Unleashing the potential of sweetpotato in Sub-Saharan Africa: Current challenges and way forward

CHALLENGE THEME PAPER 1: SWEETPOTATO BREEDING

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Overall Challenge: How do we improve the yield, resistance to biotic and abiotic stresses, nutritional and market attributes of sweetpotato varieties to farmers?

BACKGROUND

According to the Food and Agriculture Organization (FAO) statistics annual sweetpotato production in Africa has increased moderately from 11.6 million tonnes in 2002 to 12.9 million tonnes in 2006. In 2006 the FAO estimated that West-, East-, Central- and Southern Africa had an annual production of 4.2, 7.2, 1.2, and 0.5 million tonnes, respectively. These figures might be underestimated. Sweetpotato is mainly produced by smallholders (the majority of whom are women) and for home consumption. Typically less than 20% of production is traded and reaches rural and urban markets. Data on piecemeal harvested crops such as sweetpotato are difficult to collect. FAO data often do not reflect the true situation. Extreme examples of biased sweetpotato production estimates are Malawi and Mozambique. Nationally representative sample survey data for Mozambique report a production of nearly 500 thousand tonnes and Donor funded Early Warning System Statistics indicate Malawi has a production of 1444 thousand tonnes of sweetpotato, whereas the FAO Statistical Database (FAOSTAT) reports no production in Malawi and only 60,000 tonnes in Mozambique. The yield estimations over the past decades are equally dubious. The FAO statistics indicate that there has been nearly no sweetpotato yield progress in Africa over the past two decades (yield estimations were in the range of 4.0 and 4.5 tonnes per hectare from 1987 to 2006). This implies that there has been no breeding progress, which is unlikely, and reflects the lack of quality statistics for Sub-Saharan Africa (SSA). However, breeding progress has been concentrated in a few countries and there is need for improvement across SSA.

The main reason for slow sweetpotato breeding progress in Africa can be attributed to low investments into sweetpotato breeding in nearly all countries of Africa. In stark contrast, China has increased with moderate investments sweetpotato yields over the past 50 years from 7.1 to 21.3 tonnes per hectare. Rough estimates across crops conclude that about 50% of the yield

progress can usually be attributed to breeding progress. Others attribute part of the low breeding progress of sweetpotato in Africa to the inadequate adjustment of breeding objectives and selection procedures to farmer needs (Gibson *et al.*, 2008) by formal plant breeding (on-station breeding managed by a scientist and his technical staff). One additional factor causing low breeding progress for sweetpotato is probably the very complex genetics of sweetpotato: each genotype is a highly heterozygous hybrid and hexaploid, so that the basic set of chromosomes is found six times in a cell nucleus, which means that each gene occurs in up to six different alleles (different states of the same gene) in each genotype. This makes successful breeding for yield progress long term in nature and complicated in designing crossing programs. This burden, however, is also an advantage as the potential for "jumps" in yield improvement can occur in nearly all autopolyploid crops. Moreover, sweetpotato as a clonally propagated crop can be easily multiplied and maintained, which is an advantage as well as a burden, because many diseases (especially viruses) are transmitted in planting material. The cloning characteristic permits rapid and wide dissemination of successful genotypes and varieties, respectively, and the exploitation of heterosis, an important genetic effect for yield, yield stability and adaptability.

Achieving medium to long term yield gains in sweetpotato is a challenge in sweetpotato breeding because the performance of a parent in one generation is not a good indicator for the value of a parent for the next sweetpotato generation. However, the genetic constitution of sweetpotato permits the adaptation of sweetpotato populations to new needs in the broad sense (environments, quality demands, tolerance to pest and diseases) to be achieved quite rapidly from the view point of crop evolution. Examples for this potential abound in the sweetpotato gene pool; it is possible to find many genotypes which are specifically adapted to drought, heat, cold (in tropical highlands), mineral-stress (including acid soils) or extreme salinity. Furthermore, the large differences in taste, protein, starch, sugar, vitamin and mineral content in the sweetpotato gene pool can be easily found provided that the breeder can, and is willing, to screen large numbers of genotypes and has appropriate bioassays. What is required is the development of genetic variation (this is easy in sweetpotato) around higher population means (this is difficult in sweetpotato) which entails screening thousands of samples (this is laborious in sweetpotato). Increasingly elevated population means and a sufficient genetic variation for variety development is the task of medium to long term population improvement within breeding and the engine driving the breeding progress.

The needs of farmers and breeding objectives, respectively, are generally classified into yield and yield stability, quality and resistance. However, sweetpotato has an additional class of need and

this is the survivability of planting material (also called vine survival). In contrast to nearly all other major food crops (except cassava) the harvest (storage roots) and planting material (usually vine cuttings) differs in sweetpotato. Additionally, sweetpotato is harvested after a period of about 4 to 5 months and planting material must be available for the next growing season, which can be 5 to 7 months later, especially in those SSA regions with extended drought periods. In contrast, the growing period of cassava lasts about 8 to 11 months and cassava usually stays in the field a short time before the next growing season. Vine or planting material survival is one very important need for sweetpotato in SSA, and has not been a selection criterion to date. In SSA millions of farmers are losing 4 – 6 weeks of the excellent growing period at the beginning of the rainy season while they re-establish sufficient vine production for planting, obtaining initial limited planting material from residual plants, re-sprouting roots, or secondary growth of harvested fields. The limited availability of planting material might explain why the sweetpotato production area is considerably smaller than the cassava production area in SSA. De facto, sweetpotato produces more food energy per unit area and unit time than any other major food crop and sweetpotato has higher protein, vitamin and mineral contents compared to cassava.

As further background to the sweetpotato breeding challenges more general background information is provided about breeding structures and breeding objectives (yield and yield stability, quality and resistance) in sweetpotato for Africa. Yield, yield stability and adaptability (including genotype by environment [G by E] patterns) of crops are often associated with resistance to biotic and abiotic stress. This is also the case for sweetpotato in Africa; however, the effect of stress factors are more pronounced in Africa than in other regions of the world. This results in stronger G by E patterns and more distinct agro-ecological zones in which varieties must have similar adaptation. There are different opinions in breeding for wide adaptation and the necessity to breed for specific adaptation (for a discussion in the frame of sweetpotato breeding see Grüneberg *et al.*, 2005). In the case of sweetpotato it is recognized that it is not possible to breed for adaptation across agro-ecological zones in Africa. For this reason, consideration needs to be given to organizing sweetpotato breeding in a decentralized way. Each country with a significant sweetpotato production should have its own variety development program. Each variety development program should be linked with a "local" short term population improvement program, in which parents are recombined (crossed) in an efficient way according to the local breeding and test capacity (critical test capacity for a local population improvement needs to be defined for SSA). The local population improvement program should aim to generate significant genetic variation and breeding progress within two to three generation cycles and five years, respectively, where one cycle comprises one recombination step

of parents and one selection step is defined as selection within genetic variation derived from recombination. However, pre-breeding (the incorporation of specific traits into breeding material that merits use as parents in local population improvement) and to certain extent population development itself can be conducted in fewer, more "centralized", locations. That is, strategic medium to long term population improvement, such as developing and extending the non-sweet sweetpotato gene pool for West Africa (see below), could be carried out at the sub-regional level. It should be noted that pre-breeding and strategic medium to long term population improvement require significant greater capacities, both human and financial, than variety development through short term population improvement. In the short term, crossing and combining parents with medium to high genetic values across all objectives and traits is all that is required. In pre-breeding and medium to long term population improvement, parents are developed by incorporation of new attributes from sources which often only have a high genetic value in one or very few attributes (e.g. excellent disease resistance but poor yield performance and other traits).

Within the sweetpotato gene pool, there is an enormous amount of genetic variation for quality attributes. A renowned example is the concentration of pro-vitamin A in storage roots, which ranges from 0 to nearly 1000 ppm on a storage root dry weight basis (dwb). This corresponds to 0 to 20 mg β-carotene in 100 g of fresh sweetpotato storage roots (about 5 mg β-carotene meets the daily requirement of a pre-school child (400 µg/day RAE)[1]). Similar magnitudes of genetic variation are found for starch, sugars and probably for dietary fiber. Moderate genetic variation is found for protein and minerals such as iron and zinc. It is quite convenient, however, that the attributes, proteins and minerals are positively correlated genetically with β-carotene in sweetpotato storage roots, so that improvement in pro-vitamin A is linked with an improvement in iron, zinc and other minerals such as calcium and magnesium.

Breeders nearly always want to select for several traits concurrently. If the goal is to select the top 10 among 100 genotypes for each trait and seek a total number of 10 priority traits then 100^{10} genotypes have to be screened. This simple example demonstrates how the number of genotypes to be screened increases exponentially as the number of priority traits desired increases. In practical terms, quality breeding often means to improve quality (three to five traits) and simultaneously maintain sufficient genetic variation for yield, yield stability and adaptability

[1] Plant sources of pro-vitamin A in the form of β-carotene are converted into retinol. Recommended intake levels of vitamin A are expressed in Retinol Activity Equivalents (RAE) with a healthy child 1-3 years old needing 300 µg/day and a

improvement. Fortunately, several high through-put quality screening methods have proven effective for use with sweetpotato. This includes color charts for pro-vitamin A contents, taste tests for starch and sugar contents, as well as Near-Infra-Red (NIR) technology (Pfeiffer and McClafferty, 2007) for assessing levels of protein, minerals and anti-nutritional factors such as phytate. Clearly, quality breeding in sweetpotato is straightforward but labor intensive. The challenge is to incorporate or develop the quality attributes in a genetic background (a population comprising several hundred genotypes) that is adapted to the agro-ecological environment and has sufficient genetic variation for yield improvement.

Stress (biotic or abiotic) principally defines agro-ecological zones and generates distinct requirements for pre-breeding and medium and long sweetpotato population improvement. Key features of the major environments where sweetpotato is produced are briefly summarized below.

The **humid tropical low and mid-elevation regions of Eastern & Central Africa** (0 to 1200 m.a.s.l.) with only very short dry seasons, if any (Uganda, Rwanda, Burundi, Dem. Rep. Congo) have high sweetpotato virus disease (SPVD) pressure, which is extreme in regions where sweetpotato is extensively cultivated. The SPVD occurs after infection of two viruses: the sweetpotato feathery mottle virus (SPFMV) and the sweetpotato chlorotic stunt virus (SPCSV). The SPCSV is the more problematic component of SPVD, because yield losses due to SPFMV - without SPCSV infection – are low and SPFMV resistance (as well as the resistance to many other viruses) of sweetpotato breaks after the plant is infected by SPCSV. SPCSV resistance has been found in germplasm screening programs and the resistance appears to be conferred by a recessive allele which occurs in low frequency in the sweetpotato gene pool. However, this resistance still needs to be proven in extensive field tests in Africa. It is nearly certain that new sweetpotato varieties with resistance to SPVD will result in significantly higher yields and yield stability in East- and Central Africa, at least for a period of 5 to 8 years. After this period, it is likely varieties will need to be replaced because new strains have developed in the chlorotic stunt virus gene pool.

The **humid tropical highland regions of Eastern & Central Africa** (1200 to 1800 m.a.s.l.) are characterized by relatively cold temperatures at nights (Rwanda, Burundi, parts of Western Kenya and Uganda, as well as spots in Tanzania). For decades, these African regions have had very high

4-8 year old 400 µg/day. The conversion rate commonly used is 12 units of β-carotene to produce 1 RAE. Hence, 5 mg (equivalent to 5000 µg of beta-carotene) provides 416 µg RAE.

levels of sweetpotato production. Moreover, owing to the favorable climate, these regions also support the highest rural population density in Africa. For sweetpotato these regions have the advantage of a nearly whole year round production, and considerably lower SPVD pressure. In this setting, Alternaria dominates as the major sweetpotato disease. Cold nights limit sweetpotato production at around 5°C. National Agricultural Research System (NARS) partners in Rwanda, Tanzania, and Burundi consider the development of pathways for sweetpotato processing and the dual purpose sweetpotato (varieties to be used for direct human consumption and animal feed) as important new needs for sweetpotato by which the crop can contribute to income generation and poverty alleviation. Where land is limited and labor abundant, especially in those countries where zero grazing has been implemented by law (such as in Rwanda), the dual purpose sweetpotato might be the option to feed cattle, pigs and small animals (see the Challenge Paper on Value Chains and background paper on animal feeds) and could also contribute to reducing soil erosion. This might be the major impact potential of sweetpotato in the African highlands. So far, no specific breeding populations for highland sweetpotatoes have been established, but there are sufficient genetic resources in the sweetpotato gene pool (at least in the germplasm collection of the International Potato Center [CIP]) to start a highland dual purpose breeding program. In addition, there is need to select for market quality, although the amount marketed for specific end uses might be only a small proportion of the total production. However, NARS in Rwanda consider value added products in which sweetpotato is used as a secondary or primary raw product (juices, chips, puree, and bread) as an investment needed to change the image of sweetpotato as being a poor man's crop, which contributes towards declining consumption of sweetpotato connected to rising incomes, particularly in urban settings.

The **drought prone regions of Southern and Eastern Africa** (from sea level to mid elevation areas < 1200 m.a.s.l.) have very unstable rainy seasons and an extended drought season of more than 4 months (Mozambique, Malawi, Zambia, Angola, Madagascar, parts of Tanzania, Kenya, and Northern Uganda). Drought effects are associated with high storage root damage by weevils and serious shortages of planting material at the beginning of the rainy season, especially for households with poor access to valley bottom lands. Resistance to sweetpotato weevils does not exist in sweetpotato; however, different degrees of tolerance are reported by farmers among sweetpotato varieties. Farmers consider varieties which expose their storage roots close to the soil surface as highly susceptible to weevil damage. Moreover, there are indications that the latex content in root skin is associated with lower weevil damage. In Mozambique farmers consider availability of planting material and vine survival as key traits for successful varieties. After long dry

periods, farmers plant what is available and often these are varieties which produce a lot of vines meaning that access to other attributes gained through breeding will not be available to farmers if this essential trait is missing. Impact in this region by sweetpotato – especially the orange-fleshed sweetpotato (OFSP) – will require breeding populations to exhibit strong vine survival and breeding programs have to address this trait adequately in population improvement.

The **forest and savanna regions of West Africa** (nearly entirely low to mid-elevation areas < 800 m.a.s.l.) have more or less stable rainy seasons with a short to prolonged dry season (2 to 8 months). They are traditionally production zones with high a frequency of root crop production. However, the main root crop is cassava, followed by yam, then sweetpotato. Major sweetpotato production countries are Nigeria, Ghana and Sierra Leone. Agricultural infrastructure in West Africa is more developed than in East, Central and Southern Africa (e.g. laboratory facilities with high output of clean planting material can be accessed in Ghana) and export opportunities are enhanced by closer proximity to Europe. The SPVD virus pressure is moderate, but with the extension of the dry season the problem of weevil damage increases. Moreover, markets for processed root and tuber crops exist – the most well known cassava product is gari which is eaten by millions in West Africa on a daily basis. In spite of this market, sweetpotato is rarely processed because of the sweetpotato flavor. NARS in Ghana emphasize that non-sweet or bland sweetpotatoes are needed to enter into this market chain of root and tuber crops. The contribution of OFSP to income generation and improved vitamin A status could be enhanced by incorporating the non-sweet trait. The major sugars of sweetpotato are sucrose, glucose, fructose, and maltose. The total sugar content in sweetpotato varies widely within the sweetpotato gene pool (<5% and up to 30% on dwb). Moreover, genotypes with lower sugar contents exist within the OFSP gene pool gene. So far no breeding populations for the non-sweet sweetpotato have been established in SSA, but in other regions of the world national programs have successfully bred for the non-sweet sweetpotato [e.g. Sri Lanka, Puerto Rico, United States (Kays *et al.*, 2005).

Breeding is a critical factor in increasing sweetpotato yields and in opening new options for diversified use of sweetpotato in Africa. Moreover, further sweetpotato quality breeding for provitamin A, iron and zinc will increase the impact of sweetpotato consumption on public health (especially women and young children).

This paper is a result of a consultative process among CIP's senior sweetpotato breeder and breeders from seven African countries during the preparatory phase for this workshop. Six major

challenges have been identified for sweetpotato breeding in Africa: (i) improving sweetpotato breeding infrastructure, (ii) improving sweetpotato breeding methods (iii) breeding sweetpotato products / varieties for humid topical low and mid-elevated regions (0 to 1200 m.a.s.l.) with high SPVD pressure, (iv) breeding sweetpotato products / varieties for cold topical highlands (> 1200 m.a.s.l.) with attributes for dual use (human consumption and animal feed) and marketable value added products (bread, breakfast food, puree and juice), (v) breeding sweetpotato products / varieties for drought-prone, high temperature regions with high vine survival and some tolerance to weevil damage, (vi) breeding sweetpotato products / varieties for low or no sugar contents and high dry matter content (non-sweet sweetpotato) adapted to West African regions.

PRINCIPAL CHALLENGES

Challenge 1.1. Limited breeding infrastructure

Current knowledge

Several countries in SSA have sweetpotato breeding programs. However, there is only one NARS breeding program with significant medium to long-term population improvement capacity. This is the National Crops Resources Research Institute (NACRRI) in Uganda. A second program with similar capacities is mainly managed by CIP in Mozambique in cooperation with the Mozambique Institute for Agricultural Investigation (IIAM). NACRRI has allocated full time one scientist and six technicians to sweetpotato breeding. Furthermore, two scientists are working at NACRRI with sweetpotato (one agronomist and one entomologist). In the second program CIP, together with IIAM in Mozambique, has allocated two breeding scientists (one PhD CIP senior staff and one MS IIAM junior staff), six field technicians and two laboratory technicians to sweetpotato breeding. Both breeding programs recombine as standard 25 to 40 parents each year. At present NACRRI has an additional crossing block comprising 100 parents. In the past year at least 90,000 polycrosses and 3000 controlled cross seeds were developed at NACRRI. In contrast CIP-Mozambique / IIAM selected from in the past season 30,000 seeds from polycrosses and 25,000 seeds from controlled crosses. It should be noted that CIP-Mozambique obtains on a larger scale controlled cross seed from CIP-Lima (about 516 families in the last season). There is also some limited material exchange between NACRRI and CIP-Lima (e.g. SPVD resistant clones and SPVD resistant populations to NACRRI and African OFSP landraces to CIP-Lima). Both breeding programs use three to six experimental sites. Depending on the potential of the material, 50 to 500 promising clones and 10 to 25 advanced breeding clones are tested each year.

The two programs not only differ in the relative emphasis on polycrosses versus controlled crosses, but also on how they conduct selection in early breeding stages. The program at NACRRI

uses a sequential selection in which at the first stage 50,000 to 90,000 clones are screened on a single plant basis for SPVD tolerance. After 3 years the material is reduced to 50 or 500 promising clones. The program at CIP-Mozambique / IIAM uses a sequential selection in early breeding stages for clones from polycross seed, whereas clones from controlled crosses are evaluated in a simultaneous selection scheme. A simultaneous selection scheme is characterized by testing simultaneously all genotypes in very small plots (usually three plants) at two to three locations, of which one is a stress location (in this case a drought stress location). Both breeding programs – NACRRI and CIP-Mozambique / IIAM have plant quality and in-vitro laboratory facilities. However, NACRRI facilities merit improvement, whereas at CIP-Mozambique / IIAM technical staff skills merit improvement. It appears that at both institutions the laboratories need investments to better serve a medium to long term sweetpotato improvement program as well as serve as a dissemination point for "good" parents to other breeding programs working in similar agro-ecological zones.

Several NARS sweetpotato breeding programs have capacities for variety development linked with local short term population improvement programs, including the Agricultural Research Institute (ISAR)-Rubona in Rwanda, the Crop Science Research Institute (CSRI)-Kumasi in Ghana, the Kenya Agricultural Research Institute (KARI) in Nakuru, Kenya, and University of Nairobi at Kabete, Kenya, in cooperation with CIP-Nairobi. These NARS breeding programs have allocated full time one scientist and two to three technicians to sweetpotato breeding. These NARS partners are managing a crossing block in which usually 10 to 25 parents are recombined and 3000 to 7000 seeds are developed. Crossings among parents are mainly conducted by polycrosses (80 to 90% of the total seed production). Selection is conducted sequentially in early breeding stages at one location in which in the first season material is selected for SPVD tolerance and quality characteristics (exclusively for storage root and skin color, dry matter and flesh color). This is linked with observation trials for storage root size, shape and form as well as storage damage due to weevil and other biotic and abiotic stresses. First yield trials are carried out after 2 to 3 years in preliminary yield trials at one to three locations, followed by advanced yield trials conducted in at least three locations each with two replications. Evaluation capacity is usually 20-40 promising clones and 10–20 advanced clones. It is worth noting that CSRI in Ghana has active biotechnology and in-vitro lab facilities, which are stronger than the current NACRRI and CIP-Mozambique / IIAM facilities. Moreover, there is an existing in-vitro sweetpotato maintenance program at the Biotechnology and Nuclear Agriculture Research Institute (BNARI) in Accra, Ghana, which handled in the past campaign the dissemination of 20,000 virus-free plantlets to associations exporting to Europe.

Other NARS breeding programs partially allocate one scientist and one to two technicians to sweetpotato breeding such as Lake Zone Agriculture Research and Development Institute (LZARDI) at Mwanza / Tanzania. These NARS cross only few parents by polycrosses in which seeds are harvested from two to four of the most interesting parents, which were planted together with about 10 – 15 genotypes (usually local adapted material). Selection in subsequent stages for tolerance to biotic and abiotic stresses is conducted in a similar way to that described for the NARS partners above. Moreover, a group of NARS partners such as the Department of Agricultural Research Services (DARS) in Bvumbwe / Malawi, and HortiTengeru in Arusha / Tanzania have partially allocated one scientist and one to two technicians to sweetpotato research, but do not have crossing blocks. These programs occasionally conduct variety selection with introduced clones or seeds, which they obtain from NACRRI, CIP or other sources. However, all these seeds come from polycrosses. It is worth noting that these NARS partners have interesting collections of local germplasm, which include material that has been very successful in farmer fields for decades.

Future areas of work for consideration (order listing does not imply any prioritization):

1) Defining a critical capacity for a NARS sweetpotato breeding program.
2) Defining breeding platforms and their tasks, which are serving an agro-ecological region by medium to long term population improvement for priority traits within the region by providing attractive parents for local population improvement programs.
3) Selection and allocation of sub-regional platforms supporting NARS breeding programs;
4) Selection and allocation of NARS breeding programs (suggestion: 8 to 12 partners).
5) Defining clear breeding objectives on the basis of regional needs and capacities for each agro-ecological zone and milestones and breeding progress, respectively, to be reached in products and varieties respectively.
6) Developing standards to record traits and progress towards objectives, which allow sound statistic analysis.
7) Defining bottlenecks in NARS breeding programs and regional platforms.
8) Stepwise increasing of the NARS breeding capacity to the critical mass, by internal funds and supporting fund raising (e.g. Alliance for a Green Revolution in Africa [AGRA] and the Pan-African Start Secretariat [PASS]).
9) Stepwise increasing of the breeding capacity at regional platforms to fill the bottlenecks, by internal funds and further fund raising for sweetpotato breeding research (e.g. AGRA and PASS).

Challenge 1.2. Poorly developed breeding and selection methods

Current knowledge

Sweetpotato is a clonally propagated crop, meaning that all plants tracing back to the same mother plant are genetically identical. This mother plant once developed from a single seed. In sweetpotato true seed sets occur easily in nature by cross-pollination (due to insects, mainly bees). The general breeding principle underpinning breeding clonally propagated crops is to break the normal clonal propagation by introducing a crossing step, which culminates in sexual seed production and genetic variation. After the genetic recombination, all subsequent propagation steps are again asexual by clonal propagation. The creation of genetic variation in sweetpotato is very easy. When different genotypes are planted together, they naturally cross-fertilize and set seed, because sweetpotato is self-incompatible (seeds cannot develop from self-fertilization) – this principle underlies the development of polycross nurseries. The seedlings are raised in seeding nurseries and each seedling is a different genotype and has the potential to become a new variety, because clone lines are genetically fixed (no further genetic change occurs). To move from seeds to new varieties, selection criteria are applied to a large set of genetically diverse clones based on desired breeding objectives. This is usually carried out over several subsequent evaluation and selection stages. Highly heritable traits (traits which are not very much affected by the environment) are evaluated in early stages on the basis of a very small number of plants for each genotype (such as disease resistance, storage root size, shape and from, storage root skin and flesh color). Lowly heritable traits (traits which are strongly affected by the environment) such as yield, yield stability and adaptability, are evaluated in later stages, when more planting material is available, on the basis of plots, plot replications and information across several environments. Such a multistage selection program can take up to five years or more. In essence, breeding is the art of accelerating crop evolution towards plant characteristics of use by human beings.

Variety selection

Often breeding gets lost in discussions as to which traits have to be considered. The breeder Gerhard Röbbelen wisely said to his students: *There is only one breeding objective: A better product and variety, respectively, and to come with this at least one year before the competitor*. Existing selection theory models are often used with one (usually yield) or very few traits. But, theoretically it is possible for model calculations to capture the practical process of multistage and simultaneous selection in multiple environments for several traits aiming at the identification of a variety. In breeding sweetpotato for variety development there can be as many as 20 traits and attributes desired to determine the quality of a variety and an almost equal number of other

traits meriting improvement. What we basically have is an optimization problem: for a given testing capacity and budget, how can we evaluate a large number of traits in a large number of genotypes efficiently?

Some have criticized formal plant breeding - in this context, researcher-managed selection on-station in Africa and for Africa - for concentrating on breeding objectives that do not necessarily correspond to farmer needs. On-station trials conducted on good land, under good management with occasional irrigation access, often produce results that differ substantially from on-farm results. This can be a problem when "crossover interactions" occur, that is when the ranking of genotypes on the basis of on-station performance do not correspond to the ranking of genotypes on the basis of on-farm performance. In the case of sweetpotato breeding, this criticism is at least partially justified. Simple examples of areas where more attention is needed include storage root skin color (acceptable skin color varies tremendously in Africa) dry matter and sugar content (a sweetpotato with a soft sweet mouth taste is usually not acceptable in Africa). More complex examples are piecemeal harvest attributes, especially in varieties for humid tropical low and mid-elevation regions, and planting material availability or vine survival attributes in varieties for the drought prone regions of Southern Africa. The need for varieties for Africa is much more complex than the need for varieties for the developed world, with their industrialized agriculture. Farmer participation in trials of advanced clones is widespread in sweetpotato selection programs in SSA. However, sweetpotato breeding programs in Africa often do not have sufficient farmer participation at the early breeding stages. This is important because errors at the early breeding stage cannot be cleared at later breeding stages, as what is discarded is lost. Having farmers actively involved in at least one early breeding stage could be a key factor for improving selection efficiency in Africa. Breeding programs should aim to select sites that are representative of farmer field conditions and management. However, trade-offs do exist; under moderate to good conditions genotype and variety differences become more pronounced -- especially for yield – which increases selection efficiency increases, but crossover interactions for poorer environments cannot be captured.

It is essential to capture appropriate crossover interactions because well performing products and varieties for well resourced farmers often fail in environments typical of poor households. Most sweetpotato breeding programs in Africa do not select at a hot spot environment in the early breeding stages for extreme low input and extreme high stress conditions due to biotic and abiotic stresses. These environments are risky. In extreme seasons the whole breeding population can be lost. Moreover, yield differences among genotypes are smaller, and experimental errors

and least significant differences are larger. However, model calculations show that by using two sites at the first breeding stage, the efficiency of selection (or response to selection) is still close to the optimum. One hypothesis is that if the second environment used is a poor input or "hot spot" for a priority stress condition (e.g. drought; high virus pressure), this will significantly increase the selection efficiency. To reduce resource use, the poor input or hot spot environment for stress is harvested first and all genotypes that fail to perform in this stressed environment are discarded from the selection program regardless of how well they are performing on-station. The resource use-saving comes from not having to record information on these "discarded" genotypes on-station. The inclusion of a low input selection environment can also be linked to farmer participatory selection. This strategy should increase the selection efficiency for sweetpotato in Africa of formal plant breeding programs by reducing the risk of developing varieties which are not adopted by farmers.[2]

To accelerate the breeding process, our proposition is that simultaneous selection of traits is more efficient than sequential selection of traits. In practical terms, this means:

Increasing the number of tested clones at the early breeding stage to the maximum of the test capacity that can be allocated to genotypes at the early breeding stage (about 60% of the total test capacity or breeding budget).

Selecting at each breeding stage about 10% of the material.

Not investing in more than three subsequent selection stages because there will be no further gains in selection efficiency (response to selection).

Allocating about 20% of the total test capacity to the second and 20% to the third selection stage.

Selecting at two environments at the first selection stage does not differ much in its efficiency from selection at one environment; however, with more environments, efficiency becomes increasingly more distant from the optimum selection efficiency.

Increasing immediately at the second selection stage the number of locations to the maximum that can be managed with 20% of the test capacity allocated to this breeding stage. At this stage the greates efficiency is gained by increasing the number of environments instead of increasing the number of replications; hence, no plots at a site need to be replicated.

Using the maximum number of locations that can be managed with 20% of the total test capacity at the third selection stage; noting that differences between trials with two plot

[2] For detailed information concerning selection theory for variety selection, book chapters like "Selection between clones and homozygous lines" and "Selection for several characters" in selection theory textbooks such as Wricke and Weber (1986) are excellent references for breeders working with clonally propagated crops.

replications (reduced number of tested genotypes) do not differ much from trials with one plot replications with respect to the selection efficiency in the multistage selection program.

We recognize that sweetpotato experimental trials have a very large plot error for yield. Estimations show coefficient of variation (CV) values 35 – 45% in 15 plant plots and CV values 25% in plots with more than 60 plants. However, the number of environments is a more important parameter for the efficiency of selection than the number of plot replications. We also assume that the CV plot error can be further improved through specific experimental design, which merits further investigation. Hence, we propose for consideration an accelerated breeding scheme (Figure 1.1) which requires 3–4 selection stages for variety development in which the first two stages are aggregated into one season, so that new varieties with the desired traits can be developed within 2–3 seasons.

Many breeding programs in Africa allocate the majority (>50%) of their total test capacity and breeding budget to the more advanced selection stages and not to the first selection stage. Moreover, the number of tested breeding clones at the first selection stage appears to be too low to reach moderate or high selection efficiency. As mentioned above, this initial selection stage is the most critical for the selection efficiency. The two breeding programs in SSA that are heavily investing in the first selection stage are NACCRI-Uganda and CIP/IIAM-Mozambique. Both programs have at least moderate selection efficiency. Both programs might be improved by speeding up the time needed for variety selection. As the modification of a breeding program is a very sensitive issue, consideration of an accelerated breeding approach will require intensive discussions and exchange of opinions. In addition, use of better statistical tools (e.g. for simultaneous selection of traits) might also significantly improve the efficiency of variety selection programs.

Multistage selection theory needs parameters to calculate the efficiency of selection programs. These are parameters for the variance components due to genotypes, genotype by environment interaction and the plot error as well as assumptions for the test capacity (total number of plots, maximum numbers by location and replications). The most critical parameter is the variance component due to genotypes or the genetic variation, because without significant genetic variation, even the most well designed selection program is inefficient. In the next section, a detailed explanation is provided to help the reader understand the degree of the genetic variation available to draw on for certain traits and attributes in sweetpotato.

Figure 1.1
Planting early selection stages of sweetpotato for the accelerated breeding scheme in San Ramon (one of four locations used at this stage).

Genetic variation of sweetpotato traits: Results from an evaluation of germplasm from the CIP genebank

Genetic variation is a prerequisite for genetic improvement. There is abundant literature for sweetpotato quality attributes (Woolfe, 1992), but earlier findings were based on just a few clones. In this section, preliminary results concerning genetic variation in sweetpotato from at evaluation of 1148 clones from germplasm in the CIP genebank provide a more comprehensive look at the availability of exploitable genetic variation for varietal improvement. The clones have been evaluated in three distinct environments in Peru since 2004: (i) arid irrigated lowland, (ii) humid tropic lowland, (iii) humid tropical lowland without fertilization. Within sweetpotato there are large differences in storage root concentrations of protein, starch, sucrose, total sugars, β-carotene, calcium and magnesium. The differences are less pronounced for iron and zinc (Table 1.1). Storage root starch contents of up to 33.3% (on fresh matter basis) and storage root sugar contents as low as 0.6% (on fresh matter basis) were observed. Storage root β-carotene, calcium, magnesium, iron and zinc contents of up to 154, 4091, 1815, 10.0 and 6.3 ppm were observed in fresh storage roots[3]. This corresponds to 15.4 mg β-carotene, 409 mg calcium, 181 mg magnesium, 1 mg iron and 0.6 mg zinc in 100 g fresh storage roots.

[3] Breeders often report vitamin and mineral concentrations on a dry weight basis (dwb) in parts per million (ppm). In the nutrition literature, it is more common to see concentrations reported on a fresh weight basis (fwb) in mg per 100 gms or µg/g (1 mg=1000 µg). To convert, one needs to know the dry matter content of the roots. For example, 15 µg/g β-

Table 1.1. Quality attributes in the sweetpotato germplasm.
Evaluated in 1146 CIP genebank clones across three environments: (i) arid irrigated, (ii) humid tropic lowland, and (iii) mineral stress humid tropic lowland with two plot replications [plot size 10 plants] per site.

	Mean	Min	Max
Yield (t / ha)	16.2	0.3	54.0
Upper Biomass (t / ha)	22.0	0.5	65.5
Dry matter (%)	35.0	15.9	48.5
Protein (% DM[†])	4.6	1.1	10.3
(% FM[‡])	(1.6)	(0.3)	(3.7)
Starch (% DM[†])	59.5	29.3	75.6
(% FM[‡])	(20.0)	(4.9)	(33.3)
Sucrose (% DM[†])	8.4	**0**	32.1
(% FM[‡])	(2.8)	**(0)**	(7.4)
Total Sugar (%DM[†])	14.1	**1.7**	47.2
(% FM[‡])	(4.7)	**(0.6)**	(10.1)
Total carotenoids (ppm DM[‡])	82	0	812
(ppm FM[‡])	(26)	(0)	(200)
-carotene (ppm DM[†])	38.3	0	**621**[§]
(ppm FM[‡])	(10.8)	(0)	**(154)**
Calcium (ppm DM[†])	1281	185	**4091**
(ppm FM[‡])	(429)	(76)	**(1110)**
Magnesium (ppm DM[†])	642	216	**1815**
(ppm FM[‡])	(219)	(57)	**(409)**
Iron (ppm DM[†])	16.2	9.0	**27.5**[§§]
(ppm FM[‡])	(5.6)	(2.7)	**(10.0)**
Zinc (ppm DM[†])	10.0	4.8	**18.7**[§§§]
(ppm FM[‡])	(3.4)	(1.18)	**(6.3)**

[†] storage root dry matter basis, [‡] storage root fresh matter basis.
[§]up to 1000 ppm, [§§]up to 40 ppm, and [§§§]up to 29 ppm occasionally observed in clones from breeding population after 2 cycles of recurrent selection.

Overall, significant genetic variation exists for all quality traits (Table 1.2). The magnitude of the genetic variation is large for starch, sucrose, total sugar, β-carotene, calcium, and magnesium storage root concentrations. The magnitude of the genetic variation for iron and zinc is not large; however, the lower confidence limit estimates indicate a genetic variation (σ_G^2) for iron and zinc of at least 1.9 ppm^2 and 0.6 ppm^2, respectively. The genotype by environment interaction ($\sigma_{G\times E}^2$) is low for all quality traits, except protein, iron and zinc. However, it should be note that this study included a large random sample of the sweetpotato germplasm tested in two agro-ecological zones. Hence, it is highly probable that clones specifically well adapted to only one of these agro-ecological zones drive a larger genotype by environment interactions than is usually found in breeding material for a given agro-ecological zone. For protein, iron and zinc we have observed in our current breeding material larger genetic variances and smaller genotype by environment interactions compared to the observations shown here from this genebank material study.

carotene fwb = 15 ppm β-carotene fwb. If the root has a dry matter content of 27%, then 15 ppm β-carotene fwb X (1/.27)= 55.6 ppm dwb.

Table 1. 2. Estimation of variance component due to genotypes (σG2).
Genotype by environment interactions ($\sigma_{G\times E}^2$) and the plot error (σ_{ε}^2) from 1146 CIP genebank clones evaluated at three locations: (i) arid irrigated, (ii) humid tropic lowland, and (iii) mineral stress humid tropic lowland with two plot replications per site (95% confidence limits of parameter estimates in brackets).

	σ_G^2	$\sigma_{G\times E}^2$	σ_{ε}^2	Ratio $\sigma_G^2 : \sigma_{G\times E}^2 : \sigma_{\varepsilon}^2$
Yield (t^2 / ha)	36.2	39.4	64.2	1 : 1.1 : 1.8
	(20.6 - 43.6)	(33.8 – 46.9)	(60.0 - 68.9)	
Dry matter ($\%^2$)	14.8	5.7	5.7	1 : 0.4 : 0.4
	(13.3 - 16.6)	(5.0 – 6.5)	(5.3 - 6.1)	
Protein ($\%^2$ DM†)	0.21	0.67	0.73	1 : 3.2 : 3.5
	(0.16 - 0.30)	(0.59 – 0.78)	(0.68 - 0.79)	
Starch ($\%^2$ DM†)	21.5	3.2	16.3	1 : 0.2 : 0.8
	(19.3 – 24.2)	(2.3 – 4.9)	(15.2 – 17.5)	
Sucrose ($\%^2$ DM†)	5.6	2.1	7.4	1 : 0.4 : 1.3
	(4.9 – 6.5)	(1.6 – 2.8)	(6.9 – 7.9)	
Total Sugar (%DM†)	17.0	6.0	9.0	1 : 0.4 : 0.5
	(15.2 – 19.2)	5.2 - 7.1	8.4 – 9.7	
-carotene	6327	2462	1421	1 : 0.4 : 0.2
(ppm^2 DM†)	(5681 – 7091)	2224 – 2740	1323 – 1529	
Calcium (ppm^2 DM†)	74001	95990	157303	1 : 1.3 : 2.1
	(61485-90791)	(82657–112849	(147021–168708)	
Magnesium	143005	9880	17638	1 : 0.06 : 0.1
(ppm^2 DM†)	(12351–16764)	(8360 – 11858)	(16451 – 18960)	
Iron (ppm^2 DM†)	2.33	3.46	3.85	1 : 1.7 : 2.2
	(1.92 – 2.87)	3.0 – 3.97	3.59 – 4.15	
Zinc (ppm^2 DM†)	0.8	1.37	1.72	1 : 1.7 : 2.2
	(0.62 – 0.97)	(1.20 – 1.59)	(1.60 – 1.85)	

The improvement of one trait is not independent from other traits – genetic correlations exist[4] (Table 1.3). There is a strong genetic correlation between storage root dry matter and starch; and both of these traits have a strong negative genetic correlation to sugars. Given the magnitude of genetic variation for dry matter, starch, sucrose and total sugars, and the genetic correlation pattern of these traits, rapid breeding progress can be expected in selecting for non-sweet sweetpotato populations. With two recurrent selection cycles many clones should be available which are non-sweet (< 5 ppm total sugar content on dry matter basis). However, multi-trait index selection should be used and optimized to simultaneously select for desired levels of dry matter, starch, and sugars.

[4] These correlations are estimates based on means of phenotypic correlations across environments and replications; for details on how these are determined see Hill *et al.*, 1998.

Table 1.3. Estimations of genetic correlations in the sweetpotato germplasm.
Evaluated in 1146 CIP genebank clones across three environments (see Tables 1.1 and 1.2) and two plot replications; YLD storage root yield, DM storage root dry matter, PRO = protein, STA = Starch, SUC = sucrose, STOT = sugars total, BC = -carotene, Fe = iron, Zn = zinc, Ca = calcium, and Mg = magnesium storage root concentrations.

	YLD	**DM**	**PRO**	**STA**	**SUC**	**STOT**	**BC**	**Fe**	**Zn**	**Ca**
DM	-.253									
PRO	-.180	-.073								
STA	-.119	**0.748**	-.241							
SUC	0.033	-.450	0.141	**-.559**						
STOT	0.131	-.670	0.094	**-.771**	**0.674**					
BC	0.018	**-.424**	0.168	-.574	0.475	0.562				
Fe	-.150	-.286	0.813	-.433	0.335	0.346	**0.295**			
Zn	-.210	-.219	0.801	-.355	0.286	0.233	**0.275**	**0.860**		
Ca	0.014	-.331	0.262	-.384	0.286	0.367	**0.368**	0.409	0.424	
Mg	-.004	-.297	0.460	-.404	0.388	0.406	**0.311**	0.627	0.595	0.753

The breeding challenge is different in population improvement for high dry matter OFSPs, because a strong negative genetic correlation is observed between storage root dry matter and β-carotene concentrations (Table 1.4). Breeders in SSA are acutely aware that high dry matter, β-carotene-rich materials are hard to find – that is the consequence of the negative genetic correlation between these two traits. Practically, this means that breeding for high dry matter OFSPs requires intensive recombination, i.e. a large number of parents and many cross combinations, to generate the favorable alleles which demonstrate both high storage root dry matter and high β-carotene. Hence, the development of large high dry matter OFSP breeding populations requires more time than the development of non-sweet sweetpotato populations. We estimate that the former will require four recurrent selection cycles, of which one to two of these cycles (depending on the country) have already been carried out during the past few years.

A further challenge for producing micronutrient-rich OFSP is the enhancement of mineral concentrations in OFSP. Fortunately, the storage root β-carotene concentration is genetically positively correlated with calcium, magnesium, iron and zinc storage root concentrations. Moreover, using Near Infrared Technology (NIR) these traits can be determined simultaneously with β-carotene content. The additional cost is minor and this information should be used in selection decisions to enhance mineral contents in OFSP.

Table 1.4. Estimations of genetic correlations in OFSP germplasm.
Evaluated in selected clones with more than 40ppm -carotene in the CIP genebank (N = 1146); YLD storage root yield, DM storage root dry matter, PRO = protein, BC = -carotene, Fe = iron, Zn = zinc, Ca = calcium, and Mg = magnesium storage root concentrations.

	YLD	**DM**	**PRO**	**BC**	**Fe**	**Zn**	**Ca**
DM	-.181						
PRO	-.177	-.216					
BC	0.027	**-.578**	0.300				
Fe	-.152	-.475	0.824	**0.425**			
Zn	-.196	-.405	0.809	**0.421**	**0.897**		
Ca	-.033	-.361	0.368	**0.359**	0.523	0.537	
Mg	-.069	-.410	0.567	**0.366**	0.738	0.710	0.773

Using model calculations, we predict breeding progress of about 3 – 5 ppm iron and 2 – 3 ppm zinc per selection cycle; within four cycles we can reach minimum improved levels of 15 ppm iron and 8 ppm zinc. However, these model calculations do not consider the recombination effect from one generation to the next. Given the large amount of heterozygosity in sweetpotato, the potential for greater progress exists beyond these model estimates. So-called "index selection" is highly recommended for OFSP population improvement, because undesired responses to selection are inevitable due to the strong negative genetic correlation between β-carotene and storage root dry matter concentrations. The currently best index selection procedure for this task is the Pesek Baker index (Pesek and Baker, 1969). With this selection procedure it might be possible to develop many high dry matter OFSPs with high mineral density.

Clearly, model calculations for the allocation of breeding resources are a very helpful tool to demonstrate to breeders "what happens if …." An example is the allocation of breeding resources in a two stage selection (Grüneberg *et al.*, 2004); another urgently needed model investigation is the determination for the optimum ratio between number of cross combinations and number of clones to be raised per cross combination. It is important that sweetpotato breeders throughout SSA become familiarized with the results of model calculations for optimally allocating their resources.

Finally, we need to consider cases where there is no or insufficient genetic variation to achieve our targets through conventional breeding. This should be discussed for three sweetpotato traits: sweetpotato weevil tolerance and iron and zinc concentration of storage roots. It is nearly certain that a significant genetic variation can be observed in sweetpotato (Hahn and Leuschner, 1981) as we have seen above for iron and zinc concentrations of storage roots. The question we need to

answer is: is this genetic variation sufficient to achieve significant impact? In the case of iron and zinc, the answer depends on the bioavailability of these minerals once ingested and this is discussed in the Challenge theme paper on OFSP. If the answer to our question is no, there is not sufficient genetic variation in sweetpotato, biotechnology can be useful tool for breeding to incorporate new variation into the sweetpotato breeding gene pool. This can be achieved by the expressing the *Bacillus thuringiensis* (Bt) toxin in sweetpotato in the case of weevil tolerance. This issue is a separate theme paper and will not be discussed here, but suffice to say that research to date in this area appears promising.

For enhancement of iron, there is potential to exploit the ferritin gene (*pfe*). This gene has been isolated from *Phaseolus vulgaris* and used to increase iron in rice grains 2 to 3.7 fold (Lucca *et al.*, 2001; Vasconcelos *et al.*, 2003). Another reference indicates that the ferritin gene (*pfe*) isolated from *Phaseolus limensis* under control of glutelin gene promoter could lead to a 64% increase in rice grains (Liu *et al.*, 2004). Sweetpotato ferritin could be easily isolated, exploiting the available sequence information. Constitutive and storage root-specific promoters exist for sweetpotato that can maximize transgene expression and protein accumulation. Whether the observed iron accumulation in the rice endosperm will be similar or not to that of a sweetpotato root remains to be demonstrated. As revealed in transgenic rice with high and low content of ferritin, optimum iron accumulation may be limited by barriers to uptake and at the transport level (Le *et al.*, 2005). Increase of iron uptake and transport factors may add to the level obtained with a ferritin accumulation in transgenic roots. The expression of nicotianamine aminotransferase genes in rice enhanced iron uptake as well as zinc (Takahashi, 2003). However, impact of enhanced uptake of other minerals has to be carefully monitored to avoid disorders on internal transports and increased accumulation of undesirable chemicals.

In considering any non-conventional breeding approach, there are many non-technical issues that must be considered in the SSA context, due to controversy surrounding the use of genetically-modified organisms and the dearth of bio-safety policies in most African countries. This approach should only be considered when conventional approaches to addressing critical traits have clearly not worked, as is the case for sweetpotato weevil resistance. At the present time, there may be substantial risk to gaining widespread acceptance of OFSP if OFSP varietal development is associated with non-conventional breeding efforts.

Population improvement

As previously mentioned, sweetpotato breeders distinguish between short-term population improvement and medium- to long-term population improvement. Both aim to improve the

population mean of important traits. The difference is that the long-term population improvement is focusing on the long term breeding progress, which includes new genotypes clearly out of range of the normal distribution. The latter is defined as a mean at least ± 2 standard deviations from the population mean of the initial breeding population - such as the desired genotypes for iron and zinc storage root concentrations – and developed in the context of selecting simultaneously for many sweetpotato traits and attributes. A "classic" example of a practically non-existent genotype outside the range of existing multivariate normal distributions is a variety that combines high dry matter (> 30%) and very high β-carotene (> 250 ppm on dry matter basis). Such genotypes can only be generated in several cycles of recombination and selection steps. But evidence from long-term maize experiments has clearly demonstrated that such "unbelievable" genotypes can be generated. In contrast, short-term population improvement programs focus on the "near" (< 5 years) future and need to generate sufficient genetic variation around a high population mean. In many respects, population improvement is the most difficult part of any sweetpotato (or any clonally propagated crop) breeding program. Sweetpotato is a hexaploid and each sweetpotato clone is a hybrid. This heterosis contributes tremendously to clone performance in sweetpotato. A cross to generate a genetic variation around a high population mean is recombining two F1's, which are hexaploid and highly heterozygous. Nearly every maize and wheat breeder in the world will say never cross two F1's, as the segregating genetic variance and the population mean derived for such a cross is rather unpredictable. Long-term population selection theory comprising several cycles of recombination and selection stages is very limited[5]. Certainly the matrix of genetic correlations is very critical, because negative genetic correlations can lead to undesired and unexpected genetic responses to selection which can result in whole breeding populations being useless for variety development. Such a critical negative genetic correlation exists in sweetpotato. This is the strong negative genetic correlation between β-carotene and storage root dry matter content. Marker studies have demonstrated that quantitative trait loci (QTLs) for β-carotene and storage root dry matter content can occur in the same linkage groups and occasionally are closely associated with the same genetic marker – which indicates the existence of *pleiotropy*, that is, one gene determining two different traits.

Studies at CIP have shown that there is exploitable heterosis in sweetpotato. So far the largest observed heterosis in an experiment using 4 x 12 parents was 50% above the best parent of well-performing parents. The genetic correlation between parent and off-spring clones was about 0.6

[5] That is, models for the recombination of good attributes (which appear in different genotypes before recombination) into one genotype is still a challenge in population selection theory.

in controlled crossings, which is low compared to parent and off-spring correlations in wheat. The correlation between parent and off-spring clones should be about 0.6 divided by two. These studies should be now carried out in two applied breeding populations to investigate the selection efficiency of a reciprocal recurrent selection scheme. This is a scheme often applied in maize breeding but not in sweetpotato breeding. We do not know much about quantitative genetics and selection theory in autopolyploids aimed at population improvement, even if only one trait is considered. This is reflected by the fact that the first textbook detailing research in this field of selection theory was only published in recent years (Gallais, 2003). In cases where the breeder has no, or only very low, prior knowledge on the value of cross combination, as is the case with sweetpotato, mathematical proof can be given that it is required to make as many cross combinations as can be afforded by the breeding capacity and to minimize the number of seeds developed for each cross combination. For this reason CIP Lima is conducting 6 x 300 cross combinations with the target of 20 seeds per cross combination, of which about 6 x 100 cross combinations are directly discarded due to very low seed set (< 5 seeds per cross combination). The breeding capacity required to conduct such crossings is two well-skilled technicians. Moreover, the ratio between number of cross combinations and number of seeds can be optimized by model calculations, which merits further research in sweetpotato.

A major challenge in population improvement of sweetpotato is to compare polycrosses to controlled crosses. Theoretically polycrosses must be inferior to controlled crosses, but much more seed and genotypes, respectively, can be developed so that the selection intensity in polycross breeding programs is usually higher than in controlled cross breeding programs. However, in cases where in both breeding methods the selection intensity is already high, this effect on the selection efficiency is small. Of much greater relevance is that in polycrosses only half of the genetic variance can be exploited than is the case in controlled cross breeding programs. Moreover, when dealing with polycrosses, one must take the unbalanced seed set and pollination into account – this is complex. Furthermore, when well-performing crosses are identified from polycrosses, this work can not be repeated on a large scale, as would be the case with material generated from controlled crosses. Extending the use of theoretical studies, utilizing them for designing breeding strategies, and evaluating the results based on those strategies, would significantly increase the sweetpotato breeding progress in Africa.

For sweetpotato population improvement we know that the number of cross combinations must be maximized subject to the resources available in the breeding program. Most breeding programs in Africa make few cross combinations (few number of parents). A useful "rule of

thumb" is that only one out of 40 cross combinations in sweetpotato is an excellent one. To summarize, in developing sweetpotato breeding programs for SSA, consideration needs to be given to:

- the number of parents used;
- the numbers of seeds and genotypes, respectively, raised for the first selection step, the checking of breeding objectives according to farmer needs by assuring farmer participatory selection is part of early breeding stages; and
- the use of one low or hot spot stress environment together with normal on-station environment as important factors to increase the breeding efficiency in African breeding programs.

The authors recognize that the modification of any breeding program is a very sensitive issue. Other factors such as speeding up the number of recurrent selection cycles, improved multi-trait selection in population improvement in the case of negative genetic correlations, and an accelerated variety development program combining four selection stages for variety development into three seasons, will not be an approach that every breeding program in SSA can or should undertake, given their resource base. Clearly, further research and more interactive design of breeding programs on a country-specific basis would be highly desirable.

Future areas of work for consideration:

1) Defining a critical capacity of genotypes to be tested at the first breeding stage for polycross and controlled cross breeding program. Shall these two breeding programs be kept separate and treated as two breeding programs carried out by the same institution?
2) Defining procedures for farmer participatory selection in an early breeding stage of the breeding programs.
3) Discussion and decision on the incorporation of a low input or hot spot stress selection environment at the early stages of a breeding program.
4) Defining the critical capacity for the number of parents used in population improvement for polycross and controlled cross breeding programs.
5) Discussion and decision to analyze the value of cross combinations (family evaluation) to repeat well performing cross combinations on large scale.
6) Model calculations for the comparison of the efficiency of polycross versus controlled cross breeding programs and estimations of the imbalance introduced by insufficient seed set in polycrosses and controlled cross breeding programs.
7) Potential collaboration of CIP and NARS breeding programs on regional platforms to increase breeding progress for discussion includes:

a. Implementation of near infrared spectroscopy (NIRS) technology on regional platforms to increase selection efficiency for non visible quality traits and to ensure that NARS breeding programs participate in the selection progress for non-visible quality traits by restricting dissemination of parental material to those which have clearly been improved for non visible quality traits.
b. Implementation of multi-trait selection methods that avoid undesired responses to selection or trade off effects in long-term population improvement.
c. Stepwise reduction of the time needed for a recurrent selection cycle to increase the medium to long-term selection efficiency and breeding progress.
d. Open the option to implement a reciprocal recurrent selection by generating two breeding populations which are kept separate; further research on the possibility of exploiting heterosis in sweetpotato breeding programs and design breeding methods to implement this in practical breeding programs.

Challenge 1.3. Lack of sweetpotato virus disease tolerance

Current knowledge

The **humid tropical low and mid-elevation regions of East Africa** (0 to 1200 m.a.s.l.) with only very short dry seasons, if any (Uganda, Rwanda, Burundi, Dem. Rep. Congo, parts of Kenya and Tanzania—the Lake Victoria Crescent) have high SPVD pressure, which is extreme in regions where sweetpotato is extensively cultivated. SPVD occurs after infection of two viruses: the sweetpotato feathery mottle virus (SPFMV) and the sweetpotato chlorotic stunt virus (SPCSV). SPCSV is the more problematic component of SPVD, because yield losses due to SPFMV - without SPCSV infection – are relatively low and SPFMV resistance of sweetpotato breaks down after the plant is infected by SPCSV. SPCSV resistance has been found in germplasm screening programs and the resistance appears to be conferred by a recessive allele that occurs in low frequency in the sweetpotato gene pool. Field resistance to SPVD has been obtained in East Africa by screening large numbers of sweetpotato genotypes from mainly local germplasm, and open-pollinated seed and limited controlled cross progenies, evaluated on-station and on-farm. However, this resistance still needs to be proven in extensive controlled artificial inoculation with SPVD and field tests under high SPVD pressure locations in Africa. It is nearly certain that new sweetpotato varieties with resistance to SPVD will result in significantly higher yields and yield stability in East- and Central Africa, at least for a period of 5 to 8 years. After this period new strains of the sweetpotato chlorotic stunt virus gene pool are expected to emerge.

Future areas of work for consideration (order listing does not imply any prioritization):

1) Defining the critical capacity for the number of parents used in population improvement for polycross and controlled cross breeding programs.
2) Defining critical capacity for a NARS sweetpotato breeding program. Defining critical capacity of genotypes to be tested at the first breeding stage for polycross and controlled cross breeding program.
3) Discussion and defining the percentage of breeding capacity that should be allocated to white-fleshed and OFSP SPVD resistance and high dry matter in East and Central Africa.
4) Discussions and decisions on the number of parents to be used for white-fleshed and OFSP (in combination with other desirable traits) breeding program and the cross design to be used for their recombination.
5) Model calculations for the comparison of the efficiency of polycross versus controlled cross breeding programs and estimations of the imbalance introduced by insufficient seed set in polycrosses and controlled cross breeding programs.
6) Discussion and decision to analyze the value of cross combinations (family evaluation) to repeat well performing cross combinations on a large scale.
7) Defining clear breeding objectives on the basis of regional needs and capacities for each agro-ecological zone and milestones and breeding progress, respectively, to be reached in products and varieties, respectively.
8) Defining bottlenecks and how to address them in NARS breeding programs.
9) Defining procedures for farmer participatory breeding and selection in breeding programs.
10) Agreement to evaluate early breeding stage at two locations, of which one location is an off station high SPVD pressure location in which farmer participatory selection is used to discard clones.

Potential priorities identified during field visits for a CIP and NARS breeding program at a regional platform in East and Central Africa (ECA) to develop product / varieties for ECA (to be discussed):

1) Implementing NIRS technology to improve β-carotene, and mineral storage root concentrations in breeding populations at NACRRI;
2) Improving skills for sweetpotato in-vitro plantlet dissemination to NARS partners within Eastern Africa.
3) Developing procedures for later breeding stages to determine genotypic differences in market quality attributes of OFSP for home consumption and processing, and making

these available to NARS partners (each procedure should allow to evaluate 20 genotypes and a total samples size of 80 (two locations, two replications).

4) Discussion and defining the percentage of breeding capacity that should be allocated to OFSP SPVD and Alternaria resistance in combination with other desirable traits (high dry matter, dual purpose, processing quality, in ground storage) in East and Central Africa.
5) Agreement to evaluate early breeding stage at two locations of which one location is an off station high SPVD pressure location in which farmer participatory selection is used to discard clones (Determine population size at each location).
6) Clarification to determine the value of a cross combination and if elite crosses should be repeated on a large scale (if yes, the size of an elite cross has to be defined).

Challenge 1.4. Lack of varieties adapted to the cold tropical highlands

Current knowledge

Sweetpotato originated in semi-humid regions of Central America, most likely in or close to Nicaragua. However, it rapidly came into cultivation along the arid Pacific coast of South America with relatively cool and hot seasons within the year. The crop crossed the Pacific in pre-Colombian times and became a staple in the relatively cool tropical highlands of Papua New Guinea and adjacent Irian Jaya / Indonesia, where it developed a secondary center of genetic diversity. The crop reached the tropical highlands of Eastern Africa most likely in the mid-19th century. Today sweetpotato is grown in African highlands up to 2200 m.a.s.l. with night temperatures close to 5°C. It is not surprising that the most successful sweetpotato variety in the Arusha highland region of Tanzania originated from Papua New Guinea. Usually sweetpotato responds in cold tropical highlands by extensive upper biomass production and reduced storage root production. Within the sweetpotato breeding program at CIP-Lima, many genotypes have been observed that are yielding storage roots in the cold tropical highland environment at 2700 m.a.s.l. (close to Huánuco) (this location is usually used as an multiplication side with no virus pressure to obtain virus free planting material). In Africa three NARS are conducting sweetpotato breeding or variety selection in cold highlands, namely ISAR in Rubona / Rwanda, KARI in Nakuru / Kenya and HortiTenguru in Arusha / Tanzania. These breeding programs are relatively small and very new or are working only on variety selection with periodically introduced material. Given that the tropical highlands of Africa are densely populated in rural areas and sweetpotato is an important component of the diet, investment in breeding is warranted. Also, some of these areas have close access to larger urban markets, so quality traits for urban consumers will be relevant

selection criteria. Soil erosion and zero grazing commitments are also important issues in these highland regions.

Future areas of work for consideration:

1) Identification of new material for Africa from other highland regions of the world and introduction of this material to broaden the genetic basis of African sweetpotato highland material.
2) Increasing the crossing capacity in NARS breeding programs for highland regions; critical mass could be 240 cross combinations to obtain at least 160 families with about 8 to 20 clones per family.
3) Defining lowest acceptable values for storage root and upper biomass production of dual purpose sweetpotatoes.
4) Implementing the accelerated breeding scheme with a test capacity of at least 2500 clones at the early breeding stages and discarding all clones which do not meet the lowest acceptable root formation and biomass formation according to one stress environment for Alternaria by farmer participatory selection.
5) At least four products and varieties, respectively, clearly superior in dual purpose use and acceptable to farmer needs by farmer participatory variety selection in later stages (year 4) of the breeding program.
6) One cycle of pre-breeding in tropical highlands with selection of medium pro-vitamin A contents and intense selection for minerals and value added product quality (first priority if OFSP is to be used as a substitute for wheat flour in bakery products and composite flours).
7) Incorporation of the pre-breeding population into the locally selected material by introducing seed (25,000 seeds) of the second cycle of recurrent selection (seed derived from the "best" of the first cycle), selection for local acceptance among introduced seed and genotypes, respectively, and recombination of selected clones (60 clones) with the best local material.
8) At least 2500 breeding clones (or one breeding population for further population improvement) with improved dual purpose use, quality is sufficient to make a product with a higher value e.g. bread, with elevated mineral concentrations and medium pro-vitamin A concentrations.
9) Repeat the development of the best five families by recombination of their parents on large scale (1500 seeds per family) for further variety development.

Challenge 1.5. Lack of tolerant varieties

Current knowledge

Southern Africa is defined here as including: Angola, Botswana, Lesotho, Namibia, Malawi, Mozambique, Madagascar, Malawi, South Africa, Swaziland, Zambia and Zimbabwe. The region is very diverse, ranging from forest and grasslands to deserts, with both low-lying coastal areas, and mountains. For two farming systems sweetpotato is attractive: (i) Root Crop Farming System (livelihoods depending on: cassava, legumes and off farm work) and (ii) Cereal-Root Crop Mixed Systems (Livelihoods depending on: maize, cassava, legumes, cattle). These are the major farming systems in Angola, Malawi, Mozambique, Swaziland, Zambia and Madagascar (Dixon *et al.*, 2001). Sweetpotato fits well into these systems especially in rotation with a legume. However, sweetpotato is not a primary staple in the region (except in parts of Malawi), but is widely grown as a secondary staple on a small scale. The importance of sweetpotato has been increasing over the past decade in Southern Africa for the following reasons: (i) its high nutritional value, (ii) its high energy output per unit land (iii) its ability to produce on low fertility soils, (iv) the potential to be used in small-scale and industrial food processing, and (v) recently due to new breeding activities that combine these characteristics with improved adaptation to drought stress. Owing to climatic change it is expected that drought stress will increase significantly in this region of the world (Hoerling *et al.*, 2006). It should be noted that in some regions sweetpotato has reached an importance nearly comparable to maize and cassava (e.g. in 2002 Malawi produced 1.7 and 0.09 million tons of maize and rice, respectively, compared to 1.7 and 1.5 million tons of cassava and sweetpotato, respectively; the estimated production increase for cassava and sweetpotato over the past four years is 15% and 36%, respectively). This trend is expected to continue because the region has a medium risk of frequent exposure to floods due to cyclones and a medium to high risk of frequent exposure to drought. These weather disasters have repeatedly affected the dominant staple crop in the region - maize. Thus, many governments have adopted crop diversification strategies designed to reduce maize dependence. This is reflected by the recent establishment of several small sweetpotato breeding groups at FIFAMANOR (Madagascar), Mansa Technology Assessment Site (Zambia) and DARS (Malawi). The breeding program Agricultural Research Council- Roodeplat (South Africa) is the longest running in the region. In addition, the CIP/IIAM breeding program in Mozambique is relatively young, having been established in 2006 with Rockefeller Foundation support. It is expected that new sweetpotato varieties, improved for yield and quality with specific adaptation to the drought environments of Southern Africa, will contribute to stabilizing the food and nutrition security situation in the region, as it has done in Asia, where it has long contributed as a food security crop when typhoons demolish grain crops.

Most likely owing to the early cultivation centers (Central and the arid Pacific coast of South America) a strong drought and salinity tolerance evolved in the sweetpotato. Drought resistance is most frequently a combination of drought escape, avoidance and tolerance (Blum, 1988). There are many reports describing drought stress resistant varieties (Anselmo *et al.*, 1998; Chávez *et al.*, 2000; Ding *et al.*, 1997; Hou *et al.*, 1999; Wang *et al.*, 2003; Yang *et al.*, 1999). To our knowledge, all studies on drought resistance in sweetpotato have tackled drought adaptation by evaluating total biomass or storage root harvest under drought stress conditions. This is not sufficient. It is very important that breeding programs in Southern Africa (the dry season varies extremely in time and intensity) evaluate adaptation to drought environments considering both root yield and vine survival, the latter broadly defined as the availability of planting material at the beginning of the next rainy season. Farmers are very reluctant to permanently adopt varieties that produce adequate quantities of roots under drought stress if they lack good vine survival. An example is the OFSP variety Resisto that has high β-carotene values and is intensively used in Mozambique because of its good taste and high marketability.

The genetic basis of adaptation of sweetpotato to drought stress is largely unknown. Sweetpotato roots can penetrate to about 2 m in the soil and absorb water from deeper soil layers (Bouwkamp, 1985). Differences in response of genotypes in irrigated and non-irrigated experiments appeared to be correlated with the ability for deep rooting and extensive development of the root system in the early stage (Yen *et al.*, 1964). Relative water content (Chowdhury *et al.*, 1993) and water use efficiency appear (Kelm *et al.*, 2000) to be further important traits adapting sweetpotato to drought. Other traits which are correlated with drought resistance are the relative contents of free amino acids, soluble sugars, ATP and chlorophyll a/b ratio, which indicate the participation of osmotic adjustment with drought resistance in sweetpotato (Zhang *et al.*, 2003; Zhang *et al.*, 2004). However, complicated crossover interactions exist for sweetpotato between irrigated and not irrigated field trials (Andrade *et al.*, unpublished). In other words, what is good under drought stress conditions is not good under humid conditions and vice versa. Hence, breeding for drought adaptation needs its own breeding program and its own long-term population improvement. Furthermore, it is essential to record vine survival and select for this trait. The evaluation of vine survival is laborious because plants or parts of the experimental plot must be maintained quite long into the dry season after harvesting the major plot area. CIP and NARS researchers recently jointly developed breeding procedures for this on the basis of an extended plot size (an area of about 20% of each plot is maintained after harvest). There are no variance component and heritability estimates available for vine survival, but we assume that heritability for vine survival is very high, because extreme differences are

easily observed among genotypes. If this is true, breeding populations can be rapidly transformed into populations with good vine survival attributes. However, this requires that the extended plot size principle is applied to the early breeding stages (e.g. instead of 1 m row plot in early stages, 1.5 m row plots have to be planted).

The challenge for breeding for high dry matter OFSP varieties is not as great in Southern Africa when compared to East Africa. The acceptable level of storage root dry matter is lower than in East Africa (about 27% versus 30% in Southern and East Africa, respectively). Nationally representative sample survey data in Mozambique estimated that already 20% of the total sweetpotato production is OFSP. Moreover, considerable work has demonstrated that OFSP can be processed into a variety of products (juice, bread, etc.) acceptable to consumers. For these reasons, and others described in the theme paper on OFSP, breeding resources in Southern Africa should be concentrated on OFSP breeding, including the breeding for improved mineral contents in OFSP. However, this requires investments into a strong quality breeding at CIP-Mozambique and IIAM, respectively, on the basis of NIRS technology (in a first step CIP allocated a dry freezer with a capacity of 30 kg of samples per week at IIAM). CIP- Mozambique / IIAM-Maputo could serve as a platform for NARS breeding programs in Southern Africa (Malawi, Zambia, Madagascar, Swaziland, Angola, and South Africa; only South Africa has a relatively well financed sweetpotato program).

NARS partners should debate whether to allocate at least 80% of the breeding capacity in Southern Africa to OFSP breeding and if the principal goal should be to produce drought adapted OFSP, with high vine survival and moderate to high storage root dry matter. There are at least 60 OFSP clones available in and for the region of Southern Africa, which should undergo intensive recombination. The recombination intensity would need to be increased among these OFSP clones. To ensure a more balanced recombination, breeders in Southern Africa could carry out controlled crosses; for example, a factorial cross design (6 male partners x >54 female parents) with a required test capacity in early breeding stages of 6000 genotypes. This would have the advantage of being able to repeat the best cross combinations (determined on basis of the family mean of a cross combination) on a large scale. To repeat five of these so- called elite crosses with at least 1000 seeds per cross combination would require an estimated test capacity of 5000 to 8000 genotypes. Each NARS partner could evaluate two populations --one with about 6000 genotypes and one with about 5000 to 8000 genotypes in separate years. Provided that these breeding populations are evaluated in the early stage (with active farmer participation) for storage root size, shape and form, storage root dry matter, β-carotene content (using color

charts), and vine survival, it is nearly certain that within five years each breeding program could develop at set of at least five OFSP varieties adapted to farmer needs in Southern Africa.

The platform in Mozambique could potentially supply within five years parental material to NARS partners with similar attributes as developed by NARS partners (high storage root yields under drought stress, high vine survival), deep orange-fleshed (about 200 ppm β-carotene on dry matter basis and at least 28% storage root dry matter) that is additionally improved in iron and zinc storage root concentrations. One achievable target could be OFSP parental material with at least 28 ppm iron and 15 ppm zinc on storage root dry matter basis; mineral target levels will require further discussion. The work at the platform in Mozambique could also have spillover effects to other drought prone regions in the world e.g. those in South West and Central Asia (SWCA). Evidence is accumulating that Southern Africa, SWCA regions and the arid Pacific coast of South America represent very similar agro-ecological zones regarding potential sweetpotato performance (e.g. varieties like the OFSP Jonathan, a Peruvian landrace, has been adopted widely in all these three regions of the world). CIP Lima has already identified 50 drought tolerant OFSP clones in a germplasm evaluation of 1300 clones (no breeding clone included) that already have iron and zinc concentrations of 30 ppm and 20 ppm, respectively (Table 1.5).

Table 1.5. Selected OFSP (n=50) out of 1300 CIP germplasm clones evaluated for drought resistance and nutritional quality.

	Mean	Min	Max
Yield (t / ha)	10.2	3.2	34.8
Dry matter (%)	27.6	19.9	36.3
-carotene (ppm DM†)	224	80	542
Calcium (ppm DM†)	1996	1002	3146
Magnesium (ppm DM†)	874	424	1351
Iron (ppm DM†)	17.2	12.1	30.3
Zinc (ppm DM†)	9.1	5.7	17.1

† storage root dry matter basis.

Note: CIP-Mozambique and IIAM will continue to conduct variety development (promising and advanced breeding clone testing) for Mozambique and have the potential to serve - via in-vitro laboratory facilities at IIAM - the region of Southern Africa in germplasm dissemination and exchange.

It would also be beneficial if fast screening procedures could be developed to be able to screen a batch of 20 advanced breeding clones within a few days for market quality attributes of OFSP needed for processing into distinct products such as juice, bread, chips etc. from new varieties. Working groups at CIP-Peru, CIP-Mozambique and IIAM have already demonstrated that some products are acceptable to consumers and that there are distinct differences in the suitability of genotypes for the different product. It would add value if new OFSP varieties could be released with clear information concerning their potential best uses as processed products. This would

necessitate developing procedures to evaluate these attributes and ensure that NARS breeding programs are empowered to utilize them as part of their evaluation of advanced breeding material at the later breeding stages.

Future areas of work for consideration:
Priorities NARS breeding programs to develop products / varieties for Southern Africa (to be discussed):

1) Discussion and defining the percentage of breeding capacity that should be allocated to OFSP drought adaptation breeding in Southern Africa. Discussion and decisions about the number of controlled crosses versus polycrosses is appropriate for a given program;
2) Discussions and decisions on the number of parents to be used for the OFSP breeding program and the cross design to be used for their recombination.
3) Agreement to evaluate early breeding stage at two locations of which one location is an off-station drought stress location in which farmer participatory selection is used to discard clones (population size about 6000 clones x 2 locations).
4) Agreement to evaluate the vine survival (availability of planting material) on the basis of extended plot size (suggestion 1.5 m row plots in early breeding stages).
5) Determination of the value of a cross combination and whether elite crosses should be repeated on a large scale (if yes, the size of an elite cross has to be defined).

Discussion and consensus on whether elite cross populations can be evaluated at two locations using a farmer participatory approach and on the basis of the extended plot size to determine vine survival within less than 5 years.

Priorities CIP and NARS breeding program at the regional platform for Southern Africa to develop product / varieties (to be discussed):

1) Implementing NIRS technology to improve β-carotene, and mineral storage root concentrations in breeding populations at the regional platform in Mozambique;
2) Improving skills for sweetpotato in-vitro plantlet dissemination by NARS partners within Southern Africa.
3) Increasing the capacity for controlled crosses to 7 x 200 cross combinations (by using the population ZapalloSPK-Tanzania (available at CIP Mozambique), which has recently been developed and improved by one recurrent selection cycle for dry matter, β-carotene, iron and zinc storage root concentrations) – target 40 seeds per cross combination.

4) Maintaining and further recombination of the local population "Resisto-Jewel", which has been developed at CIP-Mozambique and IIAM during the years 2006 and 2007 – target 40 seeds per cross combination.
5) Multi-trait selection based on new tools for population improvement (software) to be developed by CIP-headquarters (see Challenge 2) for drought stress yield, vine survival, storage root dry mater, β-carotene, iron and zinc concentrations in the population "Resisto" and ZapalloSPK on the basis of 16,000 genotypes for each population evaluated at two locations.
6) Providing NARS partners in Southern Africa with the top 10 clones of each population (Resisto and ZapalloSPK) to be used as parents by NARS partners to elevated iron and zinc in their breeding populations.
7) Developing procedures for later breeding stages to determine genotypic differences in market quality attributes of OFSP for processing and making these available to NARS partners (each procedure should allow evaluation of 20 genotypes and a total samples size of 80 (two locations, two replications).

Challenge 1.6. Lack of non-sweet sweetpotato varieties

Current knowledge

West Africa is defined here as including: Benin, Burkina Faso, Cameroun, Cote d'Ivoire, Cape Verde, The Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone and Togo. The vast majority of the region consists of plains lying less than 300 meters above sea level. The northern section of West Africa is known as Sahel (150–500 mm of rainfall per year); the savannas (500 – 1000 mm of rainfall per year) form a belt (160 km to 240 km in width) between the Sahel and the southern coast; the southern coast region receives rainfalls of over 1000 mm per annum.

For two farming systems sweetpotato is attractive: Root Crop Systems (livelihoods depending on: yams, cassava, legumes and off-farm work) and the Cereal-Root Crop Mixed Systems (livelihoods depending on: maize, sorghum, millet, cassava, yams and cattle). These farming systems in which sweetpotato can play its greatest role, are major farming systems in all countries, except Mali, Mauritania, and Niger, in which the Agro-Pastoral Millet/Sorghum System (livelihoods depending on: sorghum, pearl millet, pulses, cattle, sheep, goats) is the major farming system (Dixon *et al.*, 2001). Sweetpotato is often not considered an important crop in many countries in the region; however, production in Nigeria increased by nearly 200 000 tons each year over the past five years. While this is likely to be an over-estimate due to poor agricultural statistics, it also reflects

demand for low-cost calories due to increasing population pressure. There is broad consensus among stakeholders in West Africa that one major reason for low sweetpotato consumption in some West African countries is due to sweetpotato not matching dominant regional taste preferences – the roots are too sweet and too low in dry matter compared to cassava, the dominant root and tuber crop. The Ghanaian national program is specifically selecting for non-sweet materials. Non-sweet sweetpotatoes have been developed in the United States and CIP has started a germplasm screening for this sweetpotato type on the basis of NIRS technology. A non-sweet sweetpotato type could potentially exhibit a major advantage over existing materials because it could be developed into a wide range of bland food products such as gari (small processed granules), which is eaten by millions of people in West Africa on a daily basis. Given the increasing land-constraint in West African farming systems sweetpotato has clear agronomic advantages over cassava due to its much shorter maturity period. An early maturing, non-sweet sweetpotato appropriate for processing could potentially transform the cost structure and diversity of staple food products in West Africa. The FAO estimations for sweetpotato storage root production in West Africa are given in Table 1.6.

Drought is, and has been, across human history, a major production constraint in the Northern regions of West Africa. This will not change, although modeling exercises suggest that the region will receive higher rainfall in the coming decades compared to the recent past (Hurrell *et al.*, 2005). There is a short and a long rainy season in many parts of West Africa. This rainfall pattern suits sweetpotato, as many potential clones fit into short crop duration requirements of 3-4 months. NARS partners in the region consider the weevil damage associated with periods of drought stress a greater problem than the drought stress itself, as it restricts the period where quality sweetpotato can be harvesting for sale. Sweetpotato weevils are in all regions and are a significant constraint in all areas with dry seasons lasting more than 3-4 months. We distinguish between *Cylas formicarius elegantulus*, which is observed in all parts of the tropics, *C. puncticollis* and *C. brunneus*, which are additionally observed in Africa, and *Euscepes postfasciatus*, which occurs so far only in the West Indies. It has been an objective to find weevil resistance for more than 50 years, but differences observed in the degree of weevil attack are likely driven by preference factors of the weevil. Farmers in Malawi believe that dense storage roots developed deep below the soil surface are less susceptible than less dense, moist-fleshed storage roots. Moreover, observations indicate that specific varieties (New Kawogo from Uganda, Santo Amaro from Brazil) are less affected by weevils due to chemical compounds in the root skin. This merits further investigation; as this compound is organic there is a very high probability that it would be possible to develop NIRS calibrations for it and to conduct fast-throughput screening in the

sweetpotato germplasm to identify genotypes with similar attributes. However, the dominant opinion is that no effective weevil resistance exists. For this reason a transgenic approach by Bt genes has raised research interest for more than a decade.

Table 1.6. Sweetpotato production in West Africa.

	Annual in 1000 tones				
Country	**2001**	**2002**	**2003**	**2004**	**2005**
Benin	57.00	74.51	51.12	50.00	64.01
Burkina Faso	41.65	37.00	28.51	40.86	70.82
Cameroun	175.11	181.98	185.90	190.07	190.00
Cote d'Ivoire	43.00	43.00	43.00	44.33	45.18
Cape Verde	n.a	n.a	n.a	n.a	n.a
The Gambia	n.a	n.a	n.a	n.a	n.a
Ghana	90.00	90.00	90.00	92.83	94.62
Guinea	135.00	86.54	60.00	98.31	109.01
Guinea-Bissau	n.a	n.a	n.a	n.a	n.a
Liberia	18.00	18.00	19.00	19.03	19.3
Mali	n.a	n.a	n.a	n.a	n.a
Mauritania	n.a	n.a	n.a	n.a	n.a
Níger	29.45	44.80	44.80	42.92	42.67
Nigeria	2473.00	2631.00	2800.00	2996.00	3205.0
Senegal	41.89	41.89	26.85	26.49	27.81
Sierra Leone	25.00	25.45	25.50	25.50	26.00
Togo	1.35	5.45	1.43	0.43	2.40

Source: FAOSTAT 2007. n.a. = not available.

NARS partners in the region usually have no or only very small sweetpotato breeding programs, concentrated on adaptive testing of introduced varieties or evaluation of local landrace performance. An exception is CSRI at Kumasi in Ghana. The breeding capacity for sweetpotato breeding in Kumasi is similar to that found in ISAR in Rubona, Rwanda. The crossing block comprises 11 parents, seed production is about 5000 seeds from polycrosses; the capacity for preliminary and advanced yield trials is roughly between 20 and 40 entries which can be tested at three locations. However, CSRI has very strong biotechnology and in-vitro laboratory facilities. In cooperation with the Biotechnology Nuclear Agriculture Research Institute, 24000 in-vitro plantlets of the variety Beauregard were provided to farmers in South Ghana to produce roots for the export market in France. The capacity of the institute is the production of 200 000 plantlets annually. Such large capacities could service large scale private-public sector initiatives to disseminate adapted OFSP varieties in the region via NGO. With investments in NIRS technology,

CSRI could become a breeding platform in West Africa that aims for long term population improvement for West African growing conditions. We feel that focusing completely on OFSP breeding in West Africa is risky. Moreover, there are no experiences to develop non-sweet OFSP varieties. One approach to consider is to allocate 50% of the breeding resources into the development of white or cream non-sweet sweetpotato and 50% into OFSP breeding adapted to West African growing conditions. In terms of population development this means that two populations must be developed. However, it appears that NARS germplasm collections are very small e.g. 150 accessions at CSRI, so that it might be difficult to find sufficient parental material to open a non-sweet sweetpotato recurrent selection gene pool. In contrast, the OFSP material is substantial due to larger seed introductions from NACRRI as part of the HarvestPlus program and there is sufficient adapted OFSP material to increase the number of parents and the number of cross combinations as needed. The critical capacity of both breeding programs (non-sweet sweetpotato and OFSP) should be 80 parents, 400 cross combinations (it must be kept in mind that about 1/3 of all cross combinations do not result in sufficient seed set in sweetpotato) and 6000 genotypes in the early breeding stages to be tested at least at two locations --one location with farmer participatory selection. In the case of the non-sweet sweetpotato breeding population, 5% of the existing germplasm at CIP has total sugar contents below 8% on dry matter basis (< 3% fresh matter basis). This material could be pre-bred for one cycle of recurrent selection for low sugar storage root concentrations and sent as seeds to NARS partners in the sub-region (Table 1.7). It should be noted that this pre-breeding strategy (gene pool ZapalloSPK) has been successful in broadening the OFSP breeding gene pool in Mozambique. However, we feel that pre-breeding and a germplasm screening in and for West Africa should be integrated in the development of the non-sweet sweetpotato breeding programs in West Africa.

Table 1.7. Selected non-sweet sweetpotato clones.
(n=50) out of 1146 CIP germplasm clones evaluated across three environments: (i) arid irrigated, (ii) humid tropic lowland, and (iii) mineral stress humid tropic lowland and two plot replications [plot size 10 plants].

	Mean	Min	Max
Yield (t / ha)	11.3	1.0	28.5
Dry matter (%)	40.3	34.7	44.8
Protein (% DM†)	4.6	1.1	10.3
Starch (% DM†)	65.2	39.3	75.6
Sucrose (% DM†)	4.0	0	6.7
Total Sugar (%DM†)	6.9	1.7	47.2
-carotene (ppm DM†)	5	0	91
Calcium (ppm DM†)	1058	185	1805
Magnesium (ppm DM†)	545	320	874
Iron (ppm DM†)	15.9	9	32.2
Zinc (ppm DM†)	10.1	6.6	13.7

† storage root dry matter basis

Priorities for NARS breeding programs to develop products / varieties for West Africa (to be discussed):

1) Discussion and decisions to develop two breeding sweetpotato gene pools (one for the non-sweet sweetpotato and the other for the OFSP).
2) If agreement is reached, work with the non-sweet sweetpotato and an OFSP gene pool defining the percentage of breeding capacity that should be allocated to these two programs in West Africa (suggested 50% to each program).
3) Local germplasm evaluation to identify at least seven potential parents for each the non-sweet and the orange program in each NARS breeding program.
4) Agreement to conduct germplasm introductions into each country mainly as seed to select introduced material on a larger scale for local adaptation (target to select 40 out of 1000 to 2000 seed introductions).
5) Discussions and decisions on the number of parents to be used for the non-sweet and the OFSP breeding program including the cross design to be used for their recombination (suggestion factorial 7 x 40).
6) Agreement to evaluate the early breeding stage at two locations of which one location is an off station location in which farmer participatory selection is used to discard clones (suggested population size about 3000 clones for each the non-sweet and the OFSP population).
7) Clarification to determine the value of a cross combination and if elite crosses should be repeated on a large scale (if yes, the size of an elite cross has to be defined).

Priorities CIP and NARS breeding program at the regional platform (Ghana) to develop product / varieties for West Africa (to be discussed):

1) Implementing NIRS technology to improve β-carotene, and mineral storage root concentrations in breeding populations at the regional platform, Ghana.
2) Discussion and decisions if a regional germplasm evaluation and pre-breeding should be conducted aiming at a broader repatriation of West African germplasm from the CIP genebank pre-breed for low sugar high dry matter.
3) Introducing drought adapted OFSP germplasm in form of seed for Southern Africa Agreement to conduct germplasm introductions mainly as seed (speed up, risk minimization) and to evaluate introduced seed populations in a farmer participatory approach.
4) Agreement to conduct germplasm introductions into West Africa mainly as seed (speed up, risk minimization) and to evaluate introduced seed populations in a farmer participatory approach.
5) Discussion and decision concerning increasing the capacity for controlled crosses to 7 x 150 cross combinations for each of the non-sweet and the OFSP breeding population – target 20 seeds per cross combination.
6) Multi-trait selection [with new tools for population improvement (software) to be developed by CIP-headquarters, see Challenge 2] for yield, yield stability, vine survival (extended plot size), storage root dry matter, and low sugar or high β-carotene, iron and zinc concentrations in the non-sweet and OFSP breeding population, respectively.
7) Providing NARS partners in West Africa with the top 10 clones of each population (non-sweet, OFSP) to be used as parents by NARS partners to elevated iron and zinc in their breeding populations.
8) Developing procedures for later breeding stages to determine genotypic differences in market quality attributes of non-sweet and OFSP varieties.

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