infects pods and seeds after the termites, as a secondary infection.

Photo: Alliance for a Green Revolution in Africa (AGRA)

Photo: Alliance for a Green Revolution in Africa (AGRA)

SOYBEAN

SPECIES INFORMATION

Botanical name: *Glycine max*
Family: Fabaceae
Common name: Soybean

INTRODUCTION

Soybean is a relatively new kid on the block in the crop world. Native to temperate East Asia, evidence of its cultivation only starts in China in about 1000 BC, while in Africa it was first planted in Egypt in 1858.

This late start hasn't stopped soybean from becoming one of the top 10 agricultural commodities in the world, with an estimated 337 million tonnes produced in 2016. The main reason for this is its high oil content of 20%, which has made it the number one oil seed in the world. It's also exceptionally high (36%) in good-quality protein. Compare that with maize at eight percent protein.

In Africa, however, soybean is a minor crop, making up less than one percent of global production. Given the right conditions and materials, this represents a huge opportunity for the continent's farmers.

DESCRIPTION

The soybean plant is an annual that grows into an erect bush up to 1.5m tall with woody stems and alternately arranged leaves. Its flowers are small and white or purple, while seed pods are curved and three to fifteen cm in length, containing one to five seeds. The seeds come in a variety of hues including yellow, green, brown, black and mottled.

USES

The seeds can be used to make flour, dairy substitutes such as milk, margarine and yoghurt and meat substitutes such as vegetable burgers. Oil can be extracted from both the seeds and pods and the by-product oilcake is used as an animal feed. The oil is used in products such as paint, linoleum and soap. Soybean foliage is also used as animal fodder or hay.

NUTRITION

Soybean seeds contains more than 36% protein; it's also high in carbohydrate (30%), oil (20%) and fibre, and contains minerals and vitamins. The protein is good quality, containing all the amino acids needed by the body. Soybean oil is 85% unsaturated, made up of linolenic acid (an omega 3 fatty acid), oleic acid and isoflavones.

AGRONOMIC REQUIREMENTS

Soybean is a short-day plant that thrives in hot weather. It can be grown year round in most parts of the tropics, requiring temperatures of 15-27°C for optimal growth. Temperatures over 40°C harm seed production. The plant tolerates a wide range of soils and climates but needs adequate soil moisture for germination. Plants are sensitive to waterlogging but are tolerant of drought conditions once established. Soybean grows best on a light, loose, well draining loam with a pH of 6.5. Acid soils stunt production.

Soybean is propagated directly from seed, and the crop is ready to harvest between 70 and 160 days after planting, depending on variety.

PROBLEMS AND BREEDING

Although soybean is quite tough and doesn't have many obstacles, it's not very drought tolerant and yield is generally low in SSA. There are a few diseases, e.g., soybean rust, which can cause serious losses.

However, breeding for improvements is difficult. The cultivated plant is relatively new, and is descended from a wild bean, so there's not a lot of genetic diversity. It's also strongly self-pollinating. Crosses are very difficult to do, and breeders have to use a jeweller's loup to see what they're doing inside the flower. Timing is also important as flowers are fertile for a brief period at night.

The plant breeder's task is mostly about adapting varieties and looking for better yields. Ethiopian Dr Abebe Abush (graduated 2012) investigated the performance of the crop in soils with high and low phosphorus. Uptake of this vital plant mineral is severely affected in acidic soils, which is a widespread condition in Ethiopia. He identified a variety that functions well under both high and low phosphorus conditions, indicating that it would be suitable for use in breeding programmes.

Photo: Jonathan Odhong'/ IITA

Photo: Apollo Habtumi/ILRI

FABA BEAN

SPECIES INFORMATION

Botanical name: *Vicia faba* var. *minor*
Family: Fabaceae
Common name: Faba bean

INTRODUCTION

Faba bean is an ancient relative of the Chinese broad bean, *Vicia faba* var. *major*, the difference being that it has smaller seeds. Hardy and highly nutritious, it was cultivated in the Middle East for 8 000 years before spreading to Western Europe.

It is very adaptable and is a staple food in Egypt and popular in Ethiopia, Morocco and Sudan.

DESCRIPTION

It is an erect thick-stemmed plant 50-180cm tall, leaves are 10-25cm long with two to seven leaflets and grey-green in colour. Flowers are white with five petals and have a strong, sweet scent. The pod is broad, leathery and green, maturing to blackish-brown.

USES

The plant is eaten in a variety of ways. The immature pods are cooked and eaten, the young leaves are eaten raw or cooked. The seeds are also eaten when young and tender, usually after being steamed or boiled, or fried to produce a crunchy snack, or dehydrated and ground into flour. This can be rehydrated at a later stage.

Faba bean foliage is also used to feed livestock and the straw is used for brick making and fuel in Sudan and Ethiopia.

NUTRITION

Faba bean seed is high in protein (26%), carbohydrate (59%) and fibre (25%), as well as folates, B vitamins (pyridoxine, thiamine, riboflavin, niacin), minerals (iron, copper, manganese, calcium, magnesium) and potassium. It's also a source of Levo-dopa, a precursor of neuro-chemicals in the brain such as dopamine, epinephrine and nor-epinephrine.

AGRONOMIC REQUIREMENTS

Faba bean prefers rich loam but can be grown in soils with clay, high salinity and a wide range of pH values. It grows best in soil temperatures of 15.5-18°C and is low-yielding in high temperatures. It should be inoculated with the bacterium *Rhizobium leguminosarum* if legumes haven't been grown in the soil before.

PROBLEMS AND BREEDING

In Ethiopia Dr Asnakech Beyene (graduated 2015) studied the crop, with her project revolving around developing resistance to chocolate spot disease, and provided valuable information about the inheritance of disease resistance.

Favism and protection against malaria

Raw faba beans contain the alkaloids vicine and convicine. These substances can induce a form of anaemia caused by the abnormal breakdown of red blood cells, in people with the hereditary condition, glucose-6-phosphate dehydrogenase (G6PD) deficiency.

This potentially fatal condition, also called favism after the bean, affects approximately 400 million people worldwide, mainly of tropical African, Middle Eastern, tropical Asian and some Mediterranean origin. Areas of origin of the bean correspond with malarial areas, with some studies suggesting that the bean offered protection from malaria by causing haemolysis, or rupturing of red blood cells, and subsequent oxidative damage, which malarial protozoa are sensitive to.

CROPS

BANANAS

Photo: Alliance for a Green Revolution in Africa (AGRA)

Photo: Alliance for a Green Revolution in Africa (AGRA)

BANANAS

SPECIES INFORMATION

Botanical name: *Musa* species (*M. acuminata, M. balbisiana and M. acuminata x M. balbisiana*)
Family: Musaceae
Common name: banana

INTRODUCTION

It may be a radioactive, hermaphroditic herb with ancient roots, but that hasn't stopped the banana from becoming one of the world's most popular fruits, and Africans are among its biggest fans.

This rather curious plant—which is naturally slightly radioactive because of the potassium content—is part of the Musa genus, which originated in Southeast Asia and the South Pacific around 7 000-10 000 years ago. The wild progenitor was probably *M. acuminata*, native to the Malay Peninsula and adjacent regions.

Relatives in the Musa family include plantain, which is longer with thicker skin and more starch, and ensete, which is grown in southern Ethiopia for its starchy stalk.

Members of Musa were introduced to Africa prehistorically, some via Madagascar by immigrants from Sumatra, and others probably from India. These became established as important crops across Africa before the arrival of Europeans.

In Africa the per capita annual consumption of banana and plantain is 21kg, and four African countries have the world's highest per capita consumption. Uganda, which tops the list at a whopping 191kg per capita per annum, relies heavily on a cooking banana called the East Africa Highland Banana (EAHB), also known as matoke.

There are more than 100 varieties of matoke in Uganda, and this starchy, non-sweet staple feeds approximately 80 million people inside and outside its borders. For the millions who depend on matoke, dessert banana, plantain and ensete, a huge potential crisis is looming in the form of a microscopic pathogen called *Fusarium oxysporum* fsp *cubense*, or *Fusarium* wilt.

This fungal disease, which attacks the plant's vascular system, causing it to wilt, is fatal and there is no known cure. Currently cutting a swathe through the world's banana plantations, a deadly tropical strain of *Fusarium* wilt has been found in Mozambique in recent years, and it's only a matter of time before it spreads across the continent.

DESCRIPTION

The banana is not what it seems. It looks like a tree, but is actually the world's largest herbaceous flowering plant. Its "trunk" is a false stem (pseudostem) made up of tightly packed sheaths, which are part of the stalks of the leaves; these grow out of a structure called a corm. And its fruit is botanically a berry.

The strangeness of this giant herb, which ranges in height from three to seven metres and can have leaves that are nearly three metres long, doesn't stop there. It's also a hermaphrodite. Unique among crops, the banana flower has three zones; male at the bottom, intersex in the middle (hermaphrodite) and female at the top.

When the plant reaches maturity the corm stops producing leaves and sends a flower spike, known as the "banana heart", up through the pseudostem. The fruits develop from the banana heart in a large hanging cluster known as a bunch or "banana stem". And then the plant dies, but only after sending out new plants, called suckers, to carry on the cycle.

USES

Different varieties of banana are used for making beer, eating as a sweet snack or cooking as a starch. Matoke smells like banana but has no sugar. It is used to make porridge or cut up in chunks and served in a stew or with a sauce. Plantain is also starchy and used in cooking. In the highlands of Ethiopia the soft, starchy tissues of the trunk and other parts of ensete are used to make bread, porridge or cooked as a vegetable.

NUTRITION

Bananas are rich in vitamin C, B6, potassium, magnesium, copper and dietary fibre. They are also made up of 22% carbohydrate.

AGRONOMIC REQUIREMENTS

Banana and plantain grow best in humid tropical and sub-tropical climates with moist, well-drained soils. Plants produce fruit year-round and can be productive for up to 100 years. They can be inter-cropped with other crops.

All bananas are grown vegetatively from suckers. Usually about four develop from growing points on the corm; one can be left on the mother plant and the rest removed and planted elsewhere. A banana plant takes about nine months to reach maturity and produce a bunch of bananas, and then it dies.

PROBLEMS AND BREEDING

Pests and diseases:

- Banana is plagued by numerous diseases. Black Sigatoka, a fungal disease that causes dark spots and die-back of the leaves is a huge problem.
- Banana Xanthomonas Wilt (BXW) destroys the fruit, while *Fusarium* wilt destroys the plant's vascular system and causes it to rot from the inside. There are numerous viruses that affect banana.
- Major pests affecting banana and plantain are the burrowing nematode and the banana weevil, that attack the plant's roots and underground corm, respectively. Nematodes and weevils eat the roots and trunks so the banana trees fall down, and monkeys and fruit bats eat the fruit.

Drought, malnourishment and premature ripening are physiological problems affecting the crop.

Breeding:

The banana we eat is a sterile mutant that has been propagated vegetatively from one plant of the Cavendish variety. The wild species would have been diploid with 2N chromosomes, i.e., containing two complete sets of chromosomes, one from each parent. Banana fruit of these diploid progeny would have been full of hard seeds like ball bearings, and not very productive.

Sometimes in nature a 4N variety occurs. These are more edible than 2N bananas but still have hard seeds. In a very rare event, a 2N banana crosses naturally with a 4N one, producing a 3N variety, that tastes better than both and has no seeds. It's sterile because three sets of chromosomes cannot divide evenly in pollen or in the ovary tissue.

The triploid banana is the one most commonly eaten all over the world, and the one that breeders usually produce if they want to improve a variety.

To produce 4N bananas a chemical called colchicsine is used, which is derived from flame lilies (*Gloriosa superba*). It interferes with the normal reproduction of cells if it is applied to the seeds, so that they remain at a full complement of chromosomes instead of splitting into a half complement (2N should split into 1N, and 4N to 2N. But after colchicine treatment 2N remains at 2N, and 4N at 4N).

Bizarrely, colchicine is also a drug taken by humans to minimize the effects of gout.

To breed bananas it's thus necessary to have a population of 2Ns to make seeds to grow successive generations, and in parallel you must also propagate 4N generations. Then with every generation the breeder makes crosses between 4Ns and 2Ns to make better 3N plants, which are then planted out. If a good candidate emerges, it's then propagated vegetatively. Triploids can be AAA, AAB or ABB genomes, with mixed contribution from *M. acuminata* or *M. balbisiana*.

Pollination is also tricky because the banana flower has three zones: male at the bottom, intersex in the middle (hermaphrodite) and female at the top.

The only ACCI work done on banana was by Dr Alex Barekye (graduated 2009). Barekye, who's now director of research at a station in south-western Uganda, focused on breeding for resistance to Black Sigatoka for his PhD project. In matoke this crippling fungal disease can wipe out up to 50% of a crop, by attacking the leaves, producing dark spots that cause malnourishment and weak bunches that aren't properly formed and can ripen prematurely.

Barekye says resistance to Black Sigatoka was identified in wild banana plants and his task was to extract the resistant genes and introduce them into the cooking banana. Because banana is a slow-growing crop, taking at least 12 months to grow from seed to the next generation, he took four years to complete the field work of his PhD instead of three. When he returned home he released a variety with resistance to Black Sigatoka and increased yields, and four more varieties are being evaluated.

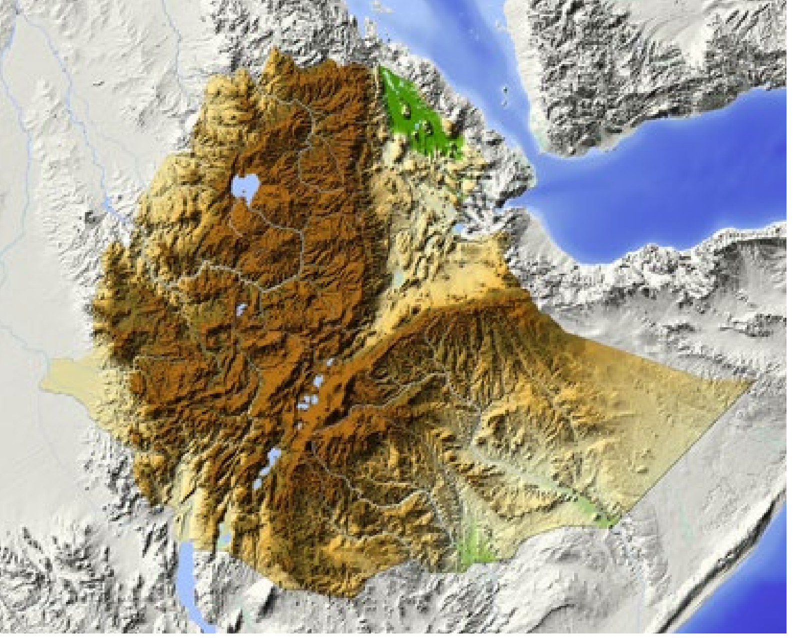
Photo: Alliance for a Green Revolution in Africa (AGRA)

Tissue Culture Bananas—Kirinyaga, Kenya.

COUNTRIES

THE ACCI HAS WORKED IN MOZAMBIQUE, TANZANIA, ZAMBIA, ZIMBABWE, UGANDA, NIGERIA, KENYA, MALAWI, SOUTH AFRICA, BURKINA FASO, ETHIOPIA, RWANDA, CÔTE D'IVOIRE, LIBERIA, NIGER, SOUTH SUDAN, MALI, NAMIBIA AND BENIN

All maps by Michael Schmeling/123RF



ETHIOPIA

In brief: The geography of Ethiopia is dominated by the central highlands in the west, that are 2000m and higher. This region is cool and wet, receiving up to 2000 mm of rain per annum. In contrast the lowlands to the east are warm and arid. Overall the country has at least five agroecologies, including dry-hot, dry-warm, sub-moist warm, cold and alpine. The soil is calcareous with high P fixation, acidity, and high leaching potential.

Ethiopia's population of 100 million, 95% of whom are engaged in agricultural activities—and wide range of agroecologies, mean it has a great need for plant breeders.

A critical concept is that most of the Ethiopian population live on the central plateau, where the soils are deep, and rainfall is reliable. A relatively small population live in the north and east in the lowlands, where rainfall is sparse and erratic. These regions are classified as semi-arid or arid. These are the regions that have made it into media and global consciousness as representing Ethiopia. However, only about 5% of the population of Ethiopia (100 million) live in this region and regularly face droughts and starvation. In the rest of the country the challenge is to deal with heavy rainfall, and leached, acidic soils in order to feed 95% of the population.

The highlands get up to 3000 mm of rain per annum, which is the reason why the country is the headlands of the Blue Nile. This also means, however, that the soil is very leached of nutrients and is becoming increasingly acidic, which impacts on the productivity of their main food crops, tef, maize and sorghum.

Low-nutrient soils mean farmers must fertilise them, and most use urea, the cheapest form of nitrogen. The downside is that it evaporates in the sun and acidifies the soil. In acid soils that are not buffered, just a small amount of acid can tip the balance into acidity. This causes aluminium and manganese to dissolve and become toxic to plants, and it also causes deficiency because other elements, such as molybdenum don't get taken up.

In addition, Ethiopian soil is very deficient in all micro and macronutrients, such as calcium, potassium and phosphorus, which have been stripped out by rain over millions of years. Soil acidity, altitude and rainfall play roles in the large variation found in crop varieties, and a lot of work done by ACCI students involves breeding for crops for each of the different agroecologies, adapting varieties to those specific conditions. Work is also done in the low altitude region, breeding for earliness and drought tolerance, in particular.

There are more than 35 official crops in Ethiopia, including some not grown anywhere else, like tef, a small, fine grass that is only eaten in Ethiopia, Eritrea and Somalia, in a pancake called injera. Tef is one of the staples along with wheat, barley, maize, sorghum and millet.

A complicating factor is that all land is owned by the state. "It's the tragedy of the commons – everybody overgrazes and overuses the land," says Laing. "There's no incentive to improve the land, and there's a huge issue with uncontrolled livestock numbers. You take what you can, otherwise your neighbour will take it, anyway."

Because the ACCI only began training students from Ethiopia in 2008, no new crop varieties have been released yet, although several are in the pipeline.

Graduates: Abush Tesfaye Abebe (soybean), Amele Assefa (sorghum), Rebeka Teshome (sorghum), Wenda Mengesha (maize), Demmissew Ababulgu (maize), Asnakech Beyene (faba bean), Netsanet Hei (wheat), Fekadu Balcha (sweet potato), Ermias Desta (tef), Hirut Betaw (potato), Hirut Getinet (wheat), Mizan Tesfay (tef), Mizan Abraha (tef), Tewodros Mulualem (yams)

Students: Mulu Fetahi Nigus (wheat), Yared Semahegn Belete (Niger oilseed), Solomon Assefa (sorghum), Girma Digafe (sorghum, non-AGRA), Kidane Tumsa (common bean, non-AGRA)

KENYA

In brief: Kenya has seven different agroecological zones, ranging from humid (1100-2700 mm) to very arid (150-350mm), with the latter covering 46% of the country. The north and east of the country is dry and hot, with less than 500mm rainfall per annum, while the west is cool and wet, other than the Rift valley, which is again hot and dry. Soil is calcareous with aluminium toxicity and high P fixation (where phosphate binds to acidic clays and is unavailable to plants).

A wide array of agroecologies make Kenya a place that really needs the help of plant breeders, and the ACCI has been able to oblige, training 19 graduates from this country.

The coastal stretch gets rain but it's sandy, and the soils have been leached of mineral nutrition. Plant varieties have to be very well adapted to grow here and they don't do well elsewhere. Some dryland rice is grown but wind is a problem because it causes the plants to fall down, and drought is also a problem.

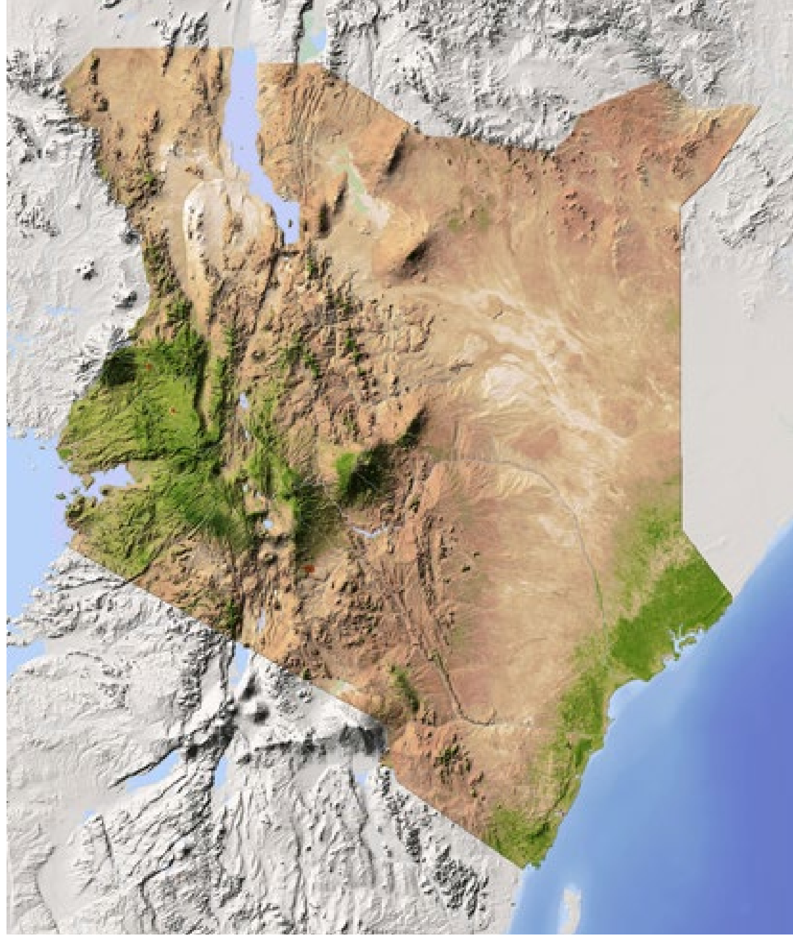
Cassava and sweet potato grow well in sandy soils and are widely planted here, as are cashews—although this crop has been badly affected by powdery mildew—and cowpea, especially some varieties adapted to grow in sandy soils.

Inland a huge area of Kenya is desert or semi-desert. Crops can't be grown here and this region is only good for a nomadic lifestyle, chasing grass with cattle, camels, sheep and goats.

Up on the escarpment where Nairobi is situated, agricultural potential is high and maize, sorghum, potatoes and sweet potatoes are gown here. In the high-altitude areas such as Kakamega, rain is plentiful and the volcanic soils help to drive up yields.

The other side of this escarpment is the Rift Valley that drops down to very dry land where sorghum and millet are grown. This area is a world hotspot for *Striga*, which sorghum farmers battle with, often losing 90% of their crop to this weed.

Kenya has many universities and is well endowed with infrastructure for agricultural research. It has research stations in all the important agroecologies and they cover both field and horticultural crops, including tea, coffee, wheat and vegetables.



It's also a major centre for international agricultural research agencies and has the best facilities outside South Africa.

ACCI graduates have made a huge impact on Kenyan agriculture, with improvements made to six food security crops and a total of 31 new varieties so far.

Graduates: Clement Karari (sorghum), Phillip Kwena (maize), Phillip Leley (maize), Theresia Munga (cassava), Chrispus Oduori (finger millet), David Ngung'u (sorghum), John Kimani (rice), Pascal Ojwang' (beans), Margaret Makelo (pigeonpea), Vincent Woyengo (cassava), Susan Wanderi (soybean), Lilian Gichuru (maize), Benjamin Kivuva (sweet potato), Beatrice Ng'ayu-Wanjau (bean), Mwimali Murenga (maize), Jane Muthoni (potato), Regina Tende (maize), Ruth Musila (rice), Joseph Kamau (cassava), Eric Okuku Manyasa (finger millet, non-AGRA)

Varieties released

Joseph Kamau: cassava, 12 varieties
Philip Leley: maize, 5 varieties
Chrispus Oduori: finger millet, 4 varieties
Joseph Kamau: sweet potato, 4 varieties
John Kimani: rice, 4 varieties
Philip Kwena: maize, 1 variety
Clement Karari: sorghum, 1 variety

UGANDA

In brief: Uganda can also be divided into seven distinct agroecologies. In the south there are two rainy seasons each year, allowing for two crops annually, with average annual rainfall around Lake Victoria of 1200-1500 mm per annum. Moving north, these two rainy seasons gradually merge into one with annual rainfall ranging between 900-1 300 mm. Temperatures throughout the year don't vary much, with maxima ranging from 25-30°C. Soil fertility is affected by aluminium toxicity, high leaching and low nutrient content.

Uganda is interesting because of its extreme variation in agroecologies. There's a sharp contrast between the area around Kampala, which is elevated with high rainfall and nutritious soil, and the dry, semi-desert of the north-east that borders Kenya, while the low-altitude, hot, fairly dry Nile Valley in between is distinct from both.

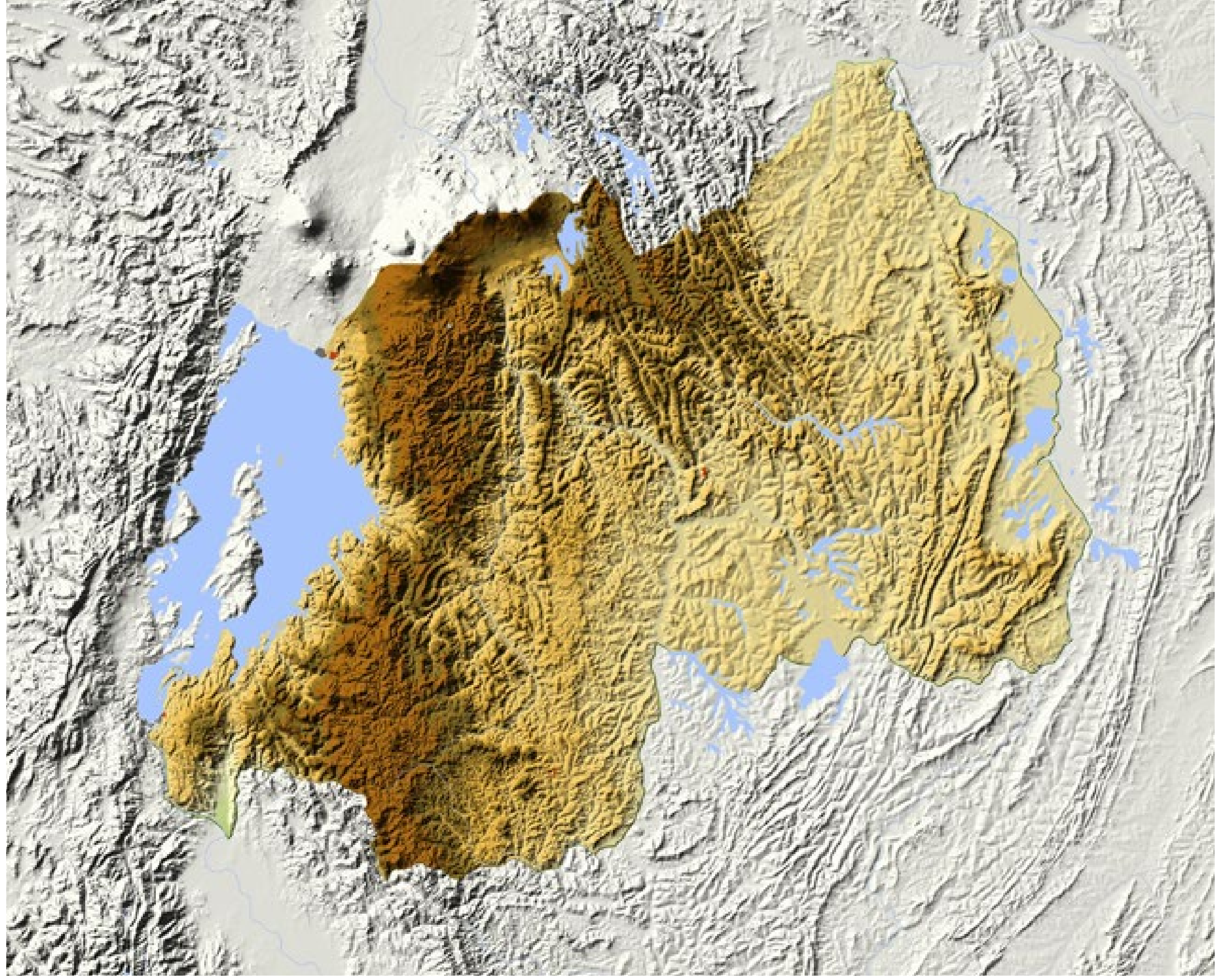
Uganda has been one of the ACCI's best sources of students, with 11 graduates who have tackled nine different crops (see below). Several of them have worked at a research station for semi-arid agriculture in the east called Serere, about an eight-hour drive from Kampala. The station is isolated and poorly resourced—it's not uncommon for students to have to drive more than 20km to get internet access.

The country's staple starch is banana, especially a variety called matoke. Maize is the next-most important staple, followed by cassava and sweet potato. In the dry areas sorghum, pearl millet and cowpeas are widely grown.

Graduates: Grace Abalo (maize), Stanley Nkalubo (beans), Martin Orawu (cowpea), Jimmy Lamo (rice), Frank Kagoda (maize), Robert John Olupot (sorghum), Lwanga Charles Kasozi (maize), Godfrey Sserewu (sweet potato), Frank Kagoda (maize), Robooni Tumuhimbise (cassava), Lawrence Owere (finger millet), Geofrey Lubbade (pearl millet), Clare Mukankusi (bean), Alex Barekye (banana), Mary Asio (rice)

Students: Prossy Namugga (sweet potato, potato), Ronald Kakeeto (groundnut)

Varieties released:
David Okello Kalule: groundnut, 10 varieties
Stanley Nkalubo: beans, 9 varieties
Jimmy Lammo: rice, 9 varieties
Martin Orawu: cowpea, 3 varieties
Grace Abalo: maize, 2 varieties
Alex Barekye: bananas, 1 variety



RWANDA

In brief: Rwanda's high altitude means that it has a temperate climate despite its close proximity to the equator. There are two rainy seasons per annum, with an average annual rainfall of 950 mm, and this is heavier in the west and northwest. Soil fertility is affected by aluminium toxicity and high P fixation but the soils are relatively fertile due to their geologically-recent volcanic origin.

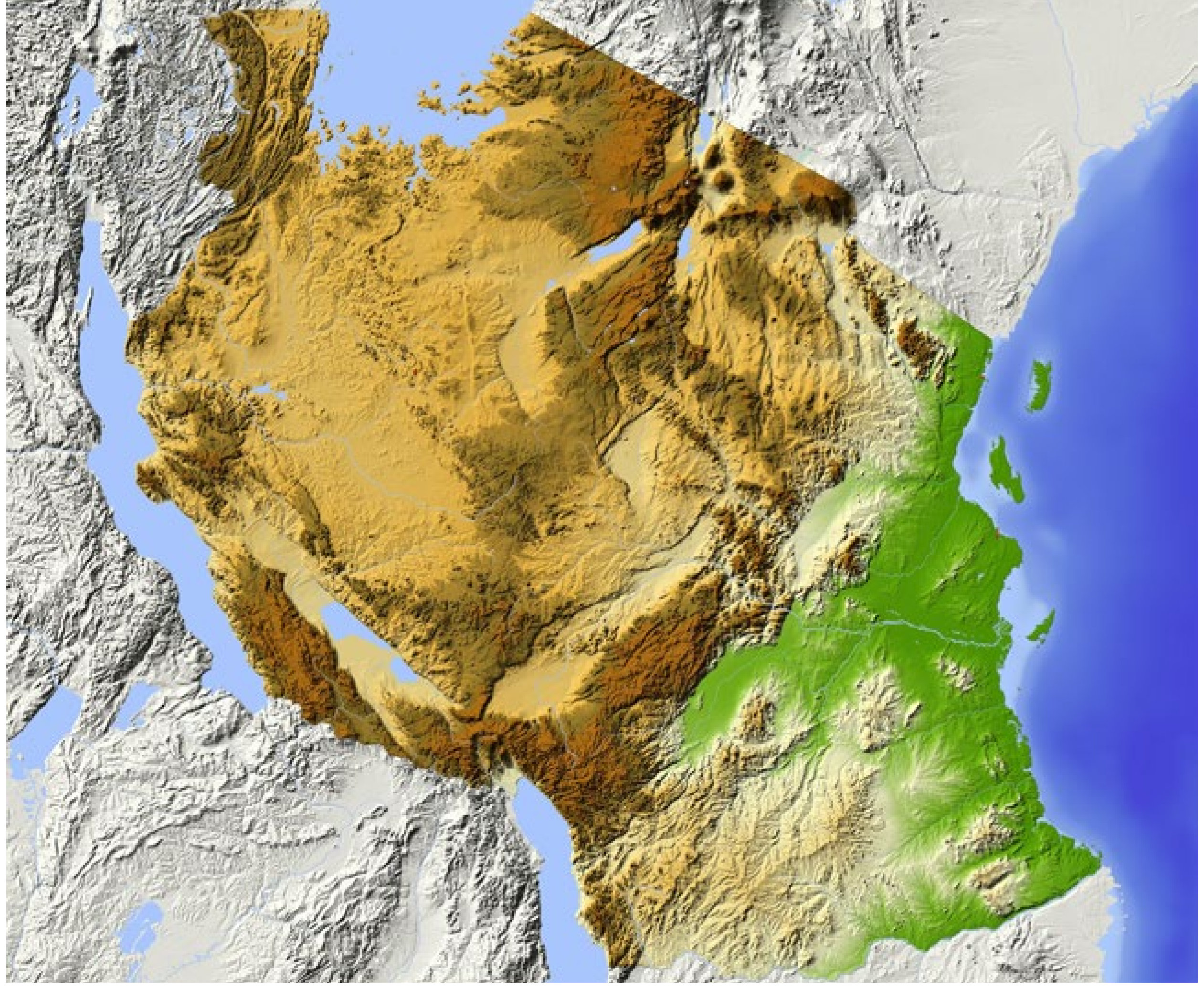
The ACCI has only worked in Rwanda for the last six years. Before that civil war made it too dangerous. The majority of the population—more than 90%—are involved in small-scale and commercial agriculture. Population density in this small, mountainous country is high, requiring intensive cultivation of available land, and it's not unusual to see crops growing on steep mountainsides. "Its incredible to see plots being cultivated on forty-five-degree slopes, one kilometre up a mountainside", says Laing.

The land is highly productive because of the rich, volcanic soils and a wide range of crops are grown, including maize, sorghum, rice, wheat, beans, soybean, Irish potato, sweet potato, cassava and banana.

Graduates: Jean Baptiste (potatoes), Placide Rukundo (sweet potatoes); Simon Martin Mvuyekure (rice), Athanase Nduwumuremyi (cassava), Alphonse Nyombayire (maize) and Urinzwenimana Clement (common bean)

Students: Damien Shumbusha (sweet potato)

Varieties released:
Damien Shumbusha (sweet potato, 8 varieties)



TANZANIA

In brief: Tanzania is a very large country with a number of factors affect the climate, including proximity of the ocean and inland lakes, altitude and latitude. Average rainfall ranges from 200-2 000 mm per annum, with agroecological zones including alpine, humid to dry subhumid, dry subhumid to semi-arid, semi-arid and arid.

Ninety percent of the country receives less than 1 000 mm of rain per annum, apart from the highlands and parts of the extreme south and west where 1 400-2 000 mm can be expected. In the central arid areas 200-600 mm falls on average, while in the south there are two rainy seasons. Soils are calcareous with aluminium toxicity, high leaching potential and high P fixation.

The size of Tanzania and the number of agroecologies make it a taxing country to work in. Travelling costs for ACCI staff are unavoidably high because distances are immense and research stations, are far from the main routes. The ACCI can't avoid taking students from isolated stations because they are in agroecologies where the research is needed. The standard of English is also an issue, being generally poor because schooling is in Swahili until high school.

Another issue is the country's socialist past, which has affected the ease with which new varieties can be released to farmers. ACCI students have done significant work on maize and cassava, but passing their gains on to farmers has been difficult (see page 147).

Graduates: Kiddo Mtunda (cassava), Arnold Mushongi (maize), Sophia Killenga (rice), Tulole Bucheyeki) (maize), Lameck Nyaligwa (maize), Stephan Ngailo (sweet potato), Rose Mongi (common bean, non-AGRA)

Students: William Titus Suvi (rice), John Lobulu Loatha (maize), Filson Mbezi Kagimbo (sweet potato), Emmanuel Mrema (sorghum), Eliud Kongola (groundnut), Seleman R. Kaoneka (pigeonpea, non-AGRA), Happy Daudi (groundnut, non-AGRA).

Varieties released:
Kiddo Mtunda: Cassava, 4 varieties
Arnold Mushongi: Maize, 1 variety

MALAWI

In brief: Malawi is a tiny land-locked country with a lake that covers 20% of it. It is hot in the low-lying areas of the south and temperate in the northern highlands. Most of the country receives between 763-1,143 mm rainfall p.a., although Mulanje, Nkhata Bay and the northern end of Lake Malawi receive up to 1500mm. Almost 90% of rainfall occurs between December to March, with no rain at all between May to October over most of the country. The soil is calcareous with aluminium toxicity and poor drainage.

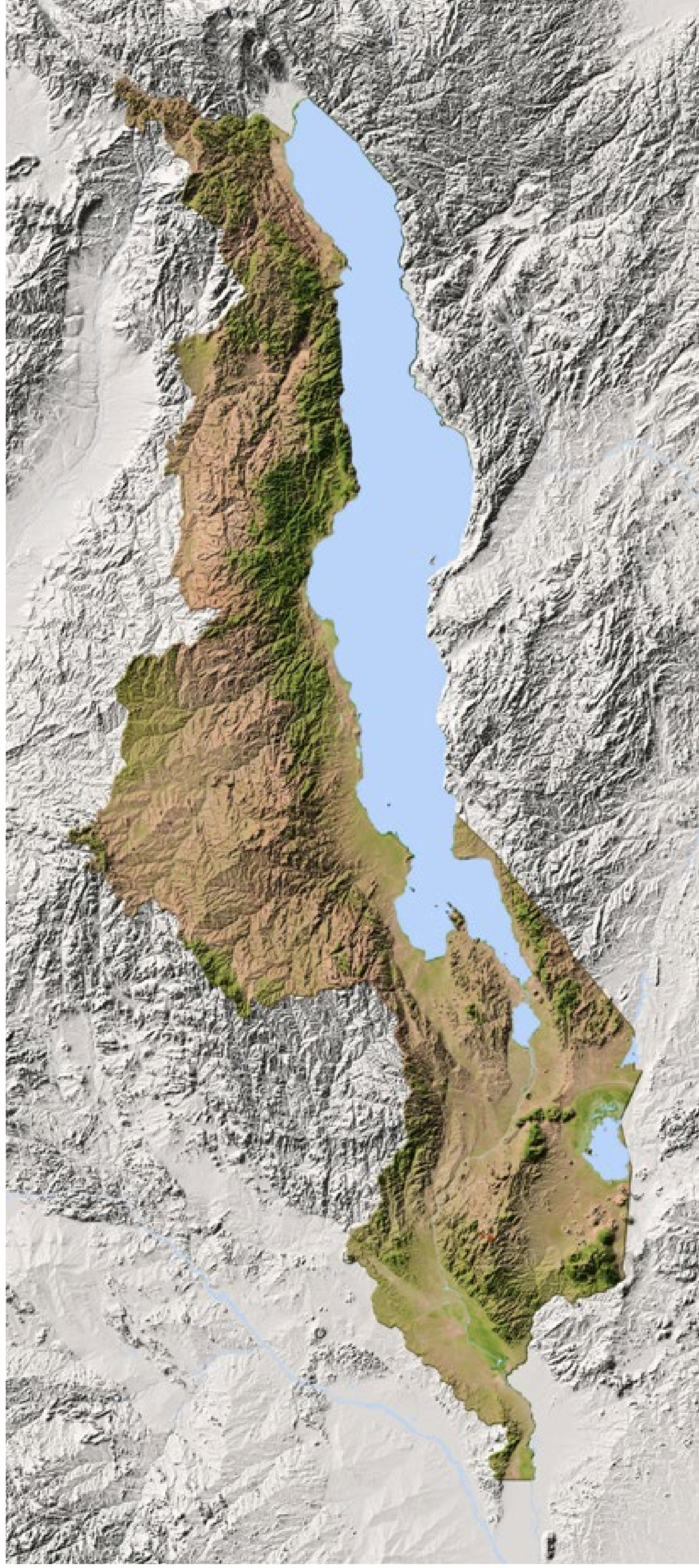
A lot depends on agriculture in Malawi. The labours of mostly small-scale farmers, who work only a third of the land because of mountains and forests, produce one third of GDP and 90% of exports. These farmers also produce 75% of the food consumed, with maize, cassava, sweet potato, rice, sorghum, groundnut and pulses being the staple crops.

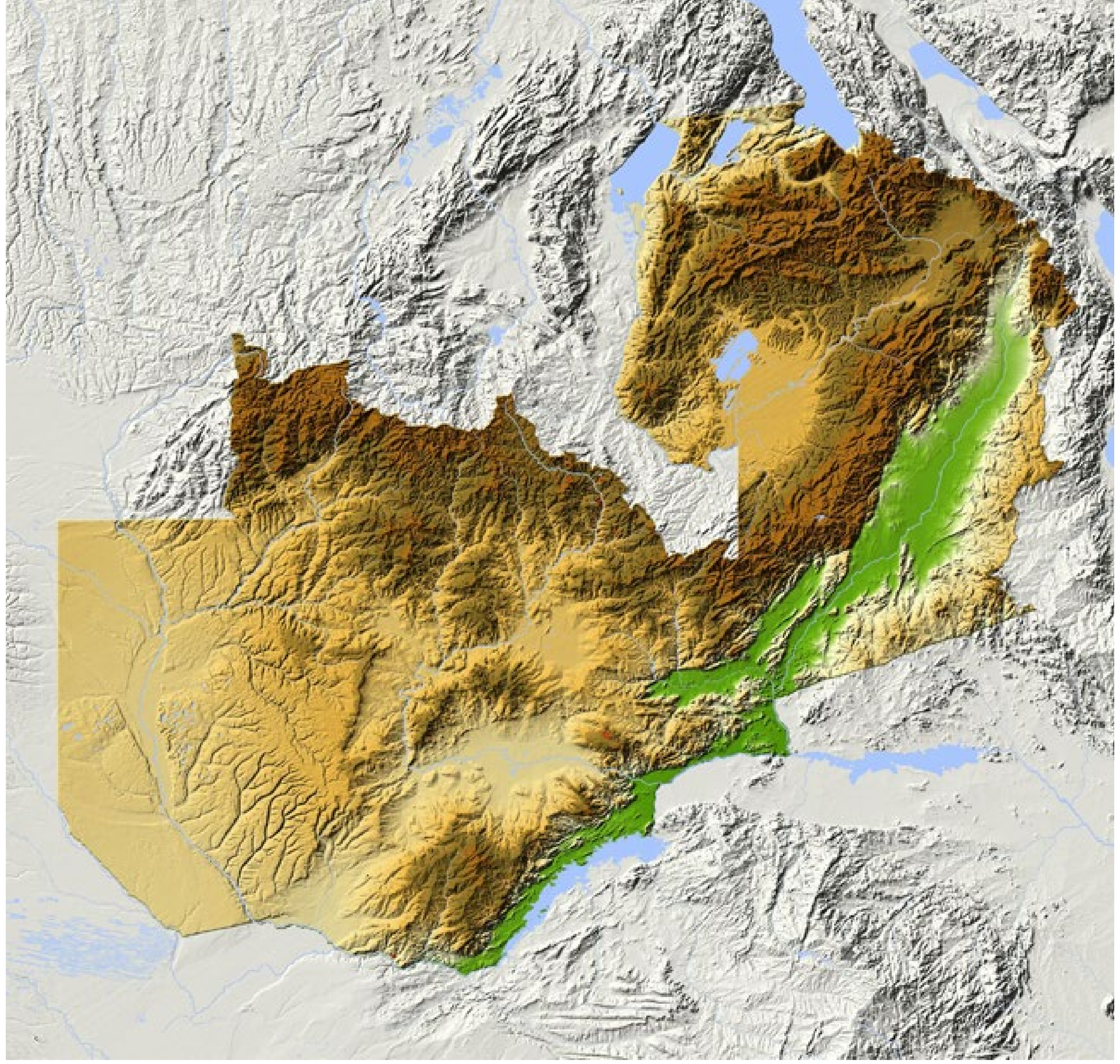
Most farmers battle to produce mixed crops on plots of less than one hectare, with declining soil quality and often unimproved seeds, but government intervention in recent years, providing seeds and fertilizer to farmers, has had a big impact. Whether this is a sustainable intervention is in question, having been based on external aid funds.

Graduates: Geoffrey Kananji (beans), Albert Changaya Banda (pigeonpea), Tenyson Mzengeza (rice), Macpherson Matawele (maize), Justice Chintu (groundnut)

Students: Wilson Nkhata (common bean), Esnat Nirenda Yohane (pigeonpea)

Varieties released:
Geoffrey Kananji: bean, 8 varieties
Geoffrey Kananji: pigeonpea, 8 varieties
Tenyson Mzengeza: rice, 3 varieties





ZAMBIA

In brief: Zambia is largely a massive flat plateau above 1000m, which means that, despite falling in the tropical zone, it's mostly pleasantly warm or even cool, apart from the basins of the Zambezi, Luangwa and Kafue rivers, which can be hot. The average rainfall is about 1000 mm per annum but this varies by region, with the south and southwest receiving around 900mm and up to 1400mm falling in the north and northwest rain. Soil fertility is affected by aluminium toxicity, low nutrient levels, poor drainage and cracking clays.

Zambian agriculture is defined by the seven-month-long dry season when no rain falls, not even drizzle or dew. While commercial farmers next to rivers can irrigate in the dry season, small-scale farmers are limited to growing cassava, madumbi and sweet potato in wetlands during this time.

The remaining five months of the year is an extended rainy season when about 1000 mm falls. Staple crops are maize, sorghum and cassava, and ACCI students have tackled maize, cassava, sweet potato, bean and wheat.

Graduates: Martin Chiona (sweet potato), Patrick Chikoti (cassava), Able Chalwe (cassava), Francisco Miti (maize), Mweshi Mkanga (maize), Batiseba Tembo (wheat), Nathan Phiri (common bean)

Students: Nelia Nkhoma Phiri (cowpea), Chapwa Kasoma (groundnut)

Varieties released
Martin Chiona: sweet potato, 5 varieties
Francisco Miti: maize, 5 varieties
Mweshi Mukanga: rice, 3 varieties

MOZAMBIQUE

In brief: Mozambique is a long, thin country on the east coast of Africa. It has a tropical climate but conditions also vary depending on altitude. Less than 600mm of rain falls per annum in the south and around 1500mm in the north. Most of the country is a low, sandy plain, which rises in the east on the borders with other countries. The soil is calcareous and affected by aluminium toxicity, high leaching and poor drainage.

Mozambique has been a difficult country for the ACCI to succeed in. The centre has struggled to find suitable candidates, people who have a masters degree in agricultural plant science as well as a job, which is necessary so that they can fund the infrastructure for the research. The ACCI funds the actual research. In addition to that, the distance from one end of the country to the other is 2 500 km, which has made the job of supervising students that much more difficult, because transport is a problem.

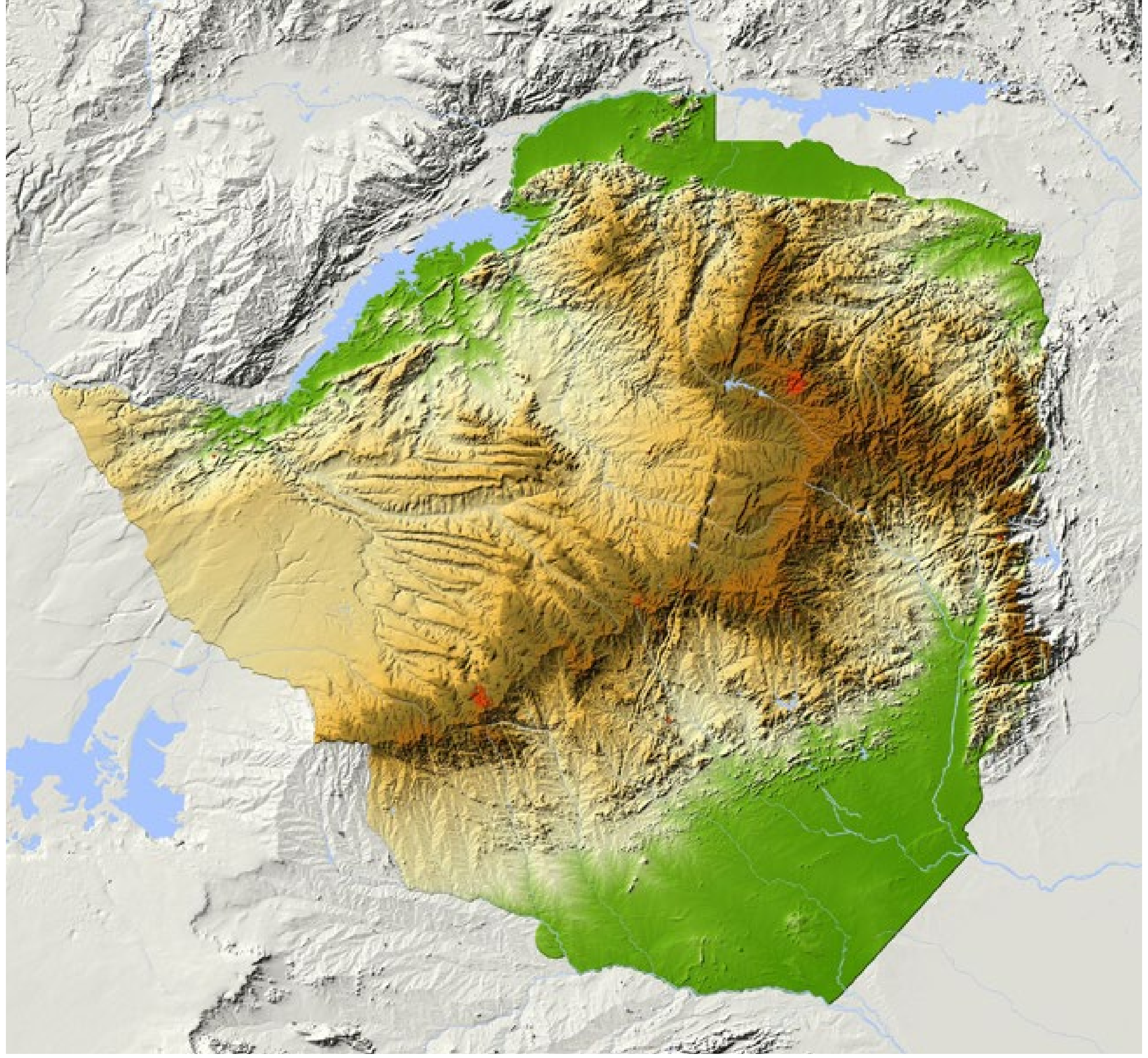
Small-scale agriculture is a mainstay of the economy, employing more than 80% of the workforce and sustaining the majority of households. To survive, people grow many crops, sometimes up to 15 on half a hectare, so that if one fails they have others to eat. Agriculture is also being held back by lack of infrastructure for irrigation and an efficient system that is able to get improved seeds to farmers, and market infrastructure for surplus produce.

Staple crops are maize, cassava, groundnut, cowpea and sorghum. Groundnut is problematic because of the pervasive presence of toxic mycotoxins produced by a fungus, *Aspergillus flavus*, which means that a large percentage of the crop can't be exported.

Graduates: David Mariote (maize), Pedro Fato (maize), Rogerio Chiulele (cowpea), Amade Muitia (groundnut) and Pedro Chauque (maize)

Students: Eduardo Mulima (sorghum)

Varieties released:
Pedro Fato: maize, 6 varieties
Amade Muitia: groundnut, 1 variety



ZIMBABWE

In brief: Zimbabwe is situated in the tropics but higher altitudes causes the highveld and eastern highlands to have a subtropical to temperate climate. The country has three seasons: hot and wet from mid-November to March (summer); cold and dry from April to July and hot and dry from August to mid-November (spring), plus five agroecological zones.

Rain falls more reliably in higher areas, moving from south to north, with 65% of the country receiving less than 650mm per annum, i.e. 65% of the country is semi-arid to arid. The soil is calcareous with aluminium toxicity, high leaching potential, poor drainage and high P fixation

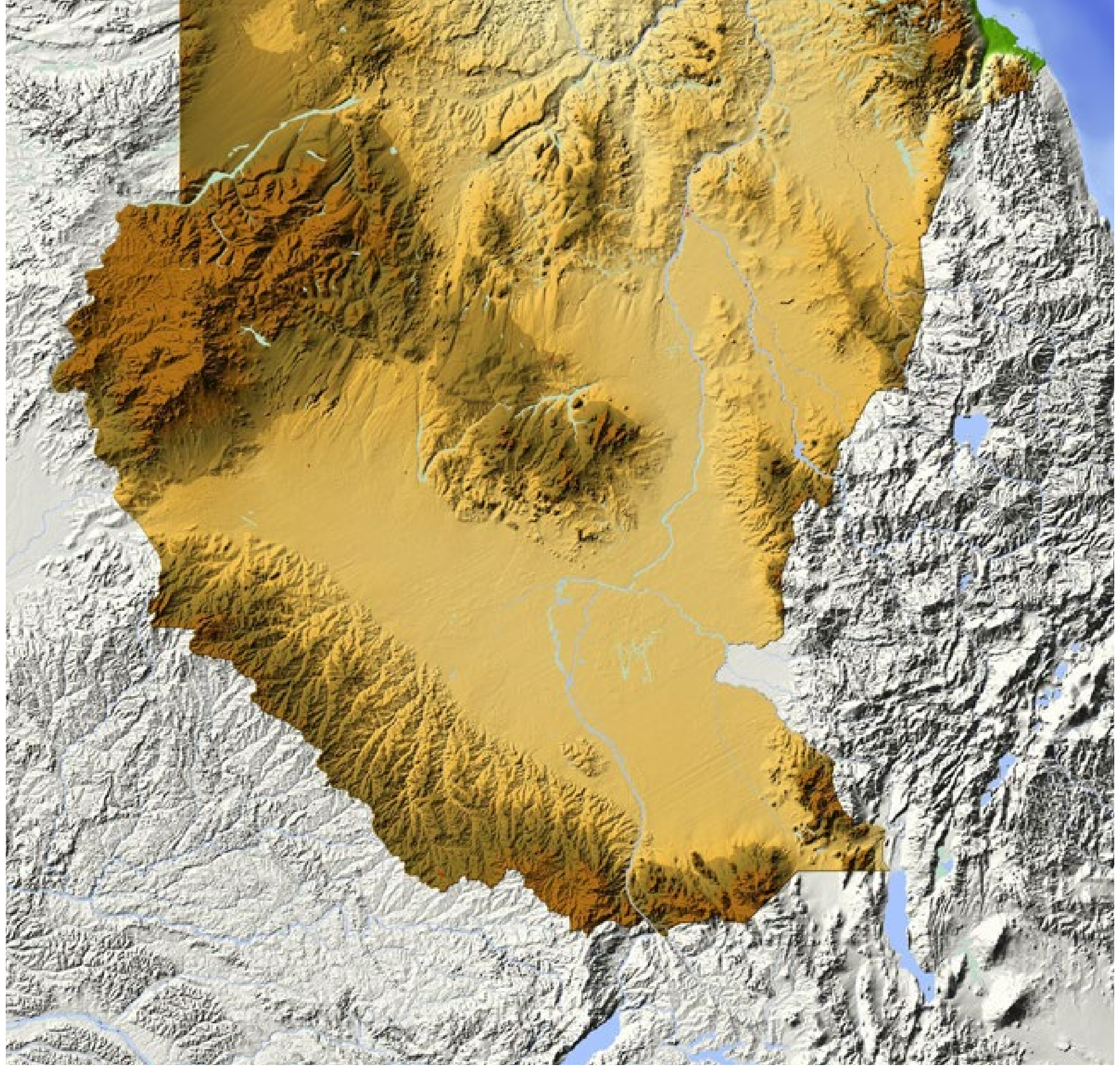
Zimbabwe has high agricultural potential and was once one of the main food producers in SSA, but a combination of politics, land reform problems, hyperinflation and drought have devastated the commercial agriculture sector and had an impact on small scale farmers, who are nevertheless an vital contributor to the country's food security.

The ACCI has strong links with Zimbabwe, with four staff members who come from there. In addition, good schooling and good universities means that Zimbabwean candidates are well trained and are very suitable candidates. However, when a large sum of money was misappropriated from a Rockefeller Foundation (RF) grantee, the RF took the decision to not operate in Zimbabwe after 2005 and the ACCI hasn't take on any more students since then.

Graduates: John Derera (maize), Lewis Machida (maize), Itai Makanda (sorghum), Julia Sibiya (maize), Godfree Ghigeza (sunflower, non-AGRA), Hapson Mushoriwa (soybean, non-AGRA), Learnmore Mwadzingeni (wheat, non-AGRA)

Students: P. Mangena (sorghum, non-AGRA), Isack Mathew (wheat, non-AGRA), Admire Shayanowako (maize, non-AGRA)

Varieties released:
John Derera: maize, 131 maize inbred lines (parent plants); 21 popcorn inbred lines.
Popcorn: 15 new varieties



SOUTH SUDAN

In brief: Firmly in the subhumid tropics-cool zone, apart from a small strip in the north that is semiarid tropics-cool, South Sudan is pleasantly warm all year round. Most of the country receives 500-1000 mm of rain, bar a small swathe on the western side that gets up to 1500 mm. Soils are affected by aluminium toxicity, poor drainage and cracking soils.

South Sudan is a challenging country to work in due to its recent creation, and subsequent civil war. Its peoples are totally dependent upon small scale agriculture so breeding better crop varieties for this country is a priority.

Students: Maurice Mogga (rice)

Varieties released
Maurice Mogga, 4 varieties of rice

SOUTH AFRICA

In brief: South Africa is highly seasonal and mostly arid to semi-arid, with a mean annual rainfall of approximately 450 mm. There is, however, wide regional variation, although only 28% of the country, mostly on the eastern side, receives more than 600 mm (72% of the country is desert to semi-arid).

The bulk of the country is found on a high, flat plateau over 1000m high. The soils are calcareous, mostly highly acidic with aluminium toxicity, cracking clays, low P and micronutrient levels, high P fixation and high leaching potential.

The ACCI has only had two AGRA graduates from South Africa (see box). Sharmane Naidoo (2010) was a government biotechnologist before joining the programme in 2004, and Alina Mofokeng (2016) was working on sorghum for a government agency before she began her PhD.

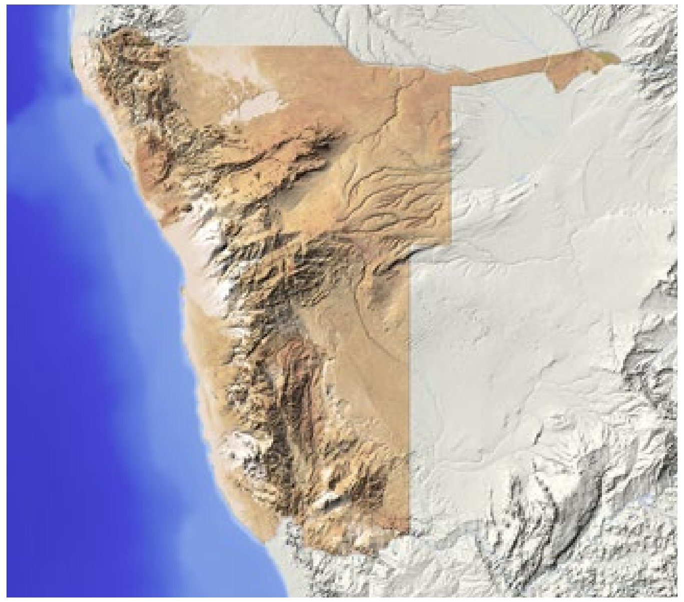
Apart from her research project work, Naidoo also learnt how to use near-infrared spectroscopy (NIRS), a valuable technique for plant breeding and forestry because it makes possible quick, cheap measurement of plant traits, including vitamins, proteins, amino acids and minerals.

After graduation she did post-doctoral work developing models in sweet potatoes for measuring different properties including protein content and beta-carotene. Naidoo also helped develop a sorghum model for nutrient content, and started working on a maize model. She subsequently joined SAPPI, a South African pulp and paper company, where she is running their NIRS studies on timber quality measurements.

Mofokeng's PhD involved a genetic analysis of South African sorghum for improved yield and protein content and composition. Using Naidoo's model, Muedi was able to determine the protein content of her sorghum, and to select for increased levels.

Graduates: Sharmane Naidoo (maize), Alina Muedi (sorghum); Kirthee Pillay (maize, non-AGRA), Tammy-Lyn Swain (Eucalyptus nitens, non-AGRA), Tertia Elizabeth Erasmus (sunflower, non-AGRA), Sandiswa Figlan (wheat, non-AGRA), Jacob Mashilo (cucurbits, non-AGRA)

Students: T Magagane (wheat, non-AGRA), Zamalotshwa Thungo (wheat, non-AGRA), Pamella Ntshakaza (wheat, non-AGRA), Sonia Ines Messo Naidoo (sweet potato, non-AGRA), Marylyn Christian (wheat, non-AGRA)



NAMIBIA

In brief: Namibia is the driest country in SSA, with mean annual rainfall of approximately 270mm. This mostly falls between November and March and varies greatly, with less than 20 mm in the west and more than 700mm in the eastern end of the Caprivi Strip. Soils are mostly sandy and deficient in most macro and some micronutrients. Only about 1% of the land surface of the country is considered to be suitable for crop production.

Students: Lydia Ndinelao Horn (cowpea, non-AGRA)

South Africa

South Africa was chosen to host the ACCI because of its fine universities, but only two of the 99 AGRA graduates have come from there. The reasons for this are complex.

Funders didn't want to spend money on "wealthy" South Africa, but they agreed to sponsor one scholarship per cohort for a local student. However, the ACCI has struggled to fill those places.

"The ACCI bursary is very handsome, but we couldn't attract South Africans. It's a big challenge here, finding people who want to work in agriculture and plant breeding," says Laing, describing this as "really bad for the food security of the country in the long term".

De Milliano believes the profession's lack of popularity "has something to do with the culture of South Africa. You're a miner, banker or a writer. A farmer is an inferior position. So why spend your time on that if you have academic strengths?"

Two applicants who were awarded scholarships walked away from them after landing jobs before undertaking their PhD studies. "The immediate money was more attractive," says Laing.

Even finding local plant breeders to teach in the ACCI programme has been difficult, and the ACCI centre has only had one South African plant breeder on the lecturing staff. Most have come from Zimbabwe, Kenya, Ethiopia or the Netherlands.

Sharmane Naidoo, one of the two South African graduates, said the attitude of employers, who were reluctant to keep a position open for staff members while they worked, were part of the problem. "People don't understand the value of four years of research," she said. "I had to resign from the job I had to take up the ACCI scholarship, but other Africans left their jobs for four years and they was still waiting for them when they went back home."

WEST AFRICA

In the early years the ACCI trained a few students from West Africa who were funded by RF and then AGRA. This ceased in 2007 when the West African Centre for Crop Improvement was set up in Ghana, as a sister centre to train west Africans. However, since then there has also been a steady stream of non-AGRA-funded students from West African and other African countries who have requested to join the programme.

MALI

In brief: More than half of Mali is desert, the northern half, receiving less than 250 mm of rain per annum, and warm and dry all year round. Heading south, it becomes progressively wetter, with the most southern zone receiving up to 1500 mm per annum. A number of large rivers, including the Niger, criss-cross the south of Mali, and this source of water allows for the production of rice, a surprising staple food for a desert country. The wetter south has soil that is affected by poor drainage, high leaching potential and cracking clays.

Graduates: Andrew Efisue (rice)

Varieties released:
Andrew Efisue: rice, 3 varieties

NIGER

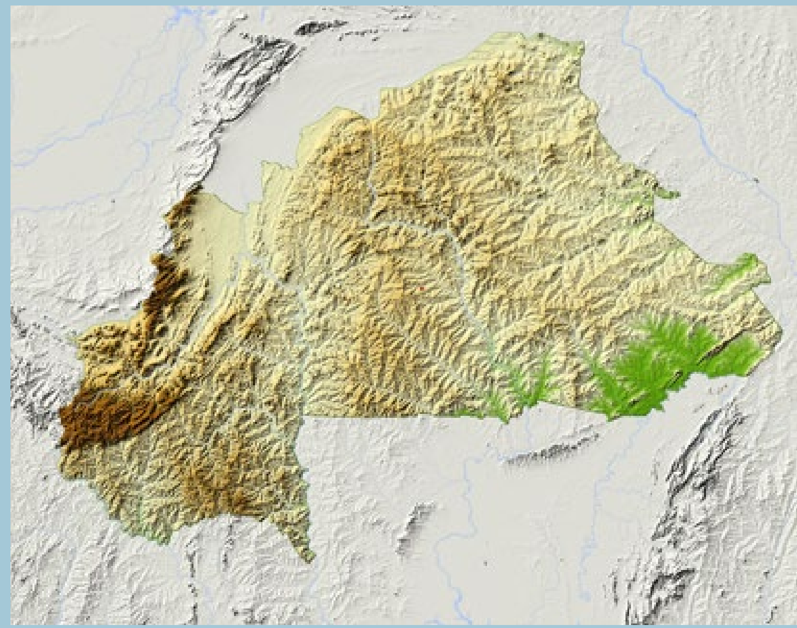
In brief: Situated in one of the sunniest regions in the world, Niger is dry and hot with aridity increasing from south to north, and almost half of the country receiving less than 100mm of rain. Again the Niger River meanders across the south of Niger, and this source of water allows for the production of rice, a surprising staple food for a desert country. The soil has high leaching potential.

Graduates: Mounirou El-Hassimi Sow (non-AGRA); African rice

NIGERIA

In brief: Nigeria is hot and most of the country gets good rains of up to 1000mm, with the south receiving up to 2500mm. It has two seasons, rainy and dry, that vary slightly from north to south, with the north of the country being notably drier. Their soils are affected by aluminium toxicity, cracking clays and high leaching, and are calcareous.

Graduates: Sagir Mohammed (Bambara groundnut, non-AGRA); Andrew Efisue (rice)



BURKINA FASO

In brief: Burkina Faso is warm and dry, with an annual rainfall below 1 000mm and aridity increasing from south to north. It has a rainy season and a dry season of similar length, but no cool season. The Volta River and its tributaries start in Burkina Faso, and along these rivers, rice can be cultivated. Soil is affected by poor drainage, high leaching potential and cracking clays.

Graduates: Jean-Baptiste de La Salle Tinegre (cowpea); Honoré Kam (rice, non-AGRA); Palé Siébou (sorghum, non-AGRA)

Varieties released:
Jean-Baptiste de La Salle Tinegre: rice, 4 varieties

BENIN

In brief: A hot, humid country, Benin has two rainy seasons and two dry seasons, with less than 1000mm of rain per annum. It is a very flat country, averaging 200m in elevation across the entire country. Soils are alluvial and suffer from poor drainage.

Graduates: Bernice Bancole (2018; sorghum, rice; non-AGRA)

CÔTE D'IVOIRE

In brief: Although Côte d'Ivoire is generally warm and humid, its climate is affected by continental and maritime air masses, with seasons more distinguishable by rainfall and wind direction than by temperature. Two rainy seasons, from May to mid-July and October to November, produce a combined annual rainfall of 1100-1600mm. Soils have aluminium toxicity and poor drainage.

Graduates: Kouadio Nasser Yao (rice; non-AGRA)

LIBERIA

In brief: Liberia has a humid, tropical climate with average temperatures throughout the year of 26°C-28°C. Rainfall ranges from 1500-2500mm in the south to 3500-4600mm in the north. Soils are affected by aluminium toxicity.

Graduates: Quaqua Mulbah (rice, non-AGRA)

Socialism, capitalism and seeds

The process of getting improved varieties to farmers in Africa is complicated. On the one hand, while socialism may have waned as an ideology, its influence lingers on in many countries, especially when it comes to seeds. On the other, small independent seed companies struggle to survive and are frequently swallowed up by global giants who are based overseas—and therefore out of touch with African agriculture—and driven by the bottom line rather than the needs of food security.

"Ex-socialist countries—like Tanzania, Ethiopia and Zambia—believe they need to control the supply of seed to farmers, and they get involved in the distribution process," says Laing. "For example, in Tanzania, Arnold Mushongi has bred wonderful maize hybrids that some indigenous seed companies want to sell to farmers, because they will double their yields. However, because of government bureaucracy, this hasn't happened."

The problem, he explained, is that the government should be licensing the inbred lines to companies. To make a hybrid the breeder must carefully grow pure inbred lines of the parent lines A and B, and then cross them to create an AB hybrid, which will give bigger yields. What happens instead is that the government tries to produce the inbred lines themselves, the A and B parent lines, and make the inbred parent seed available to farmers to grow the AB hybrids. But, because they don't have the capacity to do it properly, the parental lines are not pure and the end result is not the proper hybrid. If either the A or B lines are contaminated by external pollen from another variety, then the hybrid will not be a pure hybrid and will not perform to expectations.

"Farmers then get angry because the hybrids that they paid for are not the same anymore. And the seed companies give up if they can't control the inbred lines themselves. They can't trust inbred purity on other people, it's just too big a risk for their reputation, which is based on delivering pure hybrids," says Laing, who believes government agencies can't produce seeds effectively because there's no reward for risk taking."Plant breeding is all about risk management, guessing what farmers want 10 years before they want it, and guessing how much seed to produce because unsold seed does not keep, it dies".

"AGRA ran into this problem. The value chain goes from breeding to foundation seed (the inbred A and Bs parents) to hybrid product to agro dealers to farmers. If there's any link missing, the seed doesn't get to farmers. And downstream the agricultural output has to go to commercial markets. That requires policies that support business and capitalism. Socialist governments make that process more difficult, they see the profit element as somehow wrong."

AGRA has invested heavily in setting up seed companies so that improved varieties can be produced and distributed to farmers, but it takes a lot of capital and a long timescale before they are able to operate independently. Small companies always have capital problems, and a lot of money is tied up in equipment and resources over a long time. Acquisitions and mergers are common in the seed world because people start companies and eventually decide to cash in.

Globally, this phenomenon of big seed companies buying up little ones is common, and in the US, which used to have hundreds of seed companies that sold maize, there are now only three big companies—Monsanto, du Pont/Pioneer and Syngenta.

CROP CONSTRAINTS

ABIOTIC AND BIOTIC STRESSES

Photo: Alliance for a Green Revolution in Africa (AGRA)

Breeding work must try to overcome a wide range of negative factors affecting crops in Africa.

For a plant to flourish it must be able to overcome a multitude of constraints. These can be environmental (abiotic) factors or living organisms (biotic) that affect the plant in a negative way. Each has a particular impact.

ABIOTIC STRESSES

These are factors such as drought, heat or cold, or soil qualities that include low fertility, toxicity, acidity, alkalinity, waterlogging, compaction or low organic matter.

Drought

The difficulty with drought is that it's not just about low rainfall. Drought results from erratic rainfall and rainfall than differs from the expected quantity. If farmers get a consistent, predictable amount of rain they can grow certain crops, but not if it's patchy.

Many crops—for example, maize—are extremely dependent on consistent rainfall, particularly at the time of flowering. If no rain falls when the maize plant is flowering (silking), it won't pollinate and there won't be any grains to harvest. Therefore, with maize, breeding for drought tolerance is most of all about keeping pollen production and silking together.

Heat is an issue affecting drought because the hotter it is, the more evaporation there is, and the faster plants transpire to cool themselves down. Soils also affect drought levels if they are deep clay or deep sand, or shallow soil sitting on stone, and cannot hold much water.

Breeding for drought tolerance is difficult because predictable rainfall is required during the breeding process, but weather doesn't always perform as expected. To overcome this problem, the ACCI has invented technology to keep rain out. Instead, soil is covered with plastic and drip irrigation is used underneath, allowing the breeder to control the amount of water given to plants. (see page 159)

Drought tolerance is a very complex trait in crops, governed by many genes. The International Maize and Wheat Improvement Centre (CYMMIT) undertook a study looking at genes specifically associated with drought in maize, and found that there were at least 70 genes involved in drought tolerance

It's not possible to track so many genes, and that complexity defines how breeding is done for drought tolerance. Plant breeders must use recurrent selection because they're trying to accumulate all those different genes concurrently.

They can't just take one individual, cross it with another and hope that will give them the answer. They have to develop a population and slowly accumulate all the good genes for drought tolerance. This is not as time consuming as it sounds, and according to Laing, only takes two to three cycles. If selection pressure is appropriate it goes quickly.

"If you have a lot of genes involved you have to work with populations through recurrent selection. Our students have managed to do it in three years," says Laing. "Ironically, if you want to do it with only one individual, the process can take longer. We try to teach this to students but there's a reluctance to do it. When you do a single cross you think you know what you're getting. When you work with recurrent selection, you have to have the courage to believe that there are many minor genes there that can be accumulated to create better gene combinations. You have to trust in its power."

Choosing what approach to take can be a matter of tension among plant breeders, but the most important part is how they do their field screening. What is the field like and how will it affect the trial? How will unexpected rainfall affect the outcome of the trial?

Heat

Heat is not an important factor by itself, but it is in relation to drought because that will affect results. Plant breeders therefore tend to work on heat and drought together.

Cold

This is not a troublesome factor in most of Africa, apart from in South Africa, and the highlands of Kenya and Ethiopia.

Photo: ACCI

Maize stalk borer attacking a maize cob.

Low fertility and soil acidity

Geologically, the continent is very old and has not had many volcanoes or glaciers, which renew minerals in the soil. Africa, Asia and South America—all formerly part of Gondwanaland—have similar leached soils caused by centuries of rain removing minerals from them, and soil acidity and low fertility are significant factors.

Two critical minerals are calcium and magnesium, that buffer the soil against acidity. However, these leach over millennia, resulting in soils that are acidic, and which become more acidic very quickly because they are not buffered.

These soils have two limitations: they are acid and not buffered, so a tiny change in acidity is extreme. This causes issues because aluminium and manganese—which are toxic to plants at high levels—get dissolved in acidic soils. Aluminium poisons roots, causing them to become short, knobbly and unable to take up water, and as a result the plant becomes susceptible to drought. This is a particular difficulty for non-African crops, as local crops tend to be more tolerant of soil acidity. American maize, for example, is badly affected in Africa by acidity.

Breeding for resistance to acid soils and aluminium and manganese toxicity is therefore crucial in Africa, but often breeders do their research at stations where soils have been fixed with lime and phosphate, and they then breed varieties that need good soil to grow.

Leaching also causes low-phosphate soils, but small-scale farmers can't afford to put lime and phosphate on their fields. The cost of these additives plus their transport is prohibitively expensive, and in Ethiopia huge areas of the highland soils are becoming increasingly acidic. Phosphate-deficient soils will probably also be low in the micronutrients zinc, nickel and selenium, which causes limited growth and yields, and affects food quality for humans. Soils can also have an alkalinity problem, especially in West Africa, with a result that they release soluble iron at toxic levels. This is a big problem for rice farmers in West Africa.

The two major fertilisers used are potassium and nitrogen. Potassium can be replaced with organic

The termite is a formidable foe in Africa, attacking any crop from trees to maize and groundnut.

waste, but the cheapest form of nitrogen fertiliser, urea, vaporises if there's no rain and can burn plants once it dissolves. In addition, every molecule of urea used releases two units of acidity. Another fertilizer widely used across Africa is monoammonium phosphate, which also makes soil acid. The answer to these obstacles may be micro-dosing of fertilizer, where small quantities of balanced fertilizer is added to the planting hole of each seed, say of maize. This can cut down the quantities of fertilizer needed by 20-fold, without reducing yields substantially.

Salinity

This is a problem for rice production in much of Africa, as the marshlands can develop a "Dead Sea" situation where irrigation water evaporates constantly, leaving small quantities of salt behind in paddys. Over time, the salt builds up to toxic levels. Kashenge-Killenga in Tanzania bred for resistance to salinity. It is also a problem in parts of Mozambique where irrigation is practised, such as from the Limpopo River at Chokwe and Xai Xai.

Waterlogging

This is not problematic in Africa, except in parts of Ethiopia with deep, back clays and regular, heavy rainfall.

Low organic matter

Soils with high clay content have electric charges that enable them to hold onto minerals. Sandy soils, with their low organic matter and clay content, can't hold onto fertilizers, and instead leach them, becoming sterile.

Organic matter in the soil is important because it determines how many microbes a soil has, which is very important for plant health. Organic matter also provides food for earthworms, thereby encouraging their presence, and they in turn make holes for roots and allow for water to penetrate soil. If soil doesn't have earthworms and at least 1-2% organic matter, then it's not healthy, which is why ploughing is bad for most soils in Africa.

Ploughing dries out soils and kills microbes, especially beneficial fungi and filamentous bacteria. It's good for soils that are deep and wet and need to be dried out, but for most African soils, that are shallow and dry, it makes them even more inhospitable to plants.

BIOTIC STRESSES

These are the multitude of pests and diseases that wage constant war on the plant kingdom. Every plant has its enemies and monocultures make plants more vulnerable, because a high concentration of a particular crop will cause its pests and pathogens to congregate in the same area.

Most small-scale farmers try to manage that by having mixtures of crops. However, if they attempt to scale things up, the bigger areas of monoculture will create an unstable system with more pest damage and disease.

A conundrum plant breeders often face is that farmers' landraces have low levels of resistance which may be adequate in a small area, where maize, for example, is mixed up with sorghum and beans. Spores of the maize pathogen will tend to be more spread out, making it less likely to get lucky and land on a maize plant.

But if only maize is planted on the entire plot, then a fungal spore landing anywhere in that space is going to make contact with a host, so the efficiency of the pathogen increases phenomenally. This leads to more disease, and the system becomes more unstable.

Since monocultures are an inevitability in modern agriculture with large scale farms, the job of the plant breeder is to breed for greater resistance to crop pathogens. "The small-scale farmer can't make big enough gains without destabilising things, and can't do it fast enough," says Laing.

In some cases disease is literally the limiting factor. A virulent variety of a disease can wipe out an entire crop—for example, with cassava and *cassava mosaic virus*, or late blight and potatoes.

Storage roots and tubers

Diseases affect all parts of plants. Storage roots and tubers are affected by rots and weevils underground. Once harvested, sweet potato gets attacked by mould (*Rhizopus nigicans*), cassava self-destructs and potato tubers are attacked by about 20 different fungi. Resistance can be bred for most of these constraints.

The roots of ordinary plants get attacked by fungi, bacteria and plant nematodes. This renders them unable to take up nutrients and water and allows viruses and fungi to enter. Dr Frank Kagoda (graduated 2011) in Uganda did an outstanding job, breeding nematode-resistant maize crops in three years, using two cycles of recurrent selection to improve nematode resistance and yield. Nematode resistance increased by 39-65% and yields by 400-1200 kg/ha.

Another Ugandan student, Clare Mukankusi, did a study on beans and resistance to the number one root disease in Uganda, *Fusarium* root rot. This is a problem that develops where the crop is grown with very little rotation and there is a consequent build-up of root diseases in the soils. She made good progress in breeding beans for resistance to this disease, developing an efficient artificial inoculation regime to ensure that she compared like with like levels of disease when screening bean progenies.

Breeding for resistance to diseases found in soil can be tricky, as it's not possible to see what's going on in the soil. Breeders have to do artificial inoculations so they know that the soil they're planting into is diseased, and that the plants chosen to breed with are actually resistant and not just lucky to escape.

There is often an overlap between breeding for drought tolerance—including water use efficiency and the physiology of plants—and resistance to underground pathogens. It would be pointless, for example, for a breeder to develop varieties that produce more roots, giving them better nutrient, water and mineral uptake, if nematodes were going to eat half those roots.

Leaves

There are many pathogens that affect leaves, and every crop has its own leaf disease. There are airborne fungal and bacterial diseases like rust, and ones caused by viruses carried by aphid and white fly vectors.

Leaves are also affected by spots and streaks. Groundnut leaves can develop a number of different spots that ravage leaves and destroy crops. Small-scale farmers never spray against these diseases because they can't afford it. This crop is also attacked by the Groundnut rosette virus, which is actually a strange collection of three viruses. Two are satellite organisms that lack the full mechanism to reproduce themselves, so they piggy-back on the third.

Once the virus-collective is inside the plant it becomes a small, flat, yellow bush with tiny leaves, that looks like a rosette. The good news is that plant breeders can breed for resistance to this troublesome virus. Another disease that affects many crops is a leaf spot called Cercospora, caused by various species of a fungus that can devastate leaves, so that they look like they've been burnt with petrol.

Pods

Groundnut pods grow underground, where they are attacked by fungi and termites. Termites are a formidable foe in Africa, causing devastating losses for small-scale farmers. One solution is to apply a fungus (*Beauveria bassiana*) or pesticide to hessian or newspaper and put it down in the field. The goal is for the termites to take the infected material into their nest so they all get infected. Termites can attack any crop, from a tree crop to maize or groundnut.

Cobs and grains

There are three or four fungi that invade maize once it's in the cob stage. In Zambia, Makanga did a study on breeding for resistance to cob rots in maize and made significant progress, but did not complete his research when he was promoted to another position, heading up rice breeding in Zambia. This was unfortunate, because fungi in cob rot release mycotoxins into maize that are harmful to humans, there are currently no resistant varieties in Zambia, and the conditions in Zambia in summer are very conducive for cob rots.

Mycotoxins are toxic, nearly indestructible by-products produced by fungi. In humans the liver struggles to remove them and they can be carcinogenic, causing liver toxicity initially, and liver cancer in the long term. According to the FAO, the two most significant groups of mycotoxins affecting human health are aflotoxins and fumonisins. Aflotoxins are produced by *Aspergillus* fungi and mostly occur in maize, cotton, peanuts and tree nuts. Fumonisins are produced by several *Fusarium* fungi and are found infecting the grain of maize and wheat. They have been implicated in making people susceptible to contracting HIV (Wiliams et al, 2009).

Several insect pests including weevils, moths and beetles feed on grain in storage, and one of the consequences of these insects is the accompanying presence of mycotoxins in the grains they damage but do not fully consume. The postharvest pests typically cause losses of 40-70% to both stored grains of legumes (beans, cowpeas, pigeonpea, etc.) and cereals (maize, wheat, sorghum, millet, rice). For the farmer, it's a double whammy: the insects eat half the harvested crop, and what's left is mouldy, tastes bad, and is full of deadly toxins.

Weevils are a particular menace because they carry fungi in their gut and the grain fungi are expelled in their faeces, so they are on the spot to infect the remaining grain. This infected grain is highly toxic, but small-scale farmers and their families can't afford not to eat it.

It's possible, however, to breed for resistance to cob rots in the field, and for post-harvest resistance to weevils, moths and beetles. In one project, ACCI student Dr Charles Kasozi (graduated 2013) in Uganda proved naysayers wrong and bred successfully for post-harvest resistance to maize weevil. This was done by collecting genes from the germplasm of a very hard form of maize called flint, using recurrent selection.

In Malawi, Dr MacPherson Matewele (graduated 2015) bred for resistance in maize to two post-harvest pests, the maize weevil and the larger grain borer. He demonstrated that pest-resistance genes could be identified and incorporated into high yielding cultivars.

Stem / Stalk Borers

All cereals are attacked by several stalk borers and they are found in all regions of Africa. They're found wherever maize is grown and are probably the crop's most damaging pest. In Kenya, where losses of 70-80% have been seen, Dr Murenga Mwimali (graduated 2014) bred for resistance to the two main stalk borers—again despite predictions that this was not possible.

Beans are also affected by a stalk borer in the form of the bean fly, which has caterpillars that lay eggs at the base of the emerging bean plant. A student in Kenya, Dr Pascal Ojwang' (graduated 2011), made excellent progress in breeding for resistance to bean fly, but then he got promoted to become a lecturer at a university, and his best varieties were not released.

Weeds are a constant aggravation, with *Striga* species being the main enemy of all cereals (see page 109). There's a third species that only attacks broad leaf plants such as tobacco and cowpea. The ACCI has a dual strategy to manage this parasitic weed. It breeds for resistance and also uses a friendly version of the fungus, *Fusarium oxysporum* (fsp *strigae*) to deal with the *Striga*. This is the same genus of fungus that attacks beans and bananas, causing root rot, but it is a different species that only attacks *Striga* species. It's applied to the roots of the maize plant, which then feeds the fungus using root exudates, and in return, the friendly *Fusarium* attacks and kills the *Striga*.

The ACCI breeds for a combination of resistance to *Striga* and compatibility with this friendly fungus. An industry partner manufactures the fungus. Breeding for that is currently being done in Ethiopia and Tanzania on sorghum, and in Zimbabwe and SA on maize. The centre is also working with partners in West Africa, where *Striga* causes huge losses in the Sahel of an estimated 40-60% of sorghum yields, the staple food of the drier parts of the region.

Animals

Animals such as porcupines, baboons and bush pigs are ever-present pests for farmers of tuber crops, and this is one of the main reasons why they still grow toxic varieties of cassava. Monkeys are also an issue in some countries where maize is grown. Ironically they are the main pest affecting the maize breeding conducted by the ACCI staff and students at the university farm, Ukulinga.

Birds

Birds such as quelea, weaver, whydah and widow birds are major problems for farmers of small grained cereals such as sorghum, pearl millet, finger millet, rice and wheat, and can decimate an entire crop in days. At the university farm, staff have resorted to growing susceptible crops under bird netting, at great expense. Further bird problems can be caused by Egyptian geese and guinea fowl feeding on newly germinated crops as they emerge from the soil.

A bird sits on a sorghum plant next to a bag meant to prevent grains being eaten.

Dead cattle in drought-stricken KwaZulu-Natal province, South Africa

CROP CONSTRAINTS
CLIMATE CHANGE

Photo: Rauri Alcock

Can plant breeders develop new crop varieties fast enough to cope with changing weather patterns?

Changing weather presents a high-stake moment for plant breeders to display their skills. Globally, the last three decades have been successively warmer and in SSA, all regions experienced surface warming between 1901 and 2012, the longest period in which calculation of regional trends is complete.

Crops that have adapted to grow optimally according to certain weather patterns are being affected, mostly adversely, and especially in Africa. Given that it can take up to 20 years to breed new varieties of some crops, what are the priorities facing plant breeders and how are they tackling them?

Everyday requirements when breeding remain—i.e. new varieties should be nutritious, desirable to consumers, efficient in input use, tolerant of a range of abiotic stresses (especially drought, heat and salinity) and resistant to relevant pests and disease—but on this checklist there are new priorities, made necessary by changing weather.

What's significant about climate change is that it's not just about more heat, or one thing changing. Instead, it manifests itself in a variety of changes to existing weather patterns. One of these is erratic, unpredictable rainfall, a problem for most crops because if there's no rain at the time of flowering, pollination doesn't happen.

Another expected change is much more rain or much less rain falling than previously. Some models have shown that existing weather patterns are going to be exacerbated, so that dry places will get drier and wet places will get wetter. For example, in Ethiopia, where the highlands receive 1 000 mm-2 000 mm annually, it's projected that this will increase by up to 50%, and waterlogging will become an acute problem. The north and east lowlands, however, will see rainfall decline from 400-600 mm to 250 mm, and these areas will become unsustainable for growing crops. Similarly in South Africa, the semi-arid western and central regions will become drier desert areas, whereas the wetter eastern region will experience heavier rainfall, often in torrential storms.

An added problem is that across Africa the main rainy season is becoming shorter. If the duration becomes too short medium-duration crops run out of water before harvest. Many tropical countries—such as Kenya and Uganda—have two rainfalls per year but the shorter rainy period has become too short to grow crops successfully, and they're now stuck with only one.

Late-maturing varieties of crops like sorghum and cassava—that have lengthy growing times—are no longer viable, and farmers are moving towards planting early-maturing varieties to reduce the risk of losing their harvests, even if they have to sacrifice larger potential yields.

BREEDING FOR DROUGHT TOLERANCE

There's a growing need to breed more drought-tolerant crops—i.e. medium and short-duration varieties that need less water, and the ACCI currently has at least six students working in this area. It's also developing varieties that are compatible with *Trichoderma*, a benevolent fungus that lives in and on roots of plants in a symbiotic relationship.

This fungus controls disease and stimulates plants to grow stronger. It also encourages some plants to grow more roots, with increases of up to 50% seen in some crops such as maize and groundnut. The bigger a plant's root system, the more able it is to reach water and survive in dry conditions, a fact that the ACCI has shown by simulating drought conditions at its research centre in Pietermaritzburg (see page 159). More roots also means more fungus, so the benefits multiply.

However, not all plants are symbiotic with currently available strains of *Trichoderma* and the centre is screening crops from across Africa to find compatible varieties. Wheat grown in Africa, for example, doesn't respond to being treated with the fungus.

CROPS WILL BECOME LESS NUTRITIOUS

Rising CO_2 levels, which are linked to climate change, will also make food less nutritious. A study reported on in *Nature* in 2014 found that increased levels of carbon dioxide in the atmosphere, caused by the burning of fossil fuels, will significantly reduce the levels of iron, zinc and protein in staple crops.

The study showed that wheat, rice, maize and soybean grown in elevated CO_2 levels raised to those expected in 2050 had lower nutrient levels than those grown in ambient CO_2. These nutrients are vital for human health, especially in populations like Africa where meat is a scarcity. Breeding for enhanced levels of iron, zinc and protein in staple crops will therefore become even more important.

TOO MUCH RAIN

In areas where too much rain falls, waterlogging can be a serious issue, even for crops like rice. Rice has roots that grow up into the air to breathe, but if the water is too deep they can't do this and the plant dies. Waterlogging is also associated with fertilizer being washed away, so that plants don't receive sufficient nourishment.

Another big concern with increased rainfall, especially when coupled with heat, is the proliferation of pests and diseases, and there's an urgent need to breed for better resistance to them. However, funders and seed companies are often reluctant to sponsor research for a crisis that may only appear in 10 or 20

Drought on tap

Breeding for drought tolerance entails screening crops in drought conditions, and the centre has had to invent its own facility for doing this on a reliable basis.

At the university farm a sloping contoured land (about 18m wide and 200 m long) was covered with silage plastic. Underneath the plastic there is drip irrigation and plants are inserted at each dripper. At one end there are taps (automated solenoids controlled by a timer), and plants receive a decreasing amount of irrigation, thereby creating graduated drought. The area was covered with netting to keep out birds, that can strip an entire crop.

The timing for irrigation can also be adjusted, so that all the plants get the full amount of water up to the time of flowering, and the amount is reduced thereafter. This allows the researcher to see what the impact is of different levels of drought, and timing of drought events.

The facility allows researchers to do selection and breeding for drought and *Trichoderma* interaction under predictable, measureable drought conditions. They can also measure water-use efficiency of different varieties.

years' time, and this is a major obstacle for breeders.

In eastern South Africa where an increase in rainfall is predicted, Laing says there should be breeding being done for maize streak virus, but this is not happening because it's not yet a problem. "But it will become a problem as the climate changes. We need to be proactive."

"I went to the wheat people in South Africa and said we need to tackle rust because it's going to become more of a concern, but they weren't interested in our approach (recurrent selection for resistance and biological control). We're going to have to tackle head blight in wetter areas too, but they weren't interested in our approach there either." Resource-strapped government facilities are doing limited research in this area, not enough to move at the speed of climate change.

THE WAY FORWARD

To breed "climate-smart crops" breeders must study the models that hydrologists and meteorologists have worked out, in conjunction with looking at the different areas of Africa, what current weather patterns are, what they're going to shift to and what the primary crops are in those regions.

Their analysis must include what varieties are currently available and what changes need to happen to reach breeding goals in 20 years' time, with the weather systems predicted to occur in 20 year's time. Hybrids need a long time frame to develop, and modelling needs to be done of what the weather's going to be doing in the future. This analysis must then convert all that into what crops will need in terms of their performance.

Deciding on what traits are required—drought tolerance, heat tolerance, pest and disease tolerance, waterlogging—will depend on where the breeder is. "A lot of our students have done drought tolerance as a goal, and some have done pest and disease resistance as a goal. With all of them yield is an underlying issue, but what causes yield loss? Is it disease, is it drought, is it low fertility in the soils?" says Laing.

"Our goal is to equip them with the skill set that will enable them to breed more than just one crop for rapidly changing conditions, whether it's for more or less rain. A place like northern Rwanda, where it's wet and humid, will get more rain. There potato is the number one staple and late blight is going to become more serious, because it goes crazy in hot wet conditions," he says.

Sometimes the best-laid plans are derailed. Laing adds ruefully that the ACCI had trained a Rwandan potato breeder specifically in late blight breeding and then he got a job as a university professor. "So we need to train another one, it's really urgent that we do this."

CHANGING TASTES

Will consumers have to change their eating habits to accommodate new growing conditions? In Kenya, people who were living largely in the highlands were forced, due to population pressure, to move to the midlands where there's substantially less rain. In the highlands their staple crop had been maize and they tried to grow what they knew and wanted in their new home, but it was unsuitable for maize. Sorghum or pearl millet grow well there, but the new settlers have persisted with trying to grow maize, because that's what they want.

Laing believes that as climate change proceeds, many countries where maize is the number one crop won't be able to grow the same amount, and its production will be erratic, an annual gamble. They may need to grow climate-smart crops like sorghum, but will consumers accept that?

"We have that problem across Africa with demands for rice," he says. "It's quick to cook and it doesn't take a lot of fuel. There's a massive demand that's way bigger than the amount produced, but urban people don't look at the agriculture of a country." Consequently, in most African countries the favoured foods are subsidised to keep voters happy.

Laing said politicians don't always do what they should. "Malawi has shown that if you just subsidise the costs of crop production you can go from being a net importer to being self-sufficient, and exporting a surplus. We're going to have less and less areas that are good for crop production, so we need to make sure that those areas are more productive. And part of that is making sure that people are investing in fertilizers and adapted crops that are available. We need to get the improved varieties to the farmers, where they need them."

Derera, however, is more optimistic about the future of maize in Africa. He says it will continue to be available because demand is high; maize meal is preferred and people would rather have it than drought-tolerant crops. "More resources are put into the breeding of maize than sorghum. As a scientist you'd think that resources should be put into crops like sorghum, but if you look at the situation on the ground, people want maize to eat."

He says it's possible to breed drought-tolerant maize. "Climate change will increase the temperature by 2-3°C, which is not much for a maize plant. If you go to Sudan, where the temperature is 45°C, you find maize growing. If you select your maize for ten years under those conditions, you can breed new varieties that are heat and drought-tolerant."

TEACH THE FARMERS TO DO PLANT BREEDING

Climate is changing faster than farmers are able to adapt their varieties, and it's only by scientific breeding that the rate of breeding can be accelerated. Sorghum, for example, is a self-pollinating crop, so only one seed in a million is different. The farmers have to see that one special plant, identify it and keep it. Very few mutations that are beneficial actually get identified and bred and carried through. It's far quicker for the scientist to do artificial pollination. The same applies to rice, wheat and beans.

Maize, because it's an outcrossing crop, can adapt much quicker, but it has quite a narrow range of adaptability. Another problem is the loss of genetic diversity, due to crop failure of diverse landraces, bred over hundreds of years.

"The tragedy is that farmers are losing their landraces, which have lots of genetic diversity and plant material that can be used," says Laing. "If these are lost, then scientists end up with fewer genes to work with."

He dreams of teaching farmers to pollinate crops themselves so that they can plant out and make their own selections. "Give them the engine of diversity. It's so easy to do, especially with cassava, maize, pigeonpea. Beans and sorghum are more difficult but it could be done. That's what we really should be doing, because we aren't training enough plant breeders in Africa to do it all. We don't have enough breeders for all the crops, in all the agoecologies. We really need to train the trainers of the farmers if we are to cover all the options in time.

"It's the barefoot doctor idea. I really believe we need to train barefoot plant breeders."

Effect of climate change on smallholder farmers

- Decreases yields. A study estimated the following drops in the top five SSA crops: maize (-22%); sorghum (-17%); pearl millet (-17%); groundnut (-18%) and cassava (-8%). (Schlenker and Lobell, 2010)Af agric status rep
- Decreases water supplies. Annual rainfall projected to decrease by up to 30% under 4°C rise.
- Decreases crop nutrient levels.
- Increases pests and diseases.
- Accelerates land degradation.
- Increases extreme weather events, including drought and flooding, that can destroy crops and livelihoods.
- Decreases length of growing period (LPG)—an indicator of adequacy of moisture availability, temperature and soil conditions for growth—by up to 20% for most parts of the region by 2050.

Aden Jama takes one of his few remaining goats out to look for pasture. As the drought in 2012 worsened he and his family lost many of their animals and had to move closer to the village and the water trucking site. "Before the drought I had 220 sheep and goats and 12 camels. Now I have 40 sheep and goats and three camels left. The rest have died from the lack of water and pasture. Photo: Oxfam East Africa.

Mwadzingeni (left) and ACCI research manager Ian Doidge in the cold room of the centre's seed storage facility.

Protecting seeds of landraces and breeders' lines

One of the conundrums faced by plant breeders is that by creating better crop varieties, they are hastening the extinction of landraces. High-yielding new varieties that are drought-tolerant and resistant to pests will increase crop production, improve lives and become more popular with farmers, but will also hasten the abandonment of traditional varieties and a loss of genetic diversity. A few new varieties can replace tens, if not hundreds, of ancient landraces, and once a landrace is gone, thousands of years of farmer breeding and selection are lost forever.

Seed stores are a partial solution, but maintaining optimal conditions to keep seeds alive currently requires expensive facilities. It's difficult to store enough seeds to maintain sufficient diversity, and the problem of inbreeding arises if the seed store only collects small samples.

"If you don't have enough genetic diversity, then you will end up with inbreeding loss of vigour, and genetic drift, which happens when the population is too small. Then the factors that shape its genetic profile become random. If the best plant is killed by a locust, its entire genome is lost. This affects the potential of the remaining seed sample enormously, because all the best possibilities have disappeared".

The other seed storage problem is for plant breeders: where and how can they store their parent seeds, their inbred lines, and their elite lines? In many cases, these represent decades of collecting and breeding each crop variety. The seed is irreplaceable, but how can it be preserved in Africa ? Electricity supply is unreliable in many rural stations, and technicians to fix sophisticated cooling equipment may not be available. So the conventional solution of chilling seed to 100C and reducing humidity to below 12% is not possible. It needs a different technological solution.

Another question is: who should be maintaining that genetic diversity? "You can't ask farmers to do this, because they're already living on the edge," says Laing. "Every square metre of their land must be grown with the best varieties. It has to be government departments, with the mandate to lift the status of all people, especially the farmers."

However, he says official seed stores in Africa are often hopelessly under-resourced, describing one he visited in Malawi, where the seeds were all dead. "The air conditioner was broken and there was no dehumidifier, so the environmental conditions were entirely inappropriate—it was hot and humid. To preserve seeds it's not temperature that matters so much, it's really the humidity. If a seed absorbs moisture from the air, then enzymes inside it start to become active, chew up the available nutrients in the seed, and then it dies when the nutrients run out."

Laing has been keen to find an affordable, simple solution that does not need electricity, and has come up with a design that uses solar and wind power. In his storage facility, external air inside is warmed on the roof, and then sucked into the store room via a chimney that moves the warm, dry air through the bags of seeds, keeping the humidity low and discharging cooled, humid air. He's currently working with the Department of Agricultural Engineering to optimize the design, in an MSc project. The building materials that are needed to convert existing seed storage rooms are cheap and readily available, so he is hoping that this novel design can be implemented across the continent.

CROP CONSTRAINTS

QUALITY AND POST HARVEST

Cassava drying after being harvested.

Photo: Alliance for a Green Revolution in Africa (AGRA)

Improving the nutrition and post-harvest shelf life of crops are key considerations in the war on hunger.

QUALITY

When plant breeders talk about quality, they mean increasing nutritional traits, such as vitamins, protein and amino acids, and reducing undesirable components like toxins, poor flavour and long cooking time.

Foods may contain proteins, carbohydrates, fats, vitamins and amino acids, although not always in the desired amounts.

Minerals: These are a big issue in Africa and breeders can select for them. Zinc and iron, vital for boosting immunity and transporting oxygen respectively, are critically deficient in people across Africa, and research is being done into breeding maize and other crops for enhanced levels of these minerals.

One constraint is that it's expensive to measure their levels in crops, so the ACCI is trying to develop a better way, using Near-infrared Spectography (NIRS). The centre has the equipment to do this, so there's no cost to each investigation, and it is already able to measure zinc and iron levels in maize.

Enhancement of levels of vitamins A, C and some Bs in some crops is also necessary. Vitamin A in particular is commonly in short supply in African diets, leading to blindness and other medical conditions, especially in children.

Protein: When protein is digested it gets broken down into building blocks of 23 amino acids. If you're lacking in one amino acid, your body can't make proteins with the rest and they are excreted in your urine. We therefore depend on our food sources to get a balance of them.

The useable amount of protein may therefore be much less than the total amount. Maize, for example, has eight percent protein but we can't use much of it because it has critically low levels of lysine and tryptophan. In sorghum, it's lysine and methionine that are in short supply. In general, there's a need to breed for crops with higher lysine, tryptophan and methionine levels.

It's all very well to breed for increased protein, but quality of protein does matter and there are specific genes for that. One of the early experts on Quality Protein Maize (QPM), which has high lysine and tryptophan, was based at UKZN, and a number of ACCI students have done research on QPM in their countries.

When the gene for QPM was first discovered in the sixties, it was in a very poor variety with low yields and poor storage and milling qualities, so breeders have been breeding for high yield and other qualities, and are still working on it.

All African cereals including millets have a deficiency of lysine, methionine or tryptophan, and there's also a problem of digestibility in some. For example, sorghum has 8-15% protein but it can't be digested, because one protein in particular is very sticky and literally gums up the others. When monogastrics—humans, pigs or chickens—try to digest it, it's not susceptible to their gut enzymes and goes straight through.

"We're trying to breed for mutant proteins that are digestible, and if we can do that it will make a dramatic difference, because sorghum is the number two cereal in Africa, and for some parts of the year in drier regions, it's pretty much what most people are eating," says Laing.

Cassava

In Africa cassava is a poor source of protein, containing only about two percent. The ACCI could breed for better quality cassava with more protein, because there are varieties in Brazil that have about 10%, but Brazil doesn't want to share its germplasm. The International Centre for Tropical Agriculture (CIAT), based in Columbia, has varieties that have up to eight percent which can be accessed, an option for the future.

Breeding can also be done for more Vitamin A, using yellow cassava that has beta-carotene in it, as well as for low cyanogenic toxins and high minerals.

Another important quality issue is cassava's tendency to self-destruct after being dug up. Laing says this should be easy to breed for—by doing mutation breeding and looking for mutants where the enzymes that degrade tubers are no longer produced—but it has not been done yet. This could be because the dominant research focus has been on developing virus resistance and earliness (how soon can the crop be harvested). There are varieties that peak in six to seven months, and this could triple the yields of some farmers.

"There are early varieties of cassava available, but is it possible to breed for better yields in early varieties? Yield is good but not at the cost of earliness, so that's a compromise we have to work around," says Laing.

Sweet potato

There are three main areas of quality. First, people want to eat floury sweet potatoes with high dry matter, so for breeders that's a fundamental goal.

Then there's breeding for beta-carotene, i.e. orange-fleshed sweet potatoes. Breeding is being done for increased beta-carotene, but it can compromise palatability, with the sweet potato becoming brown and oily if there's too much beta-carotene. It's necessary to breed for a lower level so that it doesn't compromise flouriness and good taste.

The third problem breeders must tackle is the amount of protein, which is minuscule at two percent. In South Africa the ACCI is currently working on a project with a government scientist to try to breed for higher levels of protein. Six hundred varieties of sweet potato have been selected and selections have been made for those with high protein, plus high dry matter.

Maize

Derera is developing orange maize with high beta-carotene. The problem is that Africans want white maize and yellow maize isn't popular. "I think that's because it's easier to pick out weevils," says Laing. "Also, there have been droughts and when yellow maize gets imported as food aid from the northern hemisphere it's usually not good quality. So people get put off yellow maize. And it's associated with hand-outs and losing face, so there are negative connotations."

Another problem with maize is that it's deficient in niacin (Vitamin B3). People who eat only maize often get beriberi, and so there's a need to breed for niacin. In Mexico, people add lime or ash to maize and ferment it (nixtamalization), which converts a precursor into niacin, so that tortillas made with the treated maize contain adequate levels of niacin. This is why beriberi is seldom found in South America. However, in Africa there is no tradition of doing nixtamalization, so people get Vitamin B deficiency.

Rice

Some African rices are scented, for example Faya from Malawi. Faya has a relatively low yield so there's a need to breed for enhanced yield while retaining the scent.

In general, the flavour and scent of rice are often stipulated by farmers as preferred traits for rice, so breeding for these traits is important and has been included in several student breeding projects.

Potatoes

With Irish potatoes the ACCI has only really looked at yield issues.

The main constraint with potatoes is diseases. If conditions are cool with rain, then farmers will have to contend with late blight.

POST HARVEST

In Africa up to two thirds of crops are lost before consumption, and the Rockefeller Foundation have made this issue—post-harvest losses—their current theme.

In the developed world this problem centres on packaging, transportation and appearance, but in the developing world the issue is storage. Most farmers operate on a very small scale and have limited storage facilities.

The storage of grains—i.e. cereals and legumes—is a critical area of weakness in small-scale agriculture. Rats can be very destructive and useful work has been done by international agencies to address this problem, using tin to make "hats" for the legs of grain storage containers. This solution works very well.

Weevils, moths and beetles in particular, can cause losses of between 40% and 70%. “Let’s say the average is 50%,” says Laing. “If we then stopped these pests alone, that would double the amount of food available for people.”

Control of these pests is also a quality issue. Weevils cause grain to become mouldy and highly toxic, because they carry fungi in their gut which they defaecate into the grain. This causes secondary fungi to come in and make mycotoxins.

Laing says it’s possible to breed for resistance to most pests in a post-harvest situation, but difficult, so people don’t do it. The difficulty is that the breeder has to work with an entomologist who looks after the pests, while the plant breeding is being done. Pests are then lined up with different varieties of maize and observed, to see which ones they choose to eat.

Beans have a protein that is an insecticide, and in Malawi Kananji has managed to find two varieties of bean that are resistant to bean weevils (bruchids). In Tanzania, Matiwele has managed to do the same with maize.

“It’s great that we’ve succeeded with beans and maize, because those are two of the most important staple crops in Africa. If we can do it with those crops, we can do it with any crop. We just have to do it,” says Laing.

GREATER THAN THE SUM OF ITS PARTS

ACCI technician Thandazani Dlamini plants cassava clones.

Setting up the ACCI was a gamble that paid off, with huge gains for the continent and African agricultural science.

As a "decolonising" exercise, the establishment of the ACCI has been phenomenally successful. A continental centre of excellence was built, mostly staffed by Africans, teaching African students a syllabus custom-made for local conditions.

The funding came from the First World but there were no strings attached to the academic content, and the benefits to the region have been considerable. The vexing problem of the brain drain of trained plant breeders from Africa to the Northern Hemisphere was reduced to zero. At the same time, local breeding programmes have been strengthened by the hands-on experience gained by students working in their home countries. In addition, "unlike those who went to study at Cornell or Wageningen, the students here are breeding for their country, in their country. Their PhD work has direct value, and their tools and skills are directly tested in their home environment," says Laing.

Derera says those who studied overseas and returned, "came back knowing the science, but they didn't know the people, they didn't know the network of scientists and administrators. People who study here have built a network while they are working as students, and they already belong to a community of practice. Plus they are well resourced."

Having worked with the farmers, the graduates are passionate about wanting to see their projects to fruition. Derera also believes the grants given by AGRA to students to continue with their research after graduating, have been a huge incentive to stay in Africa.

At the ACCI, students are trained to do first-class research in local conditions, so that they come to see that the facilities are not the limiting factor. "That's a crucial epistemological breakthrough for an African scientist, because one of the things we all suffer from is an inferiority complex, and concerns that we don't have the fancy equipment that they do in Japan and America," says Laing.

"Our goal is to inculcate in students that it doesn't matter what your facilities look like. What's important is if you can do good research under those circumstances. That comes down to your knowledge of what you need to achieve your breeding goals, and how you'll do that. If you have to come up with novel ways, then do that," he says.

A spin-off of this is the ability to think independently. "Part of the magic of the ACCI is their sense of purpose and willingness to dispatch with mainstream schools of thought that might hinder you from being as effective as you can be, if you just go with a very knowledge-driven and purpose-driven approach," says co-founder Joe DeVries.

This field experience in the home country, and the home research station, is rare for a PhD programme, with most universities focusing on PhD research taking place at the university itself, where infrastructure and support systems are already in place. The soft skills component teaches students what they need to know to be independent and able to organise, fund and sustain their own breeding programmes. And, because of the block system, where experts are brought in—sometimes from overseas—to teach different disciplines, students are exposed to a wide range of teachers, with diverse backgrounds and ideas.

Putting all this together was tough and risky, admits DeVries. "We're talking about huge amounts of money involved, and reputational risk for donors if things went wrong."

"In the beginning my greatest fear was that the students' theses wouldn't pass muster. I remember the lead person from Cornell University said the PhDs had to be judged by an international panel of experts in genetics and plant breeding, and I said 'Oh my God, that's scary. What are they going to think of these rough and ready plant breeders who've gone and carved out their own research plots and done work on farms in Africa, will they get what we're trying to do here?' "

"I was really nervous. If those students hadn't graduated, I would probably have had to resign my position as deputy director for agriculture at RF. But it was never a problem. They all graduated and a lot went on to publish their research in refereed international journals."

In fact, the ACCI model was so successful a decision was taken by AGRA to replicate it and open

ACCI staff with the 2017 cohorts of masters and PhD students.

Cloned masters programmes

There have been two spinoff programmes inspired by the ACCI.

- A masters programme in plant breeding was started by the Bill and Melinda Gates Foundation, which is based at the ACCI, KNUST in Ghana and Makerere University in Uganda. John Derera was appointed to run the programme at UKZN and when he left, he was replaced by Julia Sibiya, another ACCI graduate.
- Based at UKZN, "Mastering the Masters" teaches soft skills to masters students and is modelled on a course started by Elizabeth de Kadt about a decade ago, largely using ACCI lecture material, which was designed to enhance throughput of postgrads.

a second centre in West Africa (see opposite), while UKZN took advantage of the work put into developing the soft skills curriculum, and established a programme for masters students, called "Mastering the Masters." (see page 173)

After graduating, many alumni have gone on to hold top positions in the agricultural sector. "The ACCI has trained leaders, me being one of them," says Sibiya, a maize breeder from Zimbabwe. She now runs the ACCI masters programme at UKZN. "In terms of active plant breeders, in most of the countries I go to now the majority were trained by the ACCI. A number of my colleagues are now centre directors, leading programmes. That has been a really positive impact of the programme."

"For me, this group are the new generation of plant breeders when it comes to knowing about breeding tools and procedures, and scientific principles," says Shimelis. "They do quite extensive breeding and have prepared a number of varieties for release. Most of our students are also publishing extensively, and some are now going to international research centres like IITA, CIMMYT and CIAT."

Over 140 new crop varieties developed by ACCI graduates have been released onto the market, and this number will grow as research that is currently in progress is completed. It's a contribution that Rufaro Madakadze, programme officer for education and training at AGRA, says has had a "huge" impact. Describing the example of Jean Baptiste Tignegre, who has released four new varieties of cowpea that are resistant to *Striga*, she says, "these are the varieties grown all over Burkina Faso now. That is an impact you can't put into a box.

"Chrispus Oduori, a finger millet breeder from Kenya, was the first to release new varieties of the crop in Africa, and now they are grown all over western Kenya," says Madakadze. "By the time they were being released, farmers were stealing them from the research station. It had gone viral. There are many stories like that."

Other impacts are less obvious. "In terms of the plant breeding population in Africa, the ACCI has made a unique contribution by creating a body of thinkers who have common ideas and experiences," says Walter de Milliano.

"We have created a bridge for people to share ideas. We are opening up science in Africa and people are more open. By travelling to other countries to see students, the experience of teachers has also been widened. These are all human impacts, and impact is also created by using technology and libraries."

DeVries describes ACCI graduates as transformed people. "I remember following John Derera into his plot and him turning around in a field of two-to-three-metre maize and shouting out all the ways in which he was improving new genetic principles, and I remember thinking I better get out of here. I thought I was going to be attacked, he was just so on fire and so full of determination, and so compelled by the knowledge he felt he had gained."

With this fire, the ACCI has made its mark on the continent.

Professor Eric Danquah, head of the WACCI

Taking the model to West Africa

Based on the model of the ACCI, the West African Centre for Crop Improvement (WACCI) was started in 2007. Led by Professor Eric Danquah and funded by AGRA, the centre is housed at the University of Ghana (UG) in Accra.

Like their ACCI counterparts, students do a four-year programme through UG that includes academic coursework, soft skills training and three years of field research in their home countries. Visiting lecturers are brought in from all over the world.

"The main difference was the number of scientists we were able to use as supervisors. From the start we took advantage of nearby international research institutions like ICRISAT and the IITA, and that helped a lot," says Danquah.

Since 2007 the centre has enrolled 108 students and graduated 52 from countries including Ghana, Nigeria, Niger, Burkina Faso, Mali, Senegal, Sierra Leone, Cameroon, Togo, Ethiopia, South Sudan, Uganda, Kenya, Malawi and Liberia. There are 54 still studying and two have dropped out.

"Our first students graduated in 2013 and almost all the first group are already releasing varieties," says Danquah. He believes that compared to the ACCI, WACCI faces particular challenges because of the weaker economy of its host country. "For example, in SA, when students publish papers the department gets the money. We don't."

Because of the greater need in the region, WACCI's focus on drought tolerance is more intense and more than half of all varieties bred by students have to include this trait.

As with the ACCI, funding is the major challenge. "We need to consider sustainability. We've been aggressive in exploring partnerships with foundations and public-private bodies," says Danquah. "We're always told by funders to go to African governments for funding, but can we wait for them? We can't wait while they sleep, so we continue to engage with the private sector for support. When they wake up, they'll find shining examples of plant breeding education."

WACCI recently became a World Bank Centre of Excellence, which is bringing in some $8 million, but Danquah says the ACCI and WACCI "deserve more from AGRA. We have changed mindsets and are getting graduates to stay in Africa. This is the surest bet for sustaining progress. These are centres of excellence that should be protected. A minimum of core funding is still important."

EVOLUTION

PhD student Marilyn Christian is working on improving the quality of drought-tolerant wheat. Like a growing number of ACCI students, she joined the programme with non-AGRA funding—in this case from the National Research Foundation. The centre will be pursuing this model of individual funding for students in the future.

The ACCI's strategy for survival is to attract students with their own funding

"Our students were expensive." Laing says this without regret. The money was spent on a Rolls-Royce education and the results speak for themselves. "American universities work on about $120 000-$180 000 per student and ours cost about $110 000 each. That's taking total costs and dividing by the number of students that came through."

However, according to his calculations, the actual cost to funders was about a third of the price. When RF was training PhDs in America, only one out of every three trained returned to Africa. The others found jobs in America.

"Our retention rate is 100%. So not only are we cheaper, but also three times more successful at getting graduates to stay in their countries and work in the agricultural sector," he says. Savings have also been made by the majority of students graduating in less time—four years—than those in America, where the average student takes seven years to graduate in science.

But despite its achievements, the centre faces choppy waters. The funding environment has changed and its main benefactors, RF and AGRA, have said they will not continue paying to support centres dedicated to training plant breeders. Although there's money to pay for the currently registered cohorts to graduate, after that, the ACCI (and WACCI) will have to find alternative sources of revenue.

The priorities now are post-harvest issues and crop management. This is because, says former RF executive Gary Toenniessen, in the 15 years since the centre began, "conditions in the agricultural sector have improved and there is now a critical mass of well-trained African scientists working at African institutions who can help train the next generation of scientists. Supplemental training programmes are now needed for food scientists and others who can help farmers convert surplus production into value-added products."

In the post-global-economic-meltdown world, sustainability is the buzzword. "Funding organisations always ask, for how long are we going to fund these institutions?" says Dr Yilma Kebede, a former senior programme manager of the Bill and Melinda Gates Foundation. "When will they stand on their own feet? It's about sustainability. If it's always run as a project, then it will never move beyond that." He says the cost per student is steep, but "what has the ACCI done to make itself sustainable and viable beyond the grant period?"

"The likelihood that the ACCI and WACCI programmes, in their current forms, may end is high. It's tragic," says DeVries, acknowledging that there is still a need for plant breeders to be trained. "A lot of graduates are now in leadership positions, they're not in the field anymore, and they need to be replaced.

"But at the same time you also have to wonder, will (this kind of work) always have to be funded by donors? If African governments can see that excellent plant breeding work being done, then isn't it time some of them also gave money?"

Funders have also remarked on the centre's relationship with UKZN. "The university administration never embraced and supported the ACCI as strongly as we hoped they would. They have been supportive but only as long as someone else pays the bill," says Toenniessen. Kebede agreed, saying the centre could be sustainable if the university integrated it into its own programme, "but I don't think there are any plans for UKZN to make it its own".

Laing defends UKZN, saying the university has been supportive in terms of providing resources such as laboratories, green house space and offices, and appointing ACCI staff to permanent positions. This allows the centre to function at a low level without external funding.

"To expect the university to fund the ACCI is an unrealistic expectation," he says, explaining that the university is short of funding for its core activity—teaching South Africans. "To take on funding a pan-African programme is beyond their remit.

"The real failure here is where the African Union and the African countries whose students we're training don't commit any funds to it. Where is Africa's investment in the future, in terms of agriculture and capacity building?"

Admire Shayaowako, a non-AGRA student in plant breeding, measuring bio-chemicals at the FOSS NIRS Laboratory.

Laing is philosophical about the changes being thrust on them. "The ACCI was a long-term vision, and short-term thinking is prevalent now. All NGOs go through these cycles." Because of a prudent fiscal approach, it's already halfway towards being sustainable, and the core staff—Laing, Shimelis, Melis and Sibiya—are all employed by the university in other capacities. This means, however, that they carry two workloads.

The centre's new goal is to attract students who come with their own research funding from different partners, and to run the programme in a slightly different way. The plan is that, in addition to specific training for plant breeders, courses in the current curriculum that would be useful to people across a broad spectrum of agricultural sciences will be offered as a package.

This will include, for example, training in throughput management, statistics, genetics and practical skills like how to lay out a trial, collect data, and manage seed stores. The centre has started to advertise and has had responses.

In addition, the centre has had several students register for training in plant breeding, because of its reputation. They came with their own funding, and are supervised by a staff member. The challenge ahead will be to find at least 8 more PhD students from Africa, per year, each with funding of around R400 000. Laing is upbeat about the prospects of succeeding.

"We have the hands-on experience, the track record, and the best weather of any South African university for plant breeding," he says. "We also have the best facilities in Africa. These include the 300-ha farm (of which the ACCI uses 18 ha of irrigated lands) and substantial greenhouse and tissue culture facilities, the labs and the NIR and biotech facilities.

"We can do pretty much anything here that they can do in America, and more, because we are in Africa. And the need is on-going. The students we train are soon promoted and move out of active plant breeding, which is where the need is greatest."

GLOSSARY

Abiotic—related to things in the environment that are not living, such as minerals or water.

Additive genes—multiple genes with cumulative effect. Combined, additive genes create a complex, quantitative outcome on the phenotype, e.g., drought tolerance in maize is governed by more than 35 additive genes.

Aflatoxin—a mycotoxin produced by several *Aspergillus* species of fungi in food crops such as maize and groundnut.

Aflatoxin B1—extremely toxic mycotoxin, often produced by the fungi *Aspergillus flavus* and *A. parasiticus*; It is considered dangerous at levels above 5 parts per billion.

Agricultural value chain—the contiguous chain of goods and services necessary for an agricultural product to be produced on a farm, then delivered to the final consumer.

Agroecology—an ecological approach to agriculture that sees agricultural systems as ecosystems: the combinations of soils, altitude, latitude and climate that determine crop responses.

Agroecological zone (AEZ)—a geographical area with specific climatic conditions that determine its ability to support rain-fed agriculture.

Allele—an alternative form of a gene which may be dominant or recessive.

Amino acids—the building blocks of proteins that are essential for all metabolic processes. Some diploids can have three or more alleles (multiple allelism).

Anaemia—a condition in the body where a deficiency of iron leads to the reduction of haemoglobin in red blood cells, and a consequent inability to transport sufficient oxygen to organs and tissues.

Annual plant—a plant that lives for only one to two seasons/years.

Anthesis—the flowering period of a plant, from the opening of the flower bud.

Antioxidant—a substance that inhibits reactive oxygen species that cause damage to plant or animal tissues, especially membranes.

***Aspergillus flavus*—**a fungus found on cereal grains, legumes and tree nuts, especially post-harvest. It causes pre-and post-harvest infections (mouldiness), and many strains produce toxic mycotoxins called aflatoxins.

Banana Xanthomonas wilt—a bacterial disease caused by a bacterium, Xanthomonas campestris pathovar *musacearum*, that affects bananas in East Africa.

Beriberi—a cluster of symptoms caused by thiamine (Vitamin B1) deficiency, affecting mainly the peripheral nervous system and the cardiovascular system.

Biochemical—relating to the chemical processes and substances which occur within living organisms.

Biotechnology—a broad set of scientific techniques to manipulate microbes, plants and animals at a molecular level.

Black sigatoka disease—a leaf spot disease affecting bananas, caused by the fungus *Mycosphaerella fijiensis*.

Blast of rice – a stem and sheath disease of rice caused by *Pyricularia oryzae*. It is widely recognized as the plant disease causing the greatest crop loss annually.

Buffer (soil)—soil buffering is the ability of soil to slow down nutrient or pH changes, especially soil acidity.

Calcareous—containing calcium carbonate; chalky, originating from chalk.

Cassava brown streak virus disease (CBSD)—a root rot disease affecting cassava plants caused by two viruses, cassava brown streak virus (CBSV) and Ugandan cassava brown streak virus (UCBSV); vectored by whitefly.

Chocolate spot disease—a disease caused by a fungus, *Botrytis fabae*, affecting Faba bean plants, causing spots on leaves, stems and flowers.

Classical/conventional plant breeding—a method of plant breeding that uses deliberate crossing of closely or distantly-related individuals followed by systematic selection of superior progeny in order to produce new crop varieties with desirable characteristics.

Colchicine—a substance extracted from plants of the genera *Colchicum* and *Gloriosa*, commonly used to treat gout; it is used in plant breeding to double the chromosomes of haploid plantlets, creating an instant doubled-haploid plants which are "inbred" plants where all alleles are identical; or to double the chromosomes of a diploid plant to create tetraploid progeny.

Convicine—a toxic substance in faba beans causing the disease favism in individuals who have a hereditary lack of the enzyme glucose-6-phosphate dehydrogenase.

Crossing—this is the natural or artificial pollination of one plant (the female, receptor) with pollen from another plant (the male, donor).

Cultivar—a group of genetically uniform and stable plants of a crop that has been systematically bred for superior, distinct and novel traits.

Cyanogenic—producing cyanide compounds on degradation, as found in some cassava varieties.

Cysteine—an amino acid that is deficient in some cereals.

Diploid—cell or nucleus containing two complete sets of chromosomes, one from each parent.

DNA—deoxyribonucleic acid (DNA) is a molecule that contains the genetic instructions used in the growth, development, functioning and reproduction of all living organisms and many viruses.

DNA fingerprint—unique patterns in a sample of an individual's DNA that can be used to identify it.

Dopamine—a neurotransmitter released by the brain in humans and animals that is involved with many functions, including movement, memory, pleasurable reward, behaviour and cognition and attention. It is found in some plants.

Downy mildew—a group of lower fungus (algae that evolved to look like fungi), that parasitize plants, infecting leaves, stems and seeds; they highly host specific.

Endosperm—a part of the seed that is a food store for the developing embryo.

Entomology—the branch of zoology concerned with the study of insects.

Epinephrine—a hormone, neurotransmitter and medication also known as adrenalin.

Favism—a genetic deficiency of glucose-6-phosphate dehydrogenase that causes a predisposition to haemolysis (spontaneous destruction of red blood cells), resulting in jaundice.

Folate—Vitamin B9, also called folic acid in another form.

Fumonisin—belonging to a group of mycotoxins produced by several species of *Fusarium* moulds, which occur mainly on maize, wheat and other cereals.

***Fusarium oxysporum f.sp.* *cubense*—**a fungal plant pathogen that causes Panama wilt disease in bananas, a disease that killed hundreds of millions of banana trees between the 1950's and 1970's. A new strain, TR4, is now spreading worldwide and kills previously resistant bananas of the cultivar Cavendish.

Fusarium root rot—root disease affecting legumes, caused by the fungus *Fusarium solani* f.sp. *phaseoli*.

Fusarium wilt—a wilt disease caused by fungus in the genus *Fusarium*.

Gene complex—a tightly linked group of genes.

Gene Migration—in population genetics, gene migration is the transfer of alleles or genes from one population to another.

Genetics—the study of genes, genetic variation and heredity in living organisms.

Genetic drift—variation in the relative frequency of genotypes in a small population, owing to the chance of disappearance of particular genes, with the death or disappearance of key individuals.

Genetic marker—a gene or short sequence of DNA used to identify a chromosome or to locate other genes on a genetic map. These can be used to select progeny where an important trait is linked to a specific gene.

Genetically modified organism (GMO)—an organism into which novel genes are introduced; with plants this is typically from other plants, but also from bacteria, fungi, or even animals.

Genotype—the part (DNA sequence) of the genetic makeup of a cell that determines a specific characteristic (phenotype) of a cell, organism or individual.

Germplasm—living genetic resources such as seeds or tissues that are maintained for the purpose of plant and animal breeding, preservation and other uses.

Glucoside—a glycoside that is derived from glucose. A glycoside is a compound formed from a simple sugar and another compound by replacement of a hydroxyl group in the sugar molecule.

Glycemic index—a value assigned to foods based on how slowly or quickly they cause increases in blood glucose levels, which especially important to diabetics.

Maize gray leaf spot—a foliar disease affecting maize, caused by two fungi, *Cercospora zeae-maydis* and *Cercospora zeina*.

Gray leaf spot of rye grass—a leaf and stem disease caused by *Pyricularia grisea* that has recently started to attack wheat; it is closely related to blast disease of rice, caused by *Pyricularia oryzae*.

Groundnut rosette disease—a disease affecting groundnut caused by a complex of three agents, groundnut rosette virus (GRV), and an associated satellite RNA and a helper virus, groundnut rosette assistor virus (GRAV). It is transmitted via insect vectors such as the groundnut aphid (*Aphis craccivora*).

Haploid—cell or nucleus having a single set of chromosomes.

Haemolysis—the rupture or destruction of red blood cells.

Herbaceous—plants that have no woody stem above ground.

Hermaphroditic—an organism in which reproductive organs of both sexes are present.

Homozygous—having identical pairs of alleles of a gene.

Hunger Gap—a term referring to the time faced by small-scale farmers in Africa, when the stored grain from the previous harvest is finished or starting to spoil, and the next grain crops are not yet ready to harvest.

Hybrid—the offspring of two parents. In plant breeding a hybrid is a product of crossing of two or more unrelated parents to create a progeny that expresses high performance through hybrid vigour or heterosis.

Hybrid vigour (heterosis)—the improved or increased function of any biological quality in a hybrid offspring.

Inbred line—a parent plant developed through continuous selfing where it's all alleleles are almost same.

Inflorescence—the complete flower head of a plant including stems, stalks, bracts and flowers.

Injera—an East African flatbread made with a sourdough starter, traditionally from tef flour.

Isoflavones—a class of phytoestrogens or plant-derived compounds with estrogenic activity, e.g., extracted from soybean.

Isoleucine—an amino acid.

Late blight—a plant disease affecting potatoes, caused by the pathogen *Phytophthora infestans*, that caused the Irish potato famine of 1845 to 1852 that killed at least 1 million people in Ireland and a similar number in Germany and Poland. It affects potatoes across Africa.

Landrace—a group of plants of a crop species or animal breed that has been developed through traditional farming practices for many years in a particular place, without intervention from modern agricultural science. Generally these are well adapted to their local environment, have lots of quality traits that farmers want, but may have low yields.

Laws of inheritance—developed by Gregor Mendel, who determined that genes come in pairs and are inherited as distinct units, one from each parent.

Leach—to remove or be removed from a substrate by a percolating liquid; prolonged heavy rainfall will leach important minerals from soils.

Leaf blight—any disease causing a browning and falling of the leaves of a plant.

Leucine—an amino acid.

Linoleic—an essential fatty acid, which humans cannot make, and have to consume from food crops.

Linolenic—the second essential fatty acid that humans have to consume.

Lodging—bending of the stalk of a plant or the entire plant onto the ground, causing crop loss.

Lysine—an amino acid that is deficient in most African cereals, including maize and sorghum.

Maize streak virus—a virus that belongs to the genus *Mastrevirus* in the family *Geminiviridae*, which causes a plant disease called maize streak disease (MSD) in its host. It is transmitted by insect vectors, especially leaf hoppers.

Marker-assisted selection—an indirect selection process where a trait of interest is selected based on the presence or absence of a marker (morphological, biochemical or DNA/RNA) that is linked to an important trait.

Molybdenum (Mo)—an important micronutrient for plants but is deficient in many African soils.

Molecular marker—a fragment of DNA that is associated with a certain location within the genome.

Mendelian—following the laws of inheritance originally proposed by Gregor Mendel.

Methionine—an essential amino acid that is deficient in some African cereals such as sorghum.

Monoammonium phosphate (MAP)—a widely used source of phosphorus and nitrogen, that also acidifies the soil.

Mutation—is a genetic change associated with the alteration of single base units of DNA, or the deletion, insertion or rearrangement of larger sections of genes or chromosomes, resulting in a variant form of the organism, that may be transmitted to subsequent generations.

Mutagenesis—it is the use of physical agents such as UV light, radioactivity or chemicals to induce mutations in a crop, after which the progeny are screened for a particular trait of interest, such as herbicide resistance or short or tall plant height.

Mycotoxin—a toxic secondary metabolite produced by some fungi (also called moulds), that is capable of causing disease and death in humans and animals.

Near-infrared spectroscopy (NIRs)—a method of examining the interaction between matter and electromagnetic radiation that uses the near-infrared region of the electromagnetic spectrum; it is used to measure a wide range of organic and inorganic molecules rapidly and non-destructively.

Nematode—a worm of the large phylum Nematoda, such as a roundworm or threadworm; in plants they are known as eelworms, and typically attack the roots causing lesions or galls (rootknots); they cause losses of billions of dollars in crop yields annually.

Niacin—a member of the Vitamin B complex, commonly known as nicotinic acid. Low levels in maize result in a disease called pellagra in people largely eating maize.

Nor-epinephrine—a hormone that is released by the adrenal medulla and the sympathetic nerves, and functions as a neurotransmitter.

Oleic acid—an unsaturated fatty acid.

Palmitic acid—a waxy crystalline saturated fatty acid.

Participatory plant breeding—an approach to plant breeding where farmers are involved in the process, making selection decisions at various stages during cultivar development.

Participatory Rural Appraisal—is a multidisciplinary research tool used by non-governmental organisations and other development agencies and researchers, where the knowledge and opinions of rural people are systematically collected, and then used as the basis for the planning and management of development programmes and projects, including plant breeding programmes.

Perennial plant—a plant that lives for longer than two years.

Phenotype—is the external appearance of individuals of a crop species. Phenotype is the outcome of the genes, the environment and their interaction determining the overall performance of a crop.

Phenylalanine—an amino acid.

Phytic acid—a saturated cyclic acid that is the principal storage form of phosphorus and minerals in the seeds of many plants. Upon germination, the seedling initially draws upon these minerals. It is also referred to as an 'anti-nutrient' because it impairs the absorption of iron, zinc and calcium in the gut on monogastric animals such as humans, pigs and chickens.

Plant breeding—is the art and science of developing new cultivars with improved genetic constitution to serve diverse human needs.

Plant pathology—the study of the organisms and environmental conditions that cause disease in plants.

Pollination—the transfer of pollen to a stigma, ovule, flower or plant to allow fertilisation.

Polygenic trait—this is a trait that is governed by many additive genes that each produce a small quantitative effect that combine to produce the expressed trait; e.g., drought tolerance, quantitative disease resistance, crop yield.

Prolamine—any of the class of simple proteins, such as gliadin, hordein or zein, found in grains

Proteomics—the study of the proteins of target organisms. In Plant Breeding proteomics is used to find quantitative protein markers for polygenic, quantitative traits as alternatives to DNA markers, especially for induced traits.

Proteome—a set of proteins produced in an organism, system, or biological context.

Protozoa—a diverse group of unicellular organisms.

Pyridoxine—a colourless, weakly basic solid found mainly in cereals, liver oils and yeast. It belongs to the Vitamin B6 group and is important in the metabolism of unsaturated fatty acids.

Quantitative—relating to or expression of quantity rather than quality; e.g., the amount of beta-carotene expressed in an orange sweet potato.

Quality Protein Maize—a mutant maize that contains nearly double the normal levels of lysine and tryptophan found in normal maize. These are amino acids that are essential for humans and monogastric animals. The trait has been bred into some maize cultivars.

Recessive allele—an allele that is phenotypically expressed only when both alleles are recessive (the homozygous state); its expression is masked when the other allele is dominant (the heterozygous state).

Recurrent selection—selecting for certain traits within a plant population, then crossing the selected plants with each other to create the next population, generation after generation, so as to create superior parents from the population. The best individuals in each subsequent population can then be selfed to create superior pure line cultivars, or inbred lines for hybrid production.

Rice yellow mottle virus—a plant pathogenic virus belonging to the genus Sobemovirus that often causes losses of 50-100% in rice crops in West Africa. It is vectored by at least 40 insect species.

***Rhizobium leguminosarum*—**a bacterium that lives in a symbiotic relationship with legumes, and has the ability to fix nitrogen from the air.

Riboflavin—antioxidant that is also known as Vitamin B2

Rust—plant diseases caused by pathogenic fungi of the order Pucciniales, typically causing rusty orange pustules on plant leaves.

Self-pollination—some crops, e.g., wheat, rice and beans, have flowers in which the pollen is produced next to the female stigma, so the plant fertilizes itself.

Selfing—this is a deliberate process of managed self-pollination, even in a naturally cross-pollinating crop such as maize. This is done to create homozygous inbred lines prior to the production of hybrids.

Shattering—the early release of seeds from seed heads or pods, as soon as they are ripe. It is undesirable in crops, and the genes for shattering need to be eliminated to stop seed falling on the ground before harvest.

Silk—shiny, thread-like fibres that grow as part of the ears of maize, which are elongated styles or female receptive parts, of the maize flower.

Soft skills—a combination of interpersonal skills including people skills, social skills, attitudes and emotional intelligence.

Spot blotch disease—a leaf, stem and head disease affecting wheat and other cereals, caused by *Cochliobolus sativus*.

Stalk borers—the larvae of several species of moths (*Chilo partellus, Sesamia calamistis* and *Busseola fusca*) burrow into the stem of maize, sorghum, rice and millet, causing severe crop losses across Africa.

Stigma—the sticky tip of a flower pistil on which pollen is deposited at the beginning of pollination

Striga—a genus of parasitic plants that occur naturally in Africa, Asia and Australia, commonly called witchweed. Two species attack cereals in Africa and cause severe crop losses; another species attacks cowpea.

Symbiotic—an interaction between two organisms living in close physical association that is beneficial to both partners.

Tetraploid—plants containing four sets of chromosomes, because the crop's chromosomes were doubled, spontaneously or artificially. Tetraploid plants are often stronger and yield much more than their diploid progenitors.

Thiamine—Vitamin B1, which is essential to human health.

Threonine—an essential amino acid for humans.

Trait—a genetically determined characteristic expressed in the phenotype.

Triploid—plants that have having three sets of chromosomes; triploid plants are sterile but are propagated vegetatively from suckers; e.g., most edible banana varieties.

***Trichoderma*—**a genus of fungi present in all soils that has been widely used as a biological control agent to control root diseases.

Tryptophan—an amino acid that is deficient in maize and sorghum..

Valine—an amino acid

Variety—a plant group within a single botanical taxon, of the lowest rank.

Vicine—a toxic glucoside found in fava beans, which causes the disease favism.

Waterlogging—the saturation of soil with water, excluding oxygen, causing root death.

Wheat rust—three species of rust fungi infect wheat, causing stem rust (Puccinia graminis f.sp. *tritici*), leaf rust (*Puccinia triticina*) and stripe rust (*Puccinia striiformis* f.sp. *tritici*). Wheat rust can cause complete crop loss in susceptible varieties.

PhD GRADUATE BREEDING PROJECTS

Crop	Trait/problem	Country	Student	Funder	Thesis topic
Sweet potato	B-carotene High dry matter	Zambia	Martin Chiona	Rockefeller	Enhancement of B-carotene in high dry matter, local sweet potato varieties in Zambia.
	Yield Alternaria leaf petiole and stem blight	Uganda	Godfrey Sserwu	AGRA	Breeding sweet potato for root yield and resistance to Alternaria leaf petiole and stem blight in Uganda
	Drought Weevils	Kenya	Benjamin Kivuva	AGRA	Breeding sweet potato for drought and weevil tolerance in Kenya
	Dry matter quality Enhanced B-carotene	Ethiopia	Fekadu Balcha	AGRA	Improving dry matter and beta carotene content of orange fleshed sweet potato clones in Ethiopia
	SPVD Wide adaptability	Tanzania	Stephan Ngailo	AGRA	Breeding sweet potato for SPVD resistance and wide adaptability in Tanzania.
	Drought High dry matter	Rwanda	Placide Rukundo	AGRA	Development of drought tolerant and high dry matter content sweet potato variety in Rwanda

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Irish potato	Bacterial wilt	Kenya	Jane Muthoni	AGRA	Developing potato lines resistant to bacterial wilt for the Kenyan highlands.
	Yield Late blight	Rwanda	Jean Baptiste	AGRA	Developing potato lines for high yield and resistance to potato late blight in Rwanda
	Drought Late blight	Ethiopia	Hirut Betaw	AGRA	Genetic analyses of drought tolerance and resistance to late blight among potato genotypes

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Cassava	Early maturing Drought	Kenya	Joseph Kamau	Rockefeller	Participatory-based development of early bulking cassava varieties for the semi-arid areas of eastern Kenya
	Brown streak disease	Kenya	Theresia Munga	Rockefeller	Breeding cassava for cassava brown streak disease resistance
	High dry matter and starch	Tanzania	Kiddo Mtunda	Rockefeller	Breeding of cassava for high root quality (dry matter and starch) for farmers and different market end uses
	Early maturing Cassava mosaic disease	Zambia	Patrick Chikoti	AGRA	Breeding cassava for earliness and resistance to cassava mosaic disease (CMD) in Zambia
	Soil pH, moisture Cold	Zambia	Able Chalwe	AGRA	Inheritance of cyanogenic potential in cassava and its relationship to soil pH, moisture, and cold stresses
	Cassava brown streak disease Early storage root bulking	Malawi	Michael Chipeta	AGRA	Identification and development of cassava brown streak disease resistant and early storage root bulking varieties in Malawi

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	Carotenoids content Delayed post-harvest deterioration	Rwanda	Athanase Nduwumur-emyi	AGRA	Participatory cassava breeding for improved total carotenoids content and delayed postharvest physiological deterioration in Rwanda
Cassava	Early maturing Yield	Uganda	Robooni Tumuhimbise	AGRA	Breeding cassava for early bulking and improved yield in Uganda
	Breeding approaches	Kenya	Vincent Woyengo	AGRA	Cassava breeding through complementary conventional and participatory aApproaches in western Kenya

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Maize	*Striga*	Kenya	Vincent Woyengo	AGRA	Development of maize varieties resistant to *Striga* for mid-late altitude ecologies of Kenya
	Maize streak virus	Uganda	Grace Abalo	Rockefeller	A comparative analysis of conventional and marker assisted selection methods in screening for resistance to maize (streak virus disease
	Drought Gray leaf spot	Zimbabwe	John Derera	Rockefeller	Genetic effects and associations between grain yield potential, stress tolerance and yield stability in southern African maize
	Gray leaf spot	Kenya	Phillip Kwena	Rockefeller	Identification of sources of resistance and inheritance of gray leaf spot in Kenyan maize germplasm
	Drought	Kenya	Phillip Leley	Rockefeller	Identification of heterotic groups and development of drought resistance in maize populations grown in the semi-arid areas of Kenya
	Low nitrogen Drought	Zambia	Francisco Miti	Rockefeller	Breeding of maize landraces for tolerance to low nitrogen and drought in Zambia.
	Protein quality Gray leaf spot Maize streak virus DM	Mozambique	David Mariote	Rockefeller	Breeding for Quality Protein Maize (QPM), resistant to GLS, DM and MSV
	Protein quality	Zimbabwe	Lewis Machida	Rockefeller	Genetic analysis of endosperm modification in Quality Protein Maize (QPM) varieties in the smallholder sector in Zimbabwe
	Ear & kernel rots	Zambia	Mweshi Mukanga	Rockefeller	Genetic improvement of host plant resistance to ear and kernel rots in Zambian maize populations.
	Gray Leaf Spot	Zimbabwe	Julia Sibiya	Rockefeller	Breeding maize for resistance to Phaeosphaeria leaf spot disease.
	Protein quality	South Africa	Roobavathie Naidoo	Rockefeller	Genetic studies on early vigour in low phytic acid, QPM and tropical inbred lines of maize
	Drought Maize downy mildew	Mozambique	Pedro Fato	Rockefeller	Genetic improvement of maize for drought tolerance and resistance to maize downy mildew in lowland areas of Mozambique
	Nematodes	Uganda	Frank Kagoda	Rockefeller	Genetic analysis of resistance to nematodes in maize
	Early maturing Stay-green Dry grain	Tanzania	Arnold Mushongi	Rockefeller	Breeding early maturing maize cultivars incorporating stay-green and grain dry-down characteristics in intermediate maize
	Northern corn leaf blight	Tanzania	Tulole Bucheyeki	AGRA	Breeding for resistance to northern corn leaf blight in maize for western Tanzania
	Early maturing Drought	Uganda	Charles Lwanga Kasozi	AGRA	Breeding for earliness and drought tolerance in Uganda maize germplasm.
	Maize streak virus	Kenya	Lilian Gichuru	AGRA	Genetic diversity in elite maize germplasm and sources for improving maize streak virus resistance in Kenyan hybrids

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Maize	Stem borer	Kenya	Mwimali Murenga	AGRA	Genetics of resistance to stem borers in Kenyan maize germplasm and the application of SNP markers for selection
	Protein quality	Ethiopia	Demmissew Ababulgu	AGRA	Genetic diversity and combining ability of selected quality protein maize (QPM) inbred lines adapted to the highland agroecology of Ethiopia
	Drought	Malawi	Macpherson Matawele	AGRA	Identification, evaluation and development of high yielding drought tolerant maize germplasm for low rainfall and drought prone areas in Malawi
	Yield Maize streak virus	Tanzania	Lameck Nyaligwa	AGRA	Genetic analysis and relationship between grain yield and resistance to maize streak virus disease among maize genotypes
	Heat Drought	Mozambique	Pedro Chauque	AGRA	Maize breeding for combined heat and drought tolerance in Mozambique
	Stem borer Post-harvest insects	Kenya	Regina Tende	AGRA	Monitoring genetic variance in combined stem borer and post harvest insect resistance in early maturing maize populations
	Heterotic grouping, gene action and genotype x environment interactions	Rwanda	Alphonse Nyombayire	AGRA	A study of heterotic grouping, gene action and genotype x environment interactions of mid-altitude and highland maize inbred lines in Rwanda
	Quality Vitamin A	South Africa	Kirthee Pillay	Other	Nutritional quality and consumer acceptability of provitamin A-biofortified maize
	Mycotoxin resistance	South Africa	Bogaleng Milcah Masemola	Other	Phenotypic characterization of mycotoxins resistant maize inbred families and regional hybrids under *Aspergillus flavus* and *Fusarium verticillioides* infestation
	Maize streak virus Downy mildew	South Africa	Isack Mathews	Other	Combining ability, genetic gains and path coefficient analyses of maize hybrids developed from maize streak virus and downey mildew resistant recombinant inbred lines
	Vitamin A Quality protein	South Africa	Lindokuhle Phakathi	Other	Genetic characterization of pro-vitamin A and quality protein maize inbred lines and their derived hybrids
	Northern corn leaf blight Yield	Ethiopia	Wenda Mengesha	AGRA	Breeding maize for the Northern corn leaf blight resistance (NCLB) and yield improvement in Ethiopia
	Biofertilizers	South Africa	Bongani Petros Kubheka	Other	Integrating microdosing of fertilizers with biological control agents for maize production in the Eastern Cape, South Africa
Maize, wheat	Growth promotion Damping-off fungi	South Africa	R.R.N Otanga	Other	Evaluation of selected free-living diazotrophic bacteria for plant growth promotion and biological control of damping-off fungi
Wheat	Stem rust	Ethiopia	Netsanet Hei	AGRA	Genetic analysis of stem rust among Ethiopian grown wheat lines
	Heat	Zambia	Batiseba Tembo	AGRA	Development of high yielding wheat genotypes tolerance of heat for irrigated conditions in Zambia
	Stripe rust	Ethiopia	Hirut Getinet	AGRA	Breeding wheat for resistance to stripe rust in Ethiopia

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Wheat	Stem rust	South Africa	Sandiswa Figlan	Other	Molecular characterization of new sources of adult plant resistance to stem rust in wheat
	Drought	Zimbabwe	Learnmore Mwadzingeni	Other	Genetic analysis of wheat for drought tolerance
Rice	Salinity Water stress	Nigeria	Andrew Efisue	Rockefeller	Comparative genetic studies of rice (Oryza sativa L) genotypes under salinity and water stress
	Genetic diversity?	Malawi	Tenyson Mzengeza	Rockefeller	Genetic studies of rice landraces in Malawi
	Drought Grain shattering	Uganda	Jimmy Lamo	Rockefeller	Genetics of drought tolerance and grain shattering of rice landraces in Uganda
	Salinity	Tanzania	Sophia Kashenge-Killenga	Rockefeller	Participatory breeding of rice for salt tolerance in Tanzania
	Salinity Water stress	Kenya	Ruth Musila	AGRA	Comparative genetic studies of rice genotypes under salinity and water stress
	Striga Nitrogen deficiency	Uganda	Mary Asio	AGRA	Genetic studies of upland rice most resistance to *Striga* (spermonthica and Asiatical) and nitrogen deficiency tolerance in Uganda
	Drought Soil phosphorus Nitrogen tolerance	Kenya	John Kimani	Rockefeller	Inheritance of drought, low soil phosphorus, and nitrogen tolerance in development of popular upland rice for medium potential areas of Kenya
	Genetic diversity Rice yellow mottle virus	Niger	Mounirou El-Hassimi Sow	Other	Genetic diversity of Oryza species in Niger; screening and breeding for resistance to Rice yellow mottle virus (RYMV)
	African Rice Gall Midge	Côte d'Ivoire	Kouadio Nasser Yao	Other	A genetic study of resistance to African Rice Gall Midge in West African rice cultivars
	Sheath rot	Rwanda	Simon Martin Mvuyekure	AGRA	Increasing the resilience of elite rice cultivars to Sheath rot in Rwanda through breeding for resistance
	Blast Drought	Liberia	Quaqua Mulbah	Other	Integrating genetic resistance with biocontrol against rice blast and drought
	Diversity Rice yellow mottle virus	Burkina Faso	Honoré Kam	Other	A study of the diversity of Burkina Faso rice landraces and identification of source of resistance to Rice yellow mottle virus (RYMV)
Sorghum	Water and population density stress	Kenya	Clement Karari	Rockefeller	Characterisation of sorghum parental lines and prediction of their hybrid performance under simulated water and population density stress
	Striga Herbicide tolerance	Kenya	David Ngung'u	Rockefeller	Mutation breeding of sorgum for tolerance to a *sulfonylurea* herbicide for protection against *Striga hermonthica* (Del.) Benth.
	Yield Drought	Zimbabwe	Itai Makanda	Rockefeller	Development of high-yielding drought-tolerant sorghum hybrid cultivars with stay-green for small-scale farmers in Zimbabwe
	Striga	Uganda	John Robert Olupot	AGRA	Breeding sorghum for multiple resistance to *Striga hermonthica* in Uganda

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Sorghum	*Striga* Drought	Ethiopia	Amele Assefa	AGRA	Breeding for *Striga* and drought resistance tolerance on sorghum for the South Eastern part of Ethiopia
	Striga	Ethiopia	Rebeka Teshome	AGRA	Intergrating sorghum breeding and biological control using fusaruim oxysporum against *Striga hermonthica* in Ethiopia
	Yield Quality	South Africa	Alina Muedi	AGRA	Genetic analysis among South African sorghum collection for improved yield and quality
	Quality Quantity	Burkina Faso	Pále Siébou	Other	Quantitative and qualitative studies on grain sorghum for traditional beer (dolo) production in Burkina Faso
Finger millet	Genetic improvement	Kenya	Chrispus Oduori	Rockefeller	Genetic improvement of finger millet
	Blast resistance Yield	East Africa	Eric Okuku Manyasa	Other	A study of the diversity, adaptation and gene effects for blast resistance and yield traits in East African finger millet landraces
	Drought Blast	Uganda	Lawrence Owere	AGRA	Genetics studies of drought tolerance and blast disease resistance in finger millet
Pearl millet	Yield Drought Disease	Uganda	Geoffrey Lubadde	AGRA	Breeding high yielding drought tolerant and disease resistant local pearl millet germplasm for Northern Uganda
Tef	Aluminium toxicity	Ethiopia	Ermias Desta	AGRA	Analysis of genetic variability in tef for aluminium toxicity tolerance and other important agronomic traits
	Drought	Ethiopia	Mizan Abraha	Other	Breeding tef for drought tolerance in Northern Ethiopia
Common bean	Bruchid	Malawi	Geoffrey Kananji	Rockefeller	Study of bruchid resistance and its inheritance in Malawian dry bean germplasm
	Anthracnose	Uganda	Stanley Nkalubo	Rockefeller	Study of anthracnose resistance and its inheritance in Ugandan dry bean germplasm
	Large seed size Fusarium root rot	Uganda	Clare Mukankusi	Rockefeller	Breeding beans for resistance to Fusarium root rot and large seed size in Uganda
	Bean fly Yield	Kenya	Pascal Ojwang'	Rockefeller	Genetics of resistance to bean fly, and seed yield in common bean under semi-arid conditions
	Drought Heat	Zambia	Nathan Phiri	AGRA	Genetic analysis of common bean genotypes for tolerance to drought and heat stress in Zambia
	Angular leaf spot	Kenya	Beatrice Ng'ayu-Wanjau	AGRA	Breeding for durable resistance to angular leaf spot in common bean in Kenya
	Angular leaf spot disease	Tanzania	Rose Mongi	Other	Breeding for resistance against angular leaf spot disease of common bean in the southern highlands of Tanzania
	Ascochyta blight	Rwanda	Clement Urinzweni-mana	AGRA	Breeding for ascochyta blight resistance of the common bean in Rwanda

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Cowpea	Mosaic virus	Uganda	Martin Orawu	Rockefeller	Improvement of resistance in local cowpea aphid-borne mosaic virus in Uganda
	Yield Striga Drought	Burkino Faso	Jean Baptiste Tignegre	Rockefeller	Development of high yielding and Striga-resistant cowpea lines for semi-arid areas of Burkina Faso
	Drought High sulphur	Mozambique	Rogerio Chiulele	Rockefeller	Genetic improvement of cowpea for drought tolerance and high sulphur-containing amino acids
	Yield Pests Drought	Namibia	Lydia Ndinelao Horn	Other	Development of cowpea germplasm for improved yield, pest and drought tolerance using gamma irradiation in Namibia
Pigeon pea	Fusarium wilt	Malawi	Albert Changaya Banda	Rockefeller	Development of pigeonpea varieties for resistance to Fusarium wilt in Malawi
	Fusarium wilt	Tanzania	Didas Kimaro	AGRA	Genetic improvement of pigeonpea for Fusarium wilt resistance in Tanzania
	Seed quality	Kenya	Margaret Makelo	AGRA	Breeding pigeon peas for improved seed quality traits
Soybean	P tolerance	Ethiopia	Abush Tesfaye Abebe	AGRA	Inheritance of low P tolerance in soybeans
	Soybean rust	Kenya	Susan Wanderi	AGRA	Genetic analyses for resistance to soybean rust and yield stability among soybean genotypes in Kenya
	Breeding gains Diversity Inheritance	Zimbabwe	Hapson Mushoriwa	Other	Breeding gains, diversity analysis and inheritance studies
Groundnut	Early maturing Aflatoxin	Mozambique	Amade Muitia	AGRA	Development of early-maturing groundnut populations with enhanced levels of resistance to aflatoxin contamination
	Foliar disease	Malawi	Justus Chintu	AGRA	Breeding groundnuts for resistance for foliar disease
Bambara ground nut	Pre-breeding	Nigeria	Mohammed Sagir Mohammed	Other	Pre-breeding of Bambara groundnut
Faba bean	Chocolate spot disease Yield	Ethiopia	Asnakech Beyene	AGRA	Genetic analysis and characterizaton of faba bean genotypes for resistance to chocolate spot disease, grain yield and yield components in Ethiopia
Eucalyptus Nitens (Deanne and Maiden) Maiden	Breeding strategy	South Africa	Tammy-Lyn Swain	Other	Development of an advanced breeding strategy for Eucalyptus Nitens (Deanne and Maiden) Maiden

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Sunflower	Moisture conditions	South Africa	Godfree Chigeza	Other	Genetic gain, advanced cycle pedigree breeding and correlated response to selection under varying moisture conditions in sunflower
	Genetic diversity	South Africa?	Tertia Elizabeth Erasmus	Other	Genetic diversity of proprietary inbred lines of sunflower, determined by mapped SSR markers and total protein analysis
Banana	Quality	Uganda	Alex Barekye	AGRA	Towards producing acceptable triploid bananas by improving diploid and tetraploid populations to *Mycosphaerella fijiensis* Morelet resistance through recurrent selection procedures
Yams	Genetic diversity, classification and evaluation	Ethiopia	Tewodros Mulualem	Other	Genetic diversity, path coefficient analysis, classification and evaluation of yams in southwest Ethiopia
Bottle gourd	Genetic diversity	South Africa	Jacob Mashilo	Other	Genetic diversity within and between bottle gourd germplasm of South Africa
Various	Biofertilizers	South Africa?	Medhin Hadish Kifle	Other	Evaluation of diazotrophic bacteria as biofertilizers

MASTERS BREEDING PROJECTS

Crop	Trait/problem	Country	Student	Funder	Thesis topic
Sweet potato	Drought Vitamin A	Mozambique	Jose Ricardo	Other	Screening sweetpotato for drought tolerance and high ß-carotene content in Mozambique
Maize	Vitamin A	South Africa	Laurencia Govender	NRF	Nutritional composition and acceptance of a complimentary food made with provitamin A-biofortified maize
	Disease resistance Aflatoxins Fumonisins	Zimbabwean but research at UKZN	Nyashadzashe Chiuraise	CIMMYT CRP	Introgression of aflatoxin and fumonisin contamination resistance genes in maize hybrids
	Green maize	South Africa	Fikile Nozipho Pricilla Qwabe	NRF	Breeding investigations for development of specialty green maize hybrids
	Yield	Zimbabwean but research in South Africa	Tatenda Rambi Musimwa	CIMMYT CRP	Why SR52 is such a great maize hybrid
	Gene analysis	Zimbabwean but research in South Africa	Lorraine Mhoswa	GCP NRF	Heterosis, genetic distance and path coefficient analysis in dent, flint and popcorn hybrids
	Agronomic Quality	South Africa	Collinet Phumelele Jele	NRF KZN-DAEA	Genetic analysis of agronomic and quality traits in popcorn hybrids
	Genetic diversity Superiority Combining ability	South Africa	Suzan Khoza	GCP NRF	Assessment of maize germplasm lines for genetic diversity, cultivar superiority and combining ability
	Genetic variation and associations	South Africa	Mxolisi Percival Sibongeleni Sithole	UKZN SeedCo	Genetic variation and associations among adaptive traits in a recombinant maize inbred line population
	To be confirmed	Malawi	Josia Chimwemwe	AGRA	To be confirmed
	Tester suitability	Tanzania	Barnaba Makavu	AGRA	Evaluation and Identification of single-cross maize hybrids for use in tester development
	Maize Streak Virus	Mozambique	Sheila Juma	AGRA	Combining ability of maize Inbred lines for grain yield and resistance to maize streak virus
	Early maturity	South Africa	Sanelisiwe Mzobe	AGRA	Phenotypic and genotypic characterisation of F4 families derived from a temperature X tropical maize population
	Genetic analysis, disease resistance	South Africa	Mathew Izack	GCP	Combining ability, genetic gains and path coefficient analyses of maize hybrids developed from maize streak virus and downy mildew resistant recombinant inbred lines
	Protein Vitamin A	Zimbabwe	Patience Kumbula	AGRA	Combining ability between quality Protein and pro-vitamin-A maize lines

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Maize or Irish Potato	To be confirmed	South Africa	Simphiwe Mnomiya	AGRA	To be confirmed
Maize or sorghum	To be confirmed	Tanzania	Zawadi Mwaikonyole	AGRA	To be confirmed
Wheat	Herbicide resistance	Zimbabwe	Vince N Ndou	NRF	Chemical mutagenesis of wheat for herbicide resistance
	Disease resistance	South Africa	Cwengile Dweba	ARC NRF	Molecular mapping of disease resistance genes in wheat
Rice	To be confirmed	Mozambique	Viriato Cossa	AGRA	To be confirmed
	Bacterial leaf blight	Tanzania	Claudia Tesha	AGRA	Evaluation of rice genotypes for resistance against bacterial leaf blight (BLB) in Tanzania
Sorghum	Gene flow	South Africa	Nico Mailula	Other	Determination of the rate and distance of pollen-mediated gene flow in sorghum in Limpopo province
	NIR analysis, Nutrition Agronomic performance	South Africa	Evan Michael Brauteseth	NRF	The mutagenesis of sorghum towards improved nutrition and agronomic performance
	To be confirmed	Malawi	Ruth Magaleta	AGRA	To be confirmed
	To be confirmed	South Africa	Nokwethaba Biyela	AGRA	To be confirmed
	Yield	Zambia	Sombo Chinyama	AGRA	Assessment of sweet sorghum lines for genetic diversity and cultivar superiority using phenotypic traits and SSR markers
	To be confirmed	Tanzania	Awadhi Mashombo	AGRA	Evaluation of advanced sorghum lines for use as possible parents in breeding for bio-ethanol production
	Multiple stress Seed production	South Africa	Lucia Ndlala	AGRA	An evaluation of maize inbred/doubles haploid lines for combining ability for multiple-stress tolerance and seed production.
	Genetic profile	Malawi	Mcdonald Nundwe	AGRA	Characterisation of sweet sorghum germplasm based on agro-morphological traits, molecular markers and juice related traits
Common bean	Common bacterial blight	Malawi	Wilson Nkhata	AGRA	Study of yield stability and breeding for common bacterial blight resistance in South African dry bean germplasm
	Angular leaf spot	Zimbabwe	Josephine Pasipanodya	AGRA	A study of angular leaf spot resistance in southern African germplasm
	Mechanised harvesting	Zambia	Mwiinga Mulube	AGRA	A genetic study of upright plant architecture and evaluation of its related traits suitable for mechanised harvesting in dry bean
Cowpea	Drought tolerance	South Africa	Jacob Mashilo	UKZN NRF	Response of dual-purpose cowpea landraces to water stress
	To be confirmed	Mozambique	Venancio Salegua	AGRA	To be confirmed

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Cowpea	To be confirmed	Tanzania	Agnes Woiso	AGRA	To be confirmed
	Yield Quality	Tanzania	Goodluck Douglas Ringo	AGRA	Characterization of cowpea accessions based on agro-morphological traits, nutritional quality traits and molecular markers
Soybean	Agronomic traits Nodule formation	South Africa	TG Magagane	Other	Genotype by environment interaction among soybean germplasm for agronomic traits and nodule formation
	Yield Nodulation	South Africa	Shiksha Jadoo	NRF	Performance of soybean genotypes for yield and nodulation formation under *Trichoderma* and silicon applications
	Agronomic performance	South Africa at Cedara Research Institute	Arthur James Arathoon	KZN-DAEA	Agronomic studies on edamame (vegetable soybean) in KwaZulu-Natal
	Stem rot	South Africa	Dael Desiree Visser	Oil Seeds Trust	Studies on Sclerotinia stem rot on soybeans
	To be confirmed	South Africa	Nomathemba Majola	AGRA	To be confirmed
	To be confirmed	Zambia	Bubala Mwiinga	AGRA	To be confirmed
	Yield stability Genetic gain Path coefficient analysis	Zambia	Mwiila Chibanda	AGRA	Grain yield stability, genetic gain and path coefficient analysis in advanced soybean lines
	Genotype x environment interaction	Malawi	Bertha Kachala	AGRA	Genotype X environment interaction and stability
	Genetic variability Phosphorus use	Mozambique	Joao Antonia Pedro	AGRA	Genetic variability and low phosphorus use efficient in soybean
Groundnut	To be confirmed	Mozambique	Nelson Mubai	AGRA	To be confirmed
	Groundnut Rosette Virus	Zambia	Lutangu Makweti	AGRA	Evaluation of the performance of elite groundnut lines and their resistance to groundnut rosette virus
	Aflatoxins Quality	Malawi	Olivia Chipeta	AGRA	Parent-offspring regression analysis of groundnut populations based on aflatoxin accumulation and quality traits
	Drought	Tanzania	Masoud Salehe	AGRA	Genetic analysis of intermittent and terminal drought in segregating population of groundnut in Malawi
Timber crops	Growth	South Africa	Christopher Komakech Otim	ICFR	Investigation of growth potential of alternative eucalyptus species for mid and high altitude sites in the summer rainfall region in South Africa
	Growth Wood density Yield	South Africa	Francois van Deventer	Mondi	A quantitative study on growth, basic wood density and pulp yield in a breeding population of *Eucalyptus urophylla* S.T. Blake, grown in KwaZulu-Natal
	Rooting	South Africa	Nuveshen Naidoo	CSIR	Genetic and environmental factors affecting rooting in *Eucalyptus grandis* X *Eucalyptus longirostrata* hybrid cuttings

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Timber crops	Growth parameters, NIR analysis	South Africa	Zama TL Ndlovu	NCT	Breeding of advanced generation of Eucalyptus macarthurii – growth parameters and development of a near infrared (NIR) calibration model to predict whole tree pulp yield using non destructive cores
Yams	Diversity	Sierra Leone, in South Africa	Prince Emmanuel Norman	FARA, AfDB	Morphological and cytological diversity of some yams in Sierra Leone
Tomato	Yield	South Africa	KG Maleka	Other	Determination of yield and yield components among selected tomato lines under organic farming
Various	Food security	South Sudan	Michael Roberto Kenyi	EU FAO	Agricultural development and food security in post-conflict southern Sudan.
	Food security	Swaziland	Nicholus Nhleko	Other	The contribution of diary credit guarantee scheme to household food security among the beneficiaries in Swaziland
	Food security	Zimbabwe, research in South Africa	Tatenda Mudzingan-yama	Other	A livelihood based analysis of the contribution of community gardens to food security in Msunduzi and Umngeni municipalities in KwaZulu-Natal, South Africa.
Vernonia	Mutagenesis	South Africa	ST Hadebe	Other	Chemical mutagenesis in Vernonia
	Seed quality	Democratic Republic of Congo in South Africa	Andre B Bwandola	Other	Seed quality development in *Vernonia galamensis*

CURRENT PhD STUDENT BREEDING PROJECTS

Crop	Trait/problem	Country	Student	Funder	Thesis topic
Sweet potato	Weevils Dry matter	Tanzania	Filson Mbezi Kagimbo	AGRA	Enhancement of sweet potato weevil resistance and dry matter content of sweet potato germplasm in western zone of Tanzania
	Dual-purpose varieties Farmer-preferred traits	Rwanda	Damien Shumbusha	AGRA	Breeding for dual-purpose sweet potato varieties through increased roots and vine dry yields and related farmer-preferred traits in Rwanda
	Nutritional quality	South Africa	Sonia Ines Messo Naidoo	ARC	Enhancing the nutritional quality of sweetpotato through breeding
Irish potato	Earliness Late Blight	Uganda	Prossy Namugga	AGRA	Genetic analysis of earliness and late blight resistance in potato
Maize	*Striga*	Tanzania	John Lobulu Loatha	AGRA	Breeding maize for *Striga asiatica* resistance in western Tanznia
	Striga	Zimbabwe	Admire Shayanowako	TWAS-NRF	Integrated control of Striga asiatica of maize using partial resistance and a biological control agent, *Fusarium oxysporum fsp strigae*
Wheat	Stem rust	Ethiopia	Mulu Fetahi Nigus	AGRA	Introgression of stem rust resistance in Ethiopian grown wheat lines
	Drought	South Africa	TG. Magagane	NRF	Breeding wheat for drought tolerance
	Drought Protein	South Africa	Zamalotshwa Thungo	NRF	Genetic analysis of drought tolerance and protein content in selected wheat genotypes
	Carbon sequestration Yield	Zimbabwe	Isack Mathew	WRC, NRF	Genotypic and phenotyping characterization of wheat genotypes for increased atmospheric carbon sequestration and high yield for climate change attenuation and food security
	Drought Quality	South Africa	Marylyn Christian	NRF, ARC-Small Grain Institute	Development of wheat cultivars with drought tolerance and quality traits
	Rust	South Africa	Pamella Ntshakaza	ARC-Small Grain Institute	Characterization of historic South African wheat cultivars for presence of rust resistance

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Rice	Rice yellow mottle virus Yield	Tanzania	William Titus Suvi	AGRA	Genetic improvement for Rice yellow mottle virus resistance and grain yield in Tanzania
	Yield Grain quality	South Sudan	Lado Maurice Mogga	AGRA	Genetic improvements for yield and grain quality traits for upland rice
Sorghum	Yield Ergot disease	Mozambique	Eduardo Mulima	AGRA	Genetic characterisation and breeding of sorghum for improved yield and ergot disease resistance in the mid-altitude agroecologies of Mozambique
	Striga	Tanzania	Emmanuel Mrema	AGRA	Evaluation of the effectiveness of *Fusarium oxysporum* in combination with sorghum genotype host resistance to *Striga* infestation in semi-arid parts of Tanzania
	Drought	Ethiopia	Solomon Assefa	AGRA	Breeding sorghum for drought tolerance in north-eastern Ethiopia
	Male gametocides	Zimbabwe	P. Mangena	Technology Innovation Agency	Development of hybrid sorghum cultivars using male gametocides
	Genetic diversity	Ethiopia	Girma Digafe	TWAS-NRF	Genotypic diversity, heterosis and combining ability of sorghum
Common bean	Bean fly resistance	Malawi	Wilson Nkhata	AGRA	Pre-breeding of common beans for bean fly resistance
	Blight	Ethiopia	Kidane Tumsa	CIAT	Breeding for blight resistance in common bean
Cowpea	Yield	Zambia	Nelia Nkhoma Phiri	AGRA	Genetic improvement of yield and yield components among cowpea genotypes in Zambia
Pigeonpea	Earliness Yield Fusarium wilt	Malawi	Esnat Nyirenda Yohane	AGRA	Development of pigeon pea varieties with early maturity, high yield and resistance to fusarium wilt in Malawi
	Yield	Tanzania	Seleman R. Kaoneka	ICRISAT	Identification of genomic regions associated with yield and related traits in Pigeonpea
Groundnut	Groundnut rosette disease	Zambia	Chapwa Kasoma	Other	Breeding groundnuts for resistance to Groundnut rosette disease
	Cercospora Leaf Spot disease Mycotoxin contamination	Tanzania	Eliud Kongola	AGRA	Genetic improvement of groundnut resistance to Cercospora leaf spot disease and mycotoxin contamination in central Tanzania
	Earliness Drought Rust	Uganda	Ronald Kakeeto	AGRA	Breeding studies for early maturity, drought tolerance and rust resistance in groundnuts
	Leaf rust	Tanzania	Happy Daudi	CIAT	Breeding groundnut for leaf rust resistance in Tanzania
Niger Oilseed	Yield Oil content	Ethiopia	Yared Semahegn Belete	AGRA	Breeding linseed for improved yield, yield related traits and oil content

FIRST TWO COHORTS

2002

Grace Abalo is a research officer and maize breeder at NaCRRI in Uganda. She has released three new varieties of maize.

John Derera is global head of research and development at Seed Co Ltd. Prior to that he was Programme Manager: Plant Breeding MSc for Africa, and a leader of the ARC-Universities Collaboration Centre on Smallholder Farmer Development, at the University of KwaZulu-Natal. He was also a professor of plant breeding and still teaches modules to ACCI students and supervises postgraduate students (MSc and PhD) in the School of Agricultural, Earth and Environmental Sciences. During the 10 years of research at UKZN he has developed 121 maize inbred lines, 10 Vitamin A orange maize inbred lines, 21 popcorn inbred lines and 15 popcorn hybrids.

Andrew Efisue is a rice breeder in the Department of Crop and Soil Science, Faculty of Agriculture, University of Port Harcourt in Uganda. He leads a team that released three new high-yielding varieties of rice in 2014.

Joseph Kamau is a lecturer in the Department of Plant and Microbial Sciences, Kenyatta University, Kenya. He also works as a seed expert for the Kenya Agricultural Research Institute (KARI) that has released certified cassava seeds for the first time. He is deputy head of the East African Agricultural Productivity Project (EAAPP) and does breeding work with funding from AGRA. He has developed 12 new varieties of cassava and four of sweet potato.

Geoffrey Kananji was deputy director responsible for legume research programs in Malawi before he joined AGRA as the country co-ordinator. He has produced six new varieties of beans, one soybean variety and three pigeon pea varieties in Malawi.

Clement Karari has released one new variety of sorghum.

Stanley Nkalubo is head of the Legumes Research Programme at the National Crops Resources Research Institute (NACRRI) in Uganda. He has released nine new varieties of beans.

Martin Orawu has released three new varieties of cowpea.

2003

Albert Banda was head of plant breeding and plant pathology for the Tea Association of Malawi, as well has head the TRFCA. He moved on to become chief executive officer of the Tobacco Control Commission (TCC) of Malawi, before being redeployed as operations manager to the Ministry of Agriculture, Irrigation and Water Development. He currently overseas extension, research, irrigation, crop development, fisheries, land resources, planning, water resources and eight agricultural development divisions.

Phillip Kwena has released one new variety of maize.

Phillip Leley has released five new varieties of maize.

Francisco Miti is a plant breeder for the Ministry of Agriculture in Zambia. He has developed six new maize varieties with AGRA funding and these have been released by the Zambia Agriculture Research Institute. Miti's main interest is to support the commercialisation of the varieties by producing and supplying foundation seeds to seed growers as well as promoting the varieties to the general farming community. However, he is limited by lack of resources to effectively carry out these activities.

David Mariote worked as a maize breeder for IIAM in Mozambique before resigning and going into business.

Clare Mukankusi works as a breeder at the International Centre for Tropical Agriculture (CIAT) in Uganda. She is also part of the Pan-African Bean Research Alliance that recently developed five new bean varieties that are bio-fortified with iron and zinc and are drought-tolerant.

Theresia Munga works for KARI where she heads the cassava breeding programme for Kenya. She was also country co-ordinator for Kenya for the 5CP project that involved five countries focussing on sharing cassava varieties that have some degree of resistance to the two main viral diseases, Cassava Mosaic Disease (CMD) and Cassava brown streak disease (CBSD). She has released six new cassava varieties that are early maturing, high-yielding and resistant to CMD and CBSD.

Chrispus Oduori has released four varieties of finger millet. He has worked for KARI and as Agicultural Centre Director, KALRO FCRI-Kisii at Kenya Agricultural and Livestock Research Organization.

REFERENCES

Alliance for a Green Revolution in Africa (AGRA). 2014. Africa Agriculture Status Report: Climate Change and Smallholder Agriculture in Sub-Saharan Africa. Nairobi, Kenya. https://agra.org/wp-content/uploads/2016/04/africa-agriculture-status-report-2014.pdf. Accessed 16 March, 2016.

Food and Agriculture Organisation of the United Nations (FAO). (2016) The State of Food and Agriculture: Climate Change, Agriculture and Food Security. http://www.fao.org/3/a-i6030e.pdf. Accessed 16 November, 2016.

Gepts, P. and Hancock J. 2006. The future of plant breeding. Crop Science 46: 1630-1634. http://www.plantsciences.ucdavis.edu/gepts/Gepts%26Hancock%20Future%20plant%20breeding.%202006.pdf. Accessed 9 March, 2017.

Guimarães, E.P., Kueneman, E. And Carena, M.J. 2006. Assessment of national plant breeding and biotechnology capacity in Africa and recommendations for future capacity building. HortScience 41: 50-52. http://cuke.hort.ncsu.edu/gpb/publications/guimaraes2006.pdf Accessed 26 January, 2017.

Morris, M, Edmeades, G and Pehu, E, 2006. The global need for plant breeding capacity: what roles for the public and private sectors? HortScience 41:30-39. http://libcatalog.cimmyt.org/download/reprints/94031.pdf. Accessed 12 November, 2016.

Myers, SS et al, 2014. Rising CO2 threatens human nutrition. Nature, 510 (75030: 139-142. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4810679/. Accessed 9 March, 2017.

National Research Council. 1996. Lost Crops of Africa. Volume I: Grains. National Academy Press, Washington, D.C. https://www.nap.edu/catalog/2305/lost-crops-of-africa-volume-i-grains. Accessed 24 August,2016.

National Research Council. 2006. Lost Crops of Africa. Volume II: Vegetables. The National Academies Press, Washington, D.C. https://www.nap.edu/catalog/11763/lost-crops-of-africa-volume-ii-vegetables. Accessed 24 August, 2016.

Noleppa, S. 2016. The economic, social and environmental value of plant breeding in the European Union: An ex post evaluation and ex ante assessment. http://www.plantetp.org/sites/default/files/HFFA_Research_Paper_03_16_final_unprotected.pdf. Accessed 13 September 2016

Jonathan H. Williams et al, 2009. HIV and hepatocellular and esophagal carcinomas related to consumption of mycotoxin-prone foods in sub-Saharan Africa. The American Journal of Clinical Nutrition Volume 92.http://ajcn.nutrition.org/content/92/1/154.full?sid=60ab33a5-01ac-490f-bd52-ac3f6a379dec. Accessed 5 August, 2017

BACKGROUND READING

Africa Progress Panel. 2015. Power, People, Planet: Seizing Africa's Energy and Climate Opportunities. Africa Progress Report 2015. https://app.box.com/s/3o4uojfqzwvhxiiad0et506vrwlkvz4e. Accessed 4 January, 2017.

Bamnetwork. http://bambaragroundnut.org. Accessed 20 August, 2016.

Carrington, D. 2014. Climate change making food crops less nutritious, research finds. https://www.theguardian.com/environment/2014/may/07/climate-change-food-crops-nutrition. Accessed 12 January, 2017.

CIP International Potato Center. http://cipotato.org. Accessed 10 August, 2016

CIP International Potato Center. Claessens L., and Van Wart J. (2014). Climate Zones for Crop Management. In K. Sebastian (Ed.), Atlas of African Agriculture Research & Development. http://dx.doi.org/10.2499/9780896298460_16 Retrieved fromhttp://agatlas.org. Accessed 1 December, 2016.

Cox C., and Koo J. (2014). Soil Fertility. In K. Sebastian (Ed.), Atlas of African Agriculture Research & Development. http://dx.doi.org/10.2499/9780896298460_18 Retrieved from http://agatlas.org. Accessed 1 December, 2016.

Department of Agriculture, Forestry and Fisheries. 2011. Production Guidelines for Cowpeas. http://www.arc.agric.za/arc-gci/Fact%20Sheets%20Library/Cowpea%20-%20Production%20guidelines%20for%20cowpea.pdf. Accessed 24 August, 2016.

Food and Agriculture Organisation of the United Nations (FAO), 2013. Save and Grow: Cassava. A guide to sustainable product intensification. http://www.fao.org/3/a-i3278e.pdf. Accessed 23 March, 2017.

Hahn, SK. An overview of traditional processing and utilisation of cassava in Africa. http://www.fao.org/wairdocs/ilri/x5458e/x5458e05.htm. Accessed 1 March, 2017.

GCP Blog. 2014. Milking' cowpeas in Mozambique for protein and profit ... plus a pox on pests! http://blog.generationcp.org/2014/05/30/milking-cowpeas-in-mozambique-for-protein-and-profit-plus-a-pox-upon-pests/. Accessed 13 December, 2016.

GSMA Intelligence. 2015. The Mobile Economy: Sub-Saharan Africa 2015. https://www.gsmaintelligence.com/research/?file=721eb3d4b80a36451202d0473b3c4a63&download. Accessed 4 January, 2017.

Guimarães, E.P., Kueneman, E. And Paganini, M. 2006. Assessment of the national plant breeding and associated biotechnology capacity around the world. Crop Sci 48. Supplied by author.

Harlan, J.R. 1992. Crops and Man. American Society of Agronomy, Inc & Crop Science Society of America, Inc, USA.

International Institute of Tropical Agriculture (IITA). http://newint.iita.org. Accessed 14 February, 2017.

Kew Royal Botanic Gardens. Plants and fungi species browser. http://www.kew.org/science-conservation/plants-fungi.

Latta, S. 2016. The hidden survivors of the Hunger Gap. https://www.mercycorps.org.uk/articles/niger/hidden-survivors-hunger-gap. Accessed 5 January, 2017.

Le Houérou, H. Cajanus cajan (L.) Millsp. http://www.fao.org/ag/agp/agpc/doc/gbase/data/pf000150.htm. Accessed 26 August, 2016.

Messiaen C.M. 1992. The Tropical Vegetable Garden. The Macmillan Press LTD, London and Basingstoke.

National Research Council, 1989. Lost Crops of the Andes: Little-Known Plants of the Andes with Promise for Worldwide Cultivation. National Academy Press, Washington, D.C.

New Agriculturalist. 2012. Country profile– Malawi. http://www.new-ag.info/en/country/profile.php?a=2488. Accessed 5 December, 2016.

New Agriculturalist. 2004. Country profile–Mozambique. http://www.new-ag.info/en/country/profile.php?a=855. Accessed 5 December, 2016.

Piperno, D.R. (2011). The origins of plant cultivation and domestication in the New World tropics. Current Anthropology, 52: 453-470. http://www.jstor.org/stable/pdf/10.1086/659998.pdf. Accessed 8 March, 2017.

PlantVillage. Peanut (groundnut). https://www.plantvillage.org/en/topics/peanut-groundnut/diseases_and_pests_description_uses_propagation. Accessed 24 August, 2016.

PlantVillage. Soybean. https://www.plantvillage.org/en/topics/soybean. Accessed 24 August, 2016.

Rice-Oxley, M and Flood, Z. 2016. Can the internet reboot Africa? https://www.theguardian.com/world/2016/jul/25/can-the-internet-reboot-africa. Accessed 4 January, 2017.

Sauer J.D. 1993. Historical Geography of Crop Plants. CRC Press LLC, Florida.

Schubert, C. 2015. Crops Under a Changing Climate: What Are the Impacts in Africa? https://ccafs.cgiar.org/blog/crops-under-changing-climate-what-are-impacts-africa#.V06zN1cbCIM. Accessed 16 March, 2016.

Sebastian K. (2014). Agroecological Zones. In K. Sebastian (Ed.), Atlas of African Agriculture Research & Development. http://dx.doi.org/10.2499/9780896298460_15 Retrieved from http://agatlas.org. Accessed 1 December, 2016.

Spooner, S. 2016. Africa's great digital divide: you're more likely to have access to the internet as a wealthy man in a coastal country. http://mgafrica.com/article/2016-04-29-africa-connectivity. Accessed 4 January, 2017.

Thornton P. (2014). Rainfall and Rainfall Variability. In K. Sebastian (Ed.), Atlas of African Agriculture Research & Development. http://dx.doi.org/10.2499/9780896298460_17 Retrieved from http://agatlas.org. Accessed 1 December, 2016.

Van Wyk, B.E. 2005. Food Plants of the World. Briza, Pretoria.

Van Wyk B.E. and Gericke N.2000. People's Plants: A Guide to Useful Plants of Southern Africa. Briza, Pretoria.

Zidenga, T. 2012. Delaying postharvest physiological deterioration in Cassava. ISB News Report. http://www.isb.vt.edu/news/2012/Aug/Zidenga.pdf. Accessed 23 March, 2017.