

Eco-Efficient Interventions to Support Cassava's Multiple Roles in Improving the Lives of Smallholders

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Abstract

Because of its long growing season and sensitivity to low temperatures, cassava (*Manihot esculenta* Crantz) is exclusively a crop of the tropics and subtropics. This effective exclusion from production in most of the developed world has had a strong and largely negative influence on the research investment in the crop. In spite of being one of the world's major calorie producers for human sustenance (second most important source of calories in sub-Saharan Africa after maize), cassava is little known in the developed world. Research investment into the crop was sparse until two centers of the CGIAR Consortium – the International Center for Tropical Agriculture (CIAT) and the International Institute of Tropical Agriculture (IITA) – began research on the crop in the mid-1970s.

Cassava produces better than many crops on acid and low-fertility soils, and under periodic or even extended droughts. Because it has no specific maturity period, there is no period of growth during which it is especially vulnerable to environmental stresses. On the other hand, because of its long growing cycle, typically 10–16 months, it may be exposed to many stresses during this period. Especially, it may endure a number of pest and disease attacks or periods of drought in some environments.

Cassava is more resilient than most crops in the face of multiple biotic and abiotic constraints, but it is vulnerable if inappropriately managed. On the one hand, this allows farmers to be moderately

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productive with low inputs, or even with crop and soil mismanagement. It is for this reason that cassava is sometimes cultivated on sloped lands without due protection against erosion, or on soils with declining fertility status and organic matter. The solutions lie in a combination of new eco-efficient technologies, education, policy, and improved market conditions so that farmers have fact-based advice and can afford to apply the appropriate inputs. Breeders, agronomists, and plant protection specialists should focus on technologies that support farmer income and food security through efficient use of inputs, natural resource management, and optimizing the genetic variability in genebanks to develop eco-efficient varieties.

Background

In early 2012 a press release picked up by several major media outlets announced that cassava is the “Rambo of the crop world” for its ability to stand up against the projected heat and drought stresses that will affect large areas of the tropics in the coming decades. The story was based on a special issue on cassava in the journal *Tropical Plant Biology* [vol. 5(1)]. This is hardly news to anyone who grows cassava or has been involved in its research for any period of time, but it was an important wake-up call for policy makers, research and development (R&D) agencies and donors – looking for opportunities to make agriculture more “climate change ready.” Most people in the developed world have never heard of cassava, in spite of its status as the fourth crop in importance in the tropics, just behind rice, maize, and wheat.

In sub-Saharan Africa, it is second behind maize as a food security crop.

The impending effects of climate change on crops are steadily gaining urgency for scientists and policy-makers. But climate change is only one of many forces that play out in the daily challenges that cassava farmers face. Eco-efficient cassava-based systems can contribute to multiple development goals aimed at some of the world’s most vulnerable people living in hotspot environments.

The people who rely on cassava to provide a significant part of their income or nutritional needs are typically among the world’s poorest (Table 1). They are often farmers who earn their living cultivating degraded and marginal lands, or urban poor who subsist on the lowest-cost sources of calories. At the same time, rapidly

Table 1. Global production (% of total) of cassava and comparison to other major starchy staples.

	Developing Countries				Least Developed Countries			
	Africa	Asia	LAC	Total	Africa	Asia	LAC	Total
Bananas	2.7	1.1	3.8	1.7	3.5	0.6	5.8	2.3
Cassava	12.4	1.1	4.7	3.6	17.9	0.4	7.5	10.7
Potatoes	1.5	2.7	2.9	2.5	1.3	2.4	0.2	1.8
Sweet potato	1.8	1.9	0.5	1.7	3	0.3	3.5	1.9
Yam	3.3	0	0.3	0.7	1	0	4.2	0.6
RT&B*	21.6	6.7	12.1	10.1	26.7	3.8	21.1	17.3
Maize	22.3	4.9	30.8	10.6	22.9	5.3	14.6	15.7
Millet	6.7	1.7	0	2.5	8.3	1	0	5.3
Rice	10.6	46.5	17.6	37	11.7	76.1	33.4	38.0
Sorghum	9.4	1.2	0.2	2.7	12.4	0.9	3.4	7.7
Wheat	23.5	35.2	31.1	32.6	11	11.5	20.4	11.3
Other crops	5.9	3.8	8.1	4.4	6.9	1.5	7.1	4.7
Total	100	100	100	100	100	100	100	100

* RT&B: Roots, tubers, and bananas.

SOURCE: www.rtb.cgiar.org/resources/proposal-documents/final-proposal-annexes/

expanding new markets for cassava products – especially in Asia, but increasingly in Africa and the Americas – are providing unprecedented opportunities for farmers to improve their income and well-being, and to better supply the needs of multiple markets. These changes are creating both opportunities and challenges across an array of system components. This chapter explores the key roles that research on eco-efficient production, processing, and marketing can play in improving farmers' and consumers' lives – through income generation, improved food security, better nutrition, and a healthier environment.

By far the most important product of the cassava plant is the starchy roots. They may be peeled, boiled, and eaten directly, or may be processed into a wide array of products for food, feed, and industry. The roots are typically about 85% starch, on a dry-matter basis (Sánchez et al., 2009). Their principal nutritional value is calories. Leaves are consumed in some countries, especially in Africa, and they are very nutrient-dense, especially in protein.

A range of evolutionary, agronomic, and commercial factors define where cassava is grown, how it is grown, how it is used, and the challenges growers face. The crop originated in

the Americas, and was widely distributed throughout the tropics and subtropics of the western hemisphere before the arrival of Europeans in the 15th century (Allem, 1990; 2002; Allem et al., 2001; Olsen and Schaal, 2001; Nassar and Ortiz, 2008). Traders carried it to Africa relatively quickly after Columbus. While the introduction to Asia is not well documented, it appears that Spanish traders introduced the species from Mexico to the Philippines in the 19th century, and independently from Africa to India.

While about 100 countries grow cassava (FAOSTAT, 2012), production is skewed toward a relatively few major ones (Figure 1). Four countries harvest almost half of global output of fresh roots: Brazil, Indonesia, Nigeria, and Thailand; and three-quarters of production come from just ten countries. Over half the production area is in Africa, but only one of the top four producers is located there. The remainder of production consists of about 30% from Asia and 16% from the Americas.

The species is uniquely tropical. Its long growing cycle of about eight months to a few years (average is about a year) and high susceptibility to frost limit its production to warm climates. In the subtropics, especially in southern Brazil, farmers

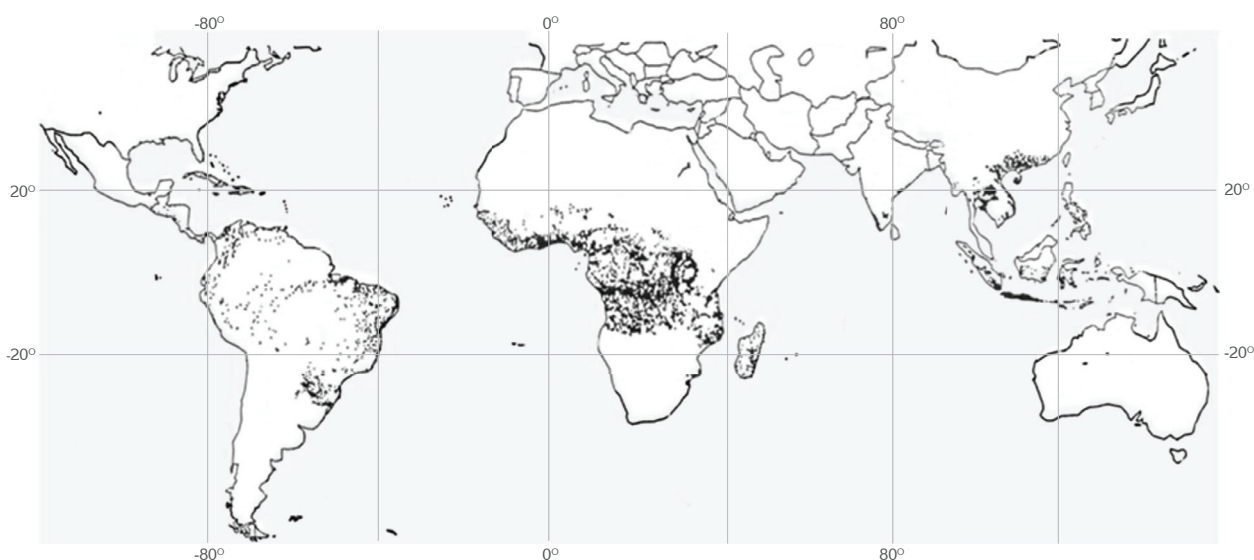


Figure 1. Distribution of cassava in the world. Each dot represents 1,000 ha. SOURCE: Henry and Gottret, 1996.

often cut back the stems at the onset of winter, and the crop continues growth again in the spring, allowing harvest at about 18 months.

Cassava roots can be “stored” in the ground for many months as part of an intact growing plant; there is no well-defined maturity period, although root quality may vary over time due to plant age and environmental factors. However, after harvest, roots begin to deteriorate quickly, often from a day to a few days (Beeching et al., 1993; Reilly et al., 2007). Over millennia, this rapid post-harvest deterioration stimulated the invention of many types of treatments and processing techniques to convert the roots into less perishable products. The main primary processes involve one or more of the following: grating or grinding and drying to produce flour; slicing or chipping and drying; and starch extraction. Variations include fermentation before or after grinding; forms of compressing to remove water; sun or artificial drying; and toasting or baking. Secondary processes include the production of a wide array of pellet-, flour-, and starch-based products for food, feed, and industry (Cock, 1985).

The primary processes not only convert a perishable product into one that can be easily stored, but also they greatly reduce the poisonous component contained at lower or higher levels in all cassava varieties – cyanogenic glucosides that enzymatically break down to release HCN when cell structure is compromised (Du et al., 1995; McMahon et al., 1995; Wheatley and Chuzel, 1995; Andersen et al., 2000; Mkumbira et al., 2003). Roots that are boiled and eaten without additional processing need to be from types with low cyanogenic potential.

While every cassava-producing continent encompasses a wide array of production systems and uses for this crop, some broad generalizations apply. These system characteristics impact the design of eco-efficient research strategies. In Africa, cassava is mostly grown on small farms (often less than one hectare) and intended for human food. Areas where fresh consumption is common include Ghana and Uganda. The leaves are an important source of protein, vitamins, and several minor nutrients, most notably in the

Democratic Republic of Congo (DR Congo). Production in Asia is also mainly by smallholders, with a few exceptions such as some large plantations for starch production in Cambodia, Indonesia, Lao People’s Democratic Republic (Lao PDR), and others. Uses are highly diversified within and across countries. India, Indonesia, and the Philippines produce mainly food products. China, Thailand, and Vietnam produce mainly animal feed and industrial starch; and China is also moving aggressively into biofuels from cassava. In the Americas, Brazil is by far the largest producer. Production systems range from the large plantations (up to a few thousand hectares) in the south, to the small landholdings for local markets in most of the rest of the country. In most other countries of the Americas, production is on small farms. In all continents, the vibrant market situation of recent years is attracting new, large investors. Often there is inadequate planning for the management implications of scaling up quickly in large plantations, and many of them have experienced early difficulties in production (Table 2).

There are several reasons why cassava tends to be a crop of the poor, and these have strong implications for the kinds of eco-efficient research interventions that can lead to positive changes, from both socio-economic and environmental perspectives.

- The crop is better adapted than many others to the harsh agro-environments where the rural poor tend to be concentrated, e.g., where rainfall is uncertain and drought stress is common; on soils with multiple production constraints, such as high acidity/high Al content and low native fertility; and on sloped lands where soils are prone to erosion and mechanization is difficult.
- It is a crop that will in many cases produce reasonable yields with few, or no purchased inputs, such as fertilizers, pesticides, or irrigation.

Table 2. Consumption of cassava as percentage of total for each region.

Region	Food	Feed	Export	Other
Africa	91	8	0	1
Asia	50	8	32	10
South America	43	51	1	5

SOURCE: Lynam, 2008.

Its vegetative multiplication means that farmers do not need to purchase seeds. The planting material is usually produced on-farm or shared among farmers. There are few commercial initiatives to produce planting material.

- Production practices are difficult to mechanize, although there has been considerable recent progress. Therefore, its cultivation can be a comparative advantage for farmers whose principal input resource is family labor.
- In many environments, cassava can produce nearly year-round (no specific maturity period, plus ability to store roots in the ground as part of the growing plant). Thus it has appeal to the poor, who may lack resources to pay for and manage storage facilities, such as might be required for a grain crop. It can be harvested when farmers need it. In Africa, even where cereals are the main crop, cassava plays a key role as a back-up crop when cereal production fails.

Although cassava is mostly cultivated under low-input and suboptimal soil and environmental conditions, in fact the crop has a very high production potential when provided optimum conditions. Both hypothetical models and field data show that cassava has a yield potential on the order of 80–90 t/ha per year (El-Sharkawy, 2012; El-Sharkawy et al., 1990). With a global average yield of about 12 t/ha, it is easy to see that there is a large yield gap that needs to be addressed to bring cassava's potential benefits to producers and consumers.

Production Constraints

It is common to find references in the early literature to cassava's "rustic nature," or its ability to produce a crop under difficult conditions. Historically many scientists considered it a crop with few pest or disease problems, and easy to grow with minimum inputs and little care. At the same time, it has developed a reputation as a crop that, more than most, causes environmental degradation, especially soil nutrient depletion and erosion. While there are elements of truth that underlie all of these assertions, none accurately reflects reality on a broad scale. Growers face a

range of biotic and abiotic constraints, which vary by region, cropping system, and season. Research organizations need to pay considerable attention to developing eco-efficient approaches to managing production constraints.

Biotic constraints

More than 200 arthropod pests and pathogens affect cassava (Bellotti, 2002; Bellotti et al., 1999). Most do not reach economic threshold levels of damage; however, they are living organisms with the capacity to move across regions and national boundaries, and to evolve and adapt to new conditions and new hosts. Climate change especially opens new possibilities for distribution and adaptation in new areas where these organisms may not have existed, or they may increase due to more favorable conditions for their etiology (Ceballos et al., 2011; Herrera et al., 2011).

One of the main features of the cassava crop that distinguishes it from the majority of annual crops is its long growing season. Pests and pathogens may complete many generations during the growing cycle. Furthermore, if host material is available in the field throughout the year, these pests and pathogens have no natural break in their cycle to limit their epidemiology. In this sense, cassava is an annual crop that has many of the features of a perennial crop, from the perspective of pest and pathogen dynamics.

The historical belief that cassava was not vulnerable to pests and diseases came from a period when most of the crop was cultivated on small and isolated plantations, often in intercropping systems, and before there was extensive international travel that readily carried pests and pathogens among regions.

Yield losses from pests and diseases are now understood to be common and widespread (Bellotti, 2002; Bellotti et al., 1999; Calvert and Thresh, 2002; Hillocks and Wydra, 2002). Nonetheless, the estimates of yield losses are generally on an experimental or localized level, and it is difficult to quantify losses on a broad scale. CIAT's Cassava Program attempted to develop realistic yield loss estimates for a broad

range of constraints, including pests and diseases (Henry, 1995).

In the Americas, where the crop evolved, the pests and pathogens co-evolved and attained their greatest genetic diversity. Additionally, the natural enemies of pests also co-evolved and became a fundamental part of the means for pest suppression. This combination of crop genetic diversity, pest/pathogen diversity, and natural enemy diversity has, for the most part, resulted in a reasonable suppression of the biological constraints in the Americas under traditional cultivation systems. The exploitation of these biological control agents can be one of the most eco-efficient approaches to pest control.

In Africa, now with a history of some 500 years of cassava cultivation, there have been both the time and the means to introduce many cassava pests from the Americas. The cassava green mite (*Mononychellus tanajoa*), cassava mealybug (*Phenacoccus manihoti*), and cassava bacterial blight (*Xanthomonas axonopodis* pv. *manihotis*) are major constraints in Africa, originally introduced inadvertently from the Americas. Others have arisen indigenously either as newly evolved species or through some form of adaptation from other crops to cassava. Cassava mosaic disease (CMD) and cassava brown streak disease (CBSD) are both caused by viruses that appear to have arisen indigenously in Africa. To date they have not been reported in the Americas, but a variant of CMD is present in India and Sri Lanka.

In Africa, green mites and mealybugs were quickly able to colonize cassava and spread across national borders. Without the genetic diversity of germplasm having some degree of host plant resistance, and without the presence of the natural enemies that helped suppress the same pests in the Americas, these pests spread virtually uninhibited throughout large areas of the African cassava belt in the 1970s and 1980s. CBSD is now raising similar concerns as it spreads widely within East Africa.

In Asia, cassava was able to escape some of the most destructive pests until very recently. Growers

in most areas did not have many concerns about pest and disease attacks, except in India (as mentioned above) where a variant of CMD from Africa has been a serious yield constraint since the first half of the 1900s. This is changing. In 2009, Thailand reported the presence of the cassava mealybug, and within a few years it was causing yield losses up to 80% in some fields. In 2010, on a national basis, yield losses were reported at 30%. Cassava is Thailand's second most economically important crop after rice, and the impact on the country was a wake-up call, both internally and for neighboring countries, facing the possibility of movement throughout the region.

There are several broad lessons from our experience with biotic constraints in cassava, which inform eco-efficient approaches to their management. We will expand on these strategies in subsequent sections.

- Cassava is host to a wide range of mites, insects, bacteria, fungi, phytoplasmas, and viruses. While a limited number are currently highly destructive, and usually on a limited regional basis, many others can evolve into economic pests if conditions are right. There is no room for complacency in any cassava growing area.
- Pests and pathogens can move globally in spite of existing quarantine regulations and the precautions of the scientific community. Most of the destructive pests and pathogens in Africa and Asia were introduced from the Americas via unauthorized movement of planting material.
- Pests and pathogens can move from other crops and evolve into major problems to cassava. They may also evolve to overcome existing resistance mechanisms. Fortunately, there have been few instances of the latter, probably in part as a result of breeding for multi-genic, multi-mechanism resistance.
- Experiences with intensified production give clear warning that changes in management can set the stage for pest and disease problems to change – often to become more severe unless integrated pest management strategies are incorporated in the production package.

- There is emerging evidence that climate change will broadly affect pest and pathogen dynamics (Ceballos et al., 2011; Herrera et al., 2011; Jarvis et al., 2012). Rising temperatures and changing rainfall patterns will affect insect/pathogen distribution and development.

Abiotic constraints

In many areas, cassava tends to be a *second choice* for farmers. If growers have better land, or have access to inputs that will improve growing conditions, they will often plant higher-value crops. It is part of the phenomenon that makes cassava a crop of the poor and one that faces a host of abiotic constraints. However, this is changing in some areas of strong market growth for cassava products, especially in Southeast Asia, where cassava prices have risen sharply in the past few years.

Soil conditions. Cassava production predominates on acid and less-fertile soils (Howeler, 2011a). It has the well-known ability to tolerate high soil Al concentrations and soil acidity without lime amendments. In fact, where there is economic response to lime, it is often as a result of response to Ca rather than response to soil pH (Howeler, 2011a). This adaptation to soil acidity favors cassava production across large areas of the cassava belt of Africa, in the southern cone of South America, the savannas of Colombia and Venezuela, in Mesoamerica and the Caribbean, and in southern China.

Cassava is especially adapted to soils with low P availability. The association with root mycorrhizae allows the plant to very effectively extract P from soils with very low levels. In fact, without the mycorrhizal associations, cassava grows poorly even where P levels are moderately high (Howeler, 2002).

Cassava production is also common in sandy soils with low water-holding capacity. In these soils, many crops suffer quickly from short dry periods. Crop failure can result from longer dry periods. Risks in these soils are often not so much related to total annual rainfall as to the likelihood of dry periods during critical phases of crop ontology such as flowering time in cereal or grain

legume crops. Cassava has no critical growth phase after establishment. Also, these soils tend to be leached and have low nutrient status because of the low organic matter status.

Rainfall. Rainfall and soil conditions are highly interrelated in their effects on crop growth and development, as noted above. Cassava is adapted in the tropics and subtropics from some of the driest (e.g., 400 mm annual rainfall) in the Sertao of Northeast Brazil, to some of the wettest agricultural environments (e.g., 4000 mm annual rainfall) in the Pacific coast region of Colombia. Cassava uses several complementary mechanisms to tolerate long dry periods, including deep rooting to access subsoil moisture reserves; stomata that respond quickly to low ambient humidity, thereby reducing transpiration when water is limiting; and the ability to draw on carbohydrate and water reserves in the starchy roots (El-Sharkawy, 2012). Some of these mechanisms come at the expense of optimum yields, but they do allow the plant to survive and produce something where other crops may fail completely.

Cassava is intolerant of flooding. Relatively short periods of submersion, of only a few days or less, can destroy a plantation. In heavy soils and in poorly drained soils, cassava often suffers from root rots and generally performs poorly.

Market Constraints

Certainly not all cassava growers are linked to markets; some are subsistence farmers, who grow only for family use. For these farmers, food security is often the first concern. However, increasingly, cassava farmers grow at least part of their crop for sale. Entry into the marketplace generates income to improve the family's ability to obtain a diversified and healthy diet, as well as broadly improve livelihoods. Access to markets is a critical part of food security for cassava growers. There is now a widespread interest, even for those countries where cassava's role is mainly for food security, to gradually transform it into a cash crop. Value addition of cassava, to bring benefits to growers, is currently a key objective in many countries in Africa, most notably in Nigeria. This

transformation should result in poverty alleviation, rural development, and strengthened links between producers and their markets (Nweke et al., 2002).

Nonetheless, in much of the cassava-growing world, and especially in Africa, most production is traded locally and is less influenced by global markets. Farmers who are connected to markets may face both the advantages and the disadvantages of a crop whose market prices are not closely linked to global grain markets.

Lack of synchronization between production and market demand, especially in emerging markets, often creates wide fluctuations in farm-gate prices. But even in countries with a long-established market tradition in cassava products, such as Thailand, the rapid market diversification is driving changes in the way the crop is grown, processed and marketed. Where there is greater market diversity, there is greater chance of stable demand and more stable prices. The mature markets of Asia include animal feed, starch for food and industry, biofuels and processed products for human food. While any one of these markets may experience considerable fluctuation in demand and prices, together they stabilize the prices that farmers receive. Stable markets encourage farmers to adopt new technologies (varieties, use of fertilizers, and soil conservation measures), which result in enhanced productivity and ultimately in more competitive prices, which in turn consolidate the competitiveness of these markets.

Typically large farms have advantages over small farms in marketing their products. This is especially a challenge for cassava, since small farms remain the norm around the world even as industrialization of the crop progresses. The move to more intensive, industry-oriented production has not necessarily meant a move toward large farms in the case of cassava. Southern Brazil and Northeast Thailand present two contrasting cases in this regard. Southern Brazil produces cassava mainly for the starch market, based on large farms, often over a thousand hectares. It is an environment where large farms have been the norm for many years, and cassava production and

processing have been adapted to this land tenure system. In Thailand and Paraguay, on the other hand, cassava farms remain small, usually a few hectares or less. Large centralized processing plants need to coordinate and aggregate the production from many farmers. Also typical in cassava processing plants is their location near the production areas because of the bulkiness and perishability of the roots. This is an important way for their operations to contribute to rural development. Nonetheless, there are increasingly examples of interest by companies buying or contracting large land areas for industrial use of cassava, e.g., in Cambodia, Colombia, Guyana, Indonesia, and Nigeria. Organizations focused on development-oriented support to cassava research will need to closely monitor the impact of such trends and the implications for target beneficiaries.

Increasingly, food security and improved livelihoods will be associated with the ability of farmers to sell their products in the marketplace. The association between capacity to improve income and expansive markets is clear worldwide. Farmers adjust their choice of crops, the way they are grown and how they are marketed based on access to markets. Few farmers, when given the choice, will remain poor subsistence growers, enduring long hours of backbreaking fieldwork, if there are available markets to sell their products at a profit and make their lives more comfortable and prosperous.

Market development for cassava has certainly evolved in most parts of the world, to one degree or another. But in Africa and in much of the Americas, these remain limited local markets, subject to easy saturation and price fluctuations. More robust, broader-scale markets typically need some initial support from public-private partnerships.

Market expansion and market development often depend as well on new products, and these new products may need new varietal traits and new processes. The intricate linkage between production, processing, and marketing is not automatic at the outset, especially in most of the situations where new cassava markets are needed,

i.e., where farmers are small scale and poor, infrastructure is limited, and credit for development is poor or non-existent. Research for development (R4D) organizations need to bring these initiatives into the context of an integrated and comprehensive project, in partnership with government agencies and the private sector. From the outset, such projects need to have a plan for reduced dependence on public subsidies and greater reliance on the marketplace for sustainable success.

An analysis of the potential markets for cassava and its products in each cassava-producing country is well beyond the scope of this paper. Both Latin America and Africa can learn considerably from the experiences of Asia, but clearly local conditions will dictate different products and different pathways. The free market tends to be a pretty effective regulator of supply and demand in mature industries, but until that situation is reached, there normally needs to be some intervention to balance the *push* and *pull* factors along the value chain development. Bringing the poorest farmers and small landholders into the equation for successful market development can be especially difficult, but that is precisely what is needed if cassava is to contribute its potential to raising the standard of living of the poor who rely on it.

An important lesson can be drawn from Vietnam. Cassava productivity in Vietnam in 1990 was almost the same as the average for Africa. However, as markets expanded there was a sharp surge of productivity that in few years almost doubled the levels of 1990. This is a clear indication of the beneficial effects of strong markets for cassava products. Where there is a market, farmers will seize the opportunity, invest in the crop, and increase their income. Another interesting example is cassava productivity in Thailand during the transition period when exports to the European Union (EU) were gradually phased out and before domestic markets in Asia developed. The upward trend in productivity reversed for few years. Only after the 1990s, yields started to increase and at a very healthy rate.

The case of Vietnam offers another lesson. An important bottleneck in the development of markets is that they require cassava to reach a competitive price, which in turn depends on farmers investing and using proper technologies and inputs. There is always a subtle and difficult step to break a vicious cycle: there is no market because there is no cassava at a competitive price, and cassava does not reach the markets at competitive prices because the lack of markets does not encourage farmers to invest in inputs and technologies. Although it is difficult to demonstrate that this was the case, it is tempting to hypothesize that in the case of Vietnam the vicious circle was broken because initially there was on-farm processing. Farmers did not sell their cassava but used it to feed pigs, which was their final product. This on-farm processing (not capital intensive) generated enough motivation for farmers to adopt new technologies that eventually allowed the conditions for the emergence of local processing plants (mostly for starch production or drying yards).

Key Eco-Efficiency Interventions for Productivity

Already in the early years of cassava research by international centers CIAT and IITA, it was understood that the *Green Revolution* approach to improving cassava was not broadly applicable. The high inputs of fertilizer and irrigation, and dwarf architecture that had brought high yields to wheat and rice were not appropriate for cassava in most of the areas where it is grown (Kawano and Cock, 2005). Production and marketing systems, policy, and the nature of the crop were all very different from the cereal grains, and different approaches were required. This was not universally understood or accepted, however, and there was a number of programs that attempted to apply high-input practices to cassava, most of which were unsuccessful. The reasons for lack of success were a combination of socio-economic, agronomic, and genetic factors.

Up to recent times, few cassava farmers anywhere in the world had access to purchased inputs to improve production, e.g., fertilizer, irrigation,

chemical pest and weed management; or mechanization for land preparation, planting, or harvesting. There were, however, some important exceptions, such as in India, where farmers achieved high yields with moderate fertilizer inputs and irrigation. Because of its long crop cycle, cassava may be exposed to a wide range of pests and diseases over many months, such that successful chemical control of pests often needs to be repeated many times, and thereby is often costly. Because of the crop's drought tolerance, it is often not cost-effective to invest in irrigation systems. Even though cassava typically responds to soil fertility improvement, access to fertilizer and credit are typically out of the reach for cassava growers.

Current buoyant demand for cassava and its by-products is motivating farmers, industry, and policy-makers to seek solutions to the problems that limit yield and income improvement from cassava production. The following sections review some of the eco-efficient alternatives that farmers and national, international, and private sector programs have developed and implemented.

Soil fertility maintenance and nutrient use efficiency

Soil fertility maintenance is a fundamental component of successful crop agriculture. Crops extract nutrients from the soil, and without their replenishment, yields in most soils will decline over time. Low soil fertility may be the single most pervasive constraint to high and sustainable cassava production worldwide. But it is highly amenable to improvements through eco-efficient intervention. Results from many cassava soil fertility trials have demonstrated that (1) yields steadily decline without soil amendments, and (2) yields can be stable when appropriate amendments are made. Substantial improvements to crop productivity usually include the application of exogenous nutrients in organic or inorganic form (Howeler, 2011a).

There are compelling reasons to work toward soil fertility solutions based on crop nutrient demand and optimized economic response. Fertilizer costs continue to rise worldwide, and their inappropriate application is frequently associated with nutrient

runoff into water systems or seepage into groundwater. This creates imbalances in aquatic ecosystems and raises human health hazards from drinking water contamination, and wastes money for producers.

In addition to practices that may be more broadly applicable to many crops, there are several innate characteristics of cassava that allow us to design eco-efficient agronomic management approaches. As already mentioned, the root association with mycorrhizae allows a very efficient extraction and uptake of soil phosphorous. The fungus exists naturally in virtually all cassava growing areas, and usually no special management is required to achieve good root infection for efficient P absorption. In some situations, where cassava is newly introduced into an area where it has not previously been planted, there may be an economic advantage to inoculation (Howeler et al., 1987).

There has been limited research on the selection of more efficient biotypes of the fungus, but there are indications that this could be a productive line of research (Howeler et al., 1987). The main constraint to testing and selection of efficient biotypes is the difficulty of managing the inoculant, e.g., artificial production, controlling native populations, and cost-effective inoculation procedures. Because of these difficulties, there has been little commercial use of mycorrhizal inoculations in cassava.

Development and application of crop management practices should avoid interference with the effectiveness of native populations. While the effect of agronomic practices on native systems is poorly understood, cassava researchers should be aware of, and test for, any deleterious effects that new inputs could cause. For example, systemic fungicides or herbicides should be especially monitored for their effect on mycorrhizal associations.

CIAT has carried out multi-year germplasm screening for efficiency of nutrient use, especially emphasizing potash (K_2Cl), which is used in relatively large quantities by cassava (reviewed by El-Sharkawy, 2012). There were large differences

among genotypes, and probably these could be exploited through breeding. However, establishing selection systems that take into account nutrient use efficiency is an expensive and complicated addition to the many other selection criteria that breeders need to include in their program. As an alternative to a complex system that evaluates nutrient use efficiency by comparing response to low and high nutrient levels, CIAT has routinely selected under low nutrient levels, to allow the more efficient types to express their favorable traits. This is a research area with potential to benefit from development of molecular markers and the use of marker-assisted selection or genome-wide selection.

Drought tolerance

Cassava is in the field for long periods, and it has no post-establishment critical period of drought vulnerability. This means that drought tolerance becomes very difficult to define. Drought can be comprised of a wide range of variables, e.g., total rainfall during the growing season; length of period(s) with low or zero rainfall; and the growing phase during which drought stress occurs (e.g., early, mid-, late season). While there would be clear advantages to better understanding of the mechanisms involved and the genetic control of tolerance to water deficits, this understanding will require much more research than is possible under natural and variable conditions.

CIAT physiologists have extensively studied genetic variation and mechanisms for drought tolerance and water use efficiency in cassava. One of the key approaches has been to compare varietal responses under irrigated and non-irrigated conditions in dry environments. There appears to be wide genetic diversity (reviewed by El-Sharkawy, 2012). Several mechanisms come into play that confer a high degree of drought tolerance to cassava compared to many other species. Water use efficiency is largely the combination of stomatal sensitivity to low atmospheric humidity (stomata close and conserve water when humidity falls), deep-rooting systems, and high photosynthetic activity. Some varieties also appear to tolerate drought by an excessive leaf area index under favorable conditions, which is reduced to ideal levels

(about four) under drought stress, thereby maximizing yield.

Breeders have capitalized on this genetic variation through various strategies, but mainly by planting breeding nurseries under drought stress conditions. This strategy has some advantages and disadvantages. The advantages include simplicity of management, and the possibility to simultaneously select different mechanisms through exposure to conditions that are representative of where new varieties will actually be grown. Disadvantages include the fact that the specific conditions of drought tend to be highly variable from year to year. This means that in any given year, it may not be possible to target the specific desired varietal traits. CIAT, for example, has had a few experiences of “drought” trials in environments with historical severe drought stress, where the trials have been destroyed by flooding (LA Becerra 2011, pers. comm.).

Weed management

Because of cassava's relatively slow early growth, canopy closure can take up to three months or more, leaving the crop vulnerable to weed infestation. Weeds can be a serious constraint to crop growth and yield, and their economic control a major challenge. Typically, manual weed control requires about 40% of labor inputs to produce a cassava crop. Weeding is often done by women, especially in Africa and Asia.

Research on eco-efficient weed management has received relatively little emphasis to date. In part this is because most weed management in cassava is still by hand hoeing, especially in Africa. However, this is changing as farmers look for more ways to reduce the high labor inputs and cost of growing cassava. Chemical weed control is possible, and herbicide use is rising, but mainly in Asia and in larger plantation systems elsewhere. Mechanized weeding is somewhat difficult in cassava except during the earliest stages of growth. Researchers face multiple challenges to integrate effective and economical weed control, with eco-efficiency principles, and gender-sensitive approaches. It is a research area that will become increasingly important and will require greater research emphasis.

Herbicide-resistant cassava could be a popular option for farmers, as it has been for crops like maize, soybeans, and canola. Technically it will probably not be very difficult to incorporate resistance (e.g., to glyphosate) through transformation protocols. But the licensing, regulatory, and the socio-economic issues (e.g., gender implications; consumer acceptance) will likely mean that any such technology is many years from widespread use.

Weed control is often the costliest input to cassava production, and it is imperative that science aggressively contribute to eco-efficient solutions as a means to reduce costs of production and increase farmer profits while protecting the environment.

Erosion control

Because cassava is among the most tolerant of crops in marginal conditions, it often occupies lands that are prone to erosion. This is true worldwide, but is particularly an issue in the Andean zone of South America and in Southeast Asia. Slow early growth and relatively wide spacing among plants mean that canopy closure can take 2–3 months – a period when the soil remains exposed to the heavy rains which typically occur near planting time. This situation can lead to severe soil erosion with devastating environmental and social consequences. Soil erosion in cassava systems is one of the most urgent problems for the long-term sustainability of cassava-based farming systems to support smallholder farmers.

Erosion control can be accomplished through soil preparation practices (e.g., ridge planting; conservation tillage, which leaves soil-protecting residue on the surface and soil-holding roots below the surface); strip cropping; intercropping; terracing; live barriers; practices that allow good ground cover (mulching; use of herbicides instead of hoeing); and practices that promote rapid canopy closure to protect exposed soil from direct rainfall impact (e.g., high early-vigor varieties; fertilization to promote rapid early growth).

One of the most successful technologies is planting of vetiver grass barriers (Howeler, 2011b). However, farmers often are reluctant to invest in

practices that do not provide short-term payback, especially if land is rented or, otherwise, not securely available for the long term.

Very little research has been done on conservation tillage systems for cassava. Clearly there are challenges, namely, the need to plant a large stem piece instead of a small seed, the inevitable soil disturbance that takes place at harvest, and the scarcity of good weed management systems without soil disturbance. Nonetheless, the potential payoff in lowering costs of production, in soil conservation, and in energy conservation makes this a research area worth pursuing.

Advances in small-plot mechanization may make no-till planting technologically feasible. Selection for herbicide-resistant varieties would also facilitate no-till technology, but is not a prerequisite for its success. Demonstration plots using farmer participatory approaches have been widely used in Asia to highlight the risks of soil erosion and the benefits of implementing preventive measures.

The bottom line is that in spite of all these practices being well known at the research level, their adoption worldwide has been limited. The solution is a combination of opportunities provided by the marketplace, education, policy, and research into new avenues for erosion control.

When market prices rise, farmers will be more easily convinced to invest in inputs that increase their productivity and profitability. In general, the market for cassava products has been buoyant over the past several years, giving hope that farmers will have greater motivation to invest in long-term sustainability of their systems through eco-efficient technologies.

The impact of erosion control is often not immediately evident to farmers, nor easily quantified. Their concept of long-term income loss may not be based on real, field-level data over time. This is also a management area which will depend almost wholly on the public sector initiatives; there are, in a broad sense, few options that can be offered that will be brought about through a profit motive of the private sector. This gives the public sector a heavy responsibility to thoroughly research

eco-efficient erosion control methods, to educate growers, and to educate policy-makers on the need for policy support.

Pest and disease management

Eco-efficient pest management systems focus on three main solutions: host plant resistance, crop management, and biological control. The combination of these approaches can be effective for most pests and pathogens of economic importance in cassava. Use of chemical control has a low priority for research, with the exception of highly targeted applications such as for planting material (stakes) treatment or infestation focal points.

Selection for resistance. Cassava evolved under pressure from many pests and diseases, and as a consequence genetic resistance co-evolved and was further brought into play by the conscious or unconscious selection by farmers. In many of the major crops, plant breeders protect nurseries with pesticides generation after generation, such that many resistance genes were probably lost due to genetic drift. In the case of cassava, this has rarely happened. First, cassava breeding has been practiced on a limited scale and for a limited time worldwide. Secondly, most cassava breeders allow natural infestations of pests and pathogens as a way of selecting for resistance. These strategies have allowed a remarkable opportunity for capitalizing on host-plant resistance in cassava, without breeders having to use exotic material or wild species in lengthy pre-breeding programs. Host-plant resistance is a clear and successful example of the development of eco-efficient practices. Nonetheless, as new pest challenges arise, especially as a result of climate change, there is greater likelihood of the need to delve further into germplasm collections and engage in pre-breeding to extract new resistance genes.

Breeders have made excellent gains in developing resistance to several key pests and pathogens, including cassava bacterial blight, CMD, superelongation disease (*Sphaceloma manihoticola*), *Phoma* leaf spot, thrips, cassava green mite, and whiteflies (Jennings and Iglesias, 2002). In recent years, molecular tools have begun to aid in selection, specifically with CMD in

Africa. A molecular marker for a single-gene resistance not only allows speeding up the breeding process, but it has allowed the selection for resistance in Colombia, where the disease does not exist. Breeders now have a greater ability to combine desired traits from the Americas with the virus resistance needed for adaptation in Africa (Okogbenin et al., 2011). While molecular-assisted selection is so far very limited for cassava, this is likely to change quickly in the next few years as the costs of sequencing and of various *-omics* technologies decline rapidly.

Crop management. The long growth cycle of cassava is conducive to the build-up of many types of pests and pathogens. This creates challenges, but also opens up many opportunities during the crop's long period in the field, to introduce variable management packages for suppressing pest and pathogen damage. Some of the common practices that can contribute to pest suppression include adjusting planting date, plant spacing, and intercropping. Early trials in the Eastern Plains of Colombia showed that planting near the end of the rainy season was a viable strategy for reducing losses from bacterial blight and superelongation disease (CIAT, unpublished). One of the challenges of using management practices to control pests and pathogens is to assure that any changes in management do not reduce yields even more than the pest under standard crop management.

Biological control. Biological control is one of the most eco-efficient practices possible for pest management. The development time can be relatively rapid (in contrast to the long lead time for developing resistant varieties, for example); there is virtually no trade-off in yield or quality with the application of biocontrol methods; and in many cases, the control can be long-lasting without the continued need to reintroduce the organisms.

In the Americas, biocontrol agents (parasites and predators) evolved along with the crop during many millennia. However, when traders introduced cassava to Africa and Asia, most of these beneficial organisms were left behind. When new pests were introduced, they were often able

to spread uninhibited by the natural enemies they faced in their evolutionary homeland. There have been several examples of the introduction of natural enemies to successfully control mites and insects. In Africa, the cassava mealybug caused devastating losses until *Anagyrus lopezi* (a parasitic wasp) – an effective natural enemy – was introduced in the 1980s, saving billions of dollars in potential crop losses (Zeddies et al., 2001).

The same predator was introduced to Thailand in 2010 after the cassava mealybug appeared there. By 2012, monitoring studies showed that *A. Lopezi* had become established throughout nearly the entire cassava-growing area where the mealybug was found, and is effective in control (Chariensak 2012, pers. comm.). It is hoped that the parasite will establish widely in other countries as well, following the mealybug spread in the region, to reduce population densities to economically insignificant levels.

The cassava green mite also became a serious introduced pest of cassava in Africa by the late 1980s. Many different phytoseiid predators (also mites) act as biological control agents against the green mite. They probably account for the absence of major outbreaks of the green mite in the Americas (Bellotti et al., 1987). CIAT and IITA introduced many of these phytoseiid predators into Africa but *Typhlodromalus aripo* was most successful, reducing populations of the green mite by 35–60% with a parallel increase in fresh-root yield by 30–37% (Bellotti, 2002). Implementation of the biological control by *T. aripo* depends on the morphology of the apex and on the volatiles emitted by the plant host. Both characteristics are determined by the cassava genotype. This is a promising case of genotype-by-biological control interaction, hypothetically representing an opportunity to breed for a cassava plant that will favor the establishment and survival of the predator for a more efficient control of the green mite.

Biological control never results in complete control, which leaves open the potential for fluctuations in levels of pest populations (similar to most types of host-plant resistance as well). In some years and in some locations, economic damage levels may be significant. Like other types of pest management,

biological control must be accompanied by constant monitoring, preparation for additional releases, and preparation for supplemental management within an integrated pest management system.

An integrated strategy for eco-efficient production

Despite cassava's global importance, the research investment has historically been far below that for other crops of similar importance. One of the reasons is its cultivation almost exclusively in developing countries. While there has been more public and private sector interest in recent years, there is not by any means a level of research funding that allows research institutions to carry out the kind of comprehensive research agenda possible for rice, wheat, maize, or potatoes, for example. This means that we need to be especially creative to find solutions with the most output per unit of input.

Research needs to begin by understanding the combinations of biotic and abiotic stresses and pressures that farmers face now and may face in the future. Only then can we offer an effective means to find the right balance of traits and practices to optimize economic yield for the grower, while protecting the environment. One of the most effective strategies over some 40 years of research at CIAT has been the identification of research sites that are representative of broad target regions, in terms of soils, climate, pests, and pathogens. This has allowed effective development of integrated variety development and management systems that balance the needs for adaptation in the agro-ecological zone, along with yield potential and root quality. As techniques are developed or new genes identified, they can then be incorporated into the system to fine-tune the adaptation and resistance features.

Cassava is exposed to a wide array of stresses during its growth in most parts of the world. Breeders and agronomists do not have the luxury of a long history of research to adequately understand mechanisms and the genetic basis for eco-efficient responses. Therefore, until now we have mainly relied on the plant response in selection environments and with management practices that

place the crop under conditions that farmers will typically encounter, or can reasonably and economically create through use of inputs. In this way, without the deep understanding of physiology or genetics of each trait, we have developed varieties and management practices that contribute to eco-efficient production. Additional investment, an ever more precise set of measurement tools for plant response, and genetic tools for crop manipulation should provide greater progress.

The key role of genebanks

In the arena of cassava technology development, some of the world's greatest assets are the germplasm collections around the world. CIAT holds the largest of these as an *in vitro* collection at headquarters in Cali, Colombia. The CIAT genebank holds about 5500 landrace accessions, along with another approximately 600 advanced varieties and breeding lines. The collection is available to all interested parties, under the conditions of exchange and use of the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA).

The genebank probably represents most of the genetic diversity that exists in cassava, although the actual tests of this hypothesis have yet to be carried out. With the decreasing costs of sequencing and molecular marker development, the time is right to begin the genome-wide characterization of cassava genetic diversity and to fill gaps in the collection (see also next section). Nonetheless, based on the coverage of collected areas, we can probably make a reasonably safe assumption that the existing diversity is adequate to continue to make progress in genetic improvement for many years to come. On the other hand, there are known gaps in the collection that need to be filled before valuable diversity is lost. CIAT's collection has limited representation from Central America or Bolivia, and no accessions from Suriname or French Guyana, for example.

In addition to cultivated cassava, there are some 100 wild relatives that are poorly collected and poorly evaluated. Many populations are at risk in their native habitats due to urbanization and expansion of agriculture. It is imperative to extend the collection of these species for their future

potential contributions to eco-efficient production solutions.

Africa has had limited exchange of germplasm with the Americas or with Asia due to the presence of some viruses in Africa that do not exist elsewhere, and several viruses in the Americas that also do not exist in Africa or Asia. Modern molecular methods now allow a very high level of security for the detection and cleaning of viruses, but it is still very difficult to exchange vegetative material between Africa and the Americas. Exchange between Asia and the Americas has been relatively straightforward.

The CIAT genebank is an engine for eco-efficient technologies – a resource that has already been extensively tapped to produce income-generating technologies for farmers worldwide. But it has much more to offer in the future as the need for new traits expands, and as our ability to find those traits improves. The coordinated phenotyping and genotyping of the cassava genetic resources held in genebanks will be a core strategy toward development of eco-efficient technologies to improve people's livelihoods from cassava while protecting the environment.

The role of molecular technologies

The development of molecular marker techniques for genetic analysis has increased our knowledge of cassava genetics and our understanding of the structure and behavior of the cassava genome. While microsatellites have been the basis for most work in cassava genetics, other valuable markers have also been used – including random amplified polymorphic DNA (RAPD) and amplified fragment length polymorphism (AFLP) markers – to produce cassava genetic maps.

The availability of a cassava genome sequence since 2006 has allowed the identification of thousands of candidate simple sequence repeat (SSR) markers which may be used for genetic mapping and marker-assisted selection. However, the sequencing of multiple genotypes (including wild species) would provide the cassava community with a much greater density of markers in the form of single nucleotide polymorphisms (SNPs). These SNPs can be used

to construct improved genetic maps and look for trait associations; the high density of SNPs will increase the likelihood of identifying markers tightly linked to loci encoding traits of interest such as drought tolerance or whitefly resistance.

The combination of sequences from both wild species as well as cassava itself will give researchers the opportunity to discover genomic regions and individual genes which have played a role in the domestication of cassava. Having whole genome sequences allows the exploration of copy-number variations (CNVs) and genomic rearrangements which may be related to different characteristics of interest. While use of SNP markers can focus the search for causative trait loci, having a large number of genomic sequences from a variety of genotypes for a given region provides the wider genomic context and will enhance genomics-assisted breeding in cassava, boosting our breeding activities to develop desirable breeding lines in a shorter term.

Molecular technologies have evolved at astonishing speed. The cost and efficiency of genotyping have advanced so much that the phenotyping that is often required along the molecular work is now the real bottleneck. Deficient field data and unreliable phenotypic information constrains the applied uses of molecular markers in cassava genetic enhancement. Plans are underway to sequence a large sample representing nearly the full range of cassava genetic diversity, set to begin in late 2012 and 2013.

Eco-Efficiency in Processing

Cassava conversion to marketable products can involve a wide range of processing techniques and some of them produce large amounts of waste that can contribute significantly to environmental pollution and depletion of water resources (FAO, 2001). Into the early 1990s, much of Thailand's cassava was chipped and dried on large patios, a process that was essentially pollution free and relied primarily on sun energy for drying (plus use of tractor power for turning and collecting the chips). With the rise of the starch industry throughout Southeast Asia, and the ethanol

industry in China, waste management is a growing concern, and many creative new technologies and systems are being developed to minimize environmental impact and increase profitability.

The main issues are:

- Use of large quantities of water for starch extraction
- Environmental risks of wastewater disposal, especially when discharged into streams or bodies of water
- Potential pollution from residues of processing
- High energy use for artificial drying of chips for animal feed, starch, flour, or other end products (cost and CO₂ generation)
- High energy use for ethanol distillation (cost and CO₂ generation).

The treatment of effluent waters is a major issue in the process of starch extraction. It results in major economic costs (if the effluents are not properly recycled or otherwise managed) or environmental costs (if effluents are dumped into the surrounding environment). CLAYUCA Corporation has developed technology to efficiently produce high-quality flour that can substitute for starch for many uses, but whose processing has far less impact on the environment. Water is used only in the whole-root washing, while the flour is extracted simply by grinding dried root.

Arising technologies

Cassava markets will continue to change quickly. Eco-efficient production and processing technologies are closely linked and need to be developed in parallel. This can be quite challenging, given the lead time required for many types of technology, and especially for the breeding of new varieties.

Two examples of production technologies that impact eco-efficiency of processing involve variations in starch functional properties:

- The identification of a natural mutation of amylose-free starch in cassava (Ceballos et al., 2007) has generated a keen interest and

investment by the starch sector. This mutation will allow industry to develop certain starch-based products without the chemical modification that is currently required, with potential benefits to both the environment and human health.

- A different starch mutation (Ceballos et al., 2008) was generated through mutagenesis, resulting in the production of small starch granules (about 1/3 the normal size) with rough surfaces. This mutation would be ideal for the bioethanol industry as the starch is more easily degraded into simple sugars, a necessary step before fermentation can be initiated. This should result in lower energy use in the conversion process.

The FAO study (FAO, 2001) concluded that cassava processing can have negative – mainly site-specific – effects on the environment, by producing unpleasant odors and an unsightly display of waste. However, the long-term and broad-based impact on the environment is generally minimal and can be corrected by proper waste treatment with technologies that are presently available or under development.

Moreover, there is ever greater economic incentive to make use of the by-products from the development process of marketable value-added products. The residue from starch factories can be used in animal feed rations, to reapply to fields as a crop nutrient, or as a substrate for the culture of mushrooms, for example. While policy will be an important element for limiting environmental impact from cassava processing, the more-effective strategies will be based on methods that generate greater income for processors.

Addressing Climate Change

As mentioned at the outset of this chapter, there is an emerging consensus that cassava is among the most promising options of tropical crops in the context of rising temperatures and increasingly uncertain rainfall patterns. Achieving an eco-efficient response to climate change represents one of the great challenges of agricultural research, and cassava presents unique opportunities.

Climate change may have direct effects on crop growth and development (temperature, rainfall, CO₂ levels) or indirect effects (soil organic matter, soil erosion, pest and disease patterns), and therefore the needed response through eco-efficient solutions can be complex and far-ranging.

Temperature and rainfall patterns

Climate maps combining temperature and rainfall parameters specific to cassava's growth responses (Figure 2) indicate that cassava will probably continue to be grown in nearly all areas where it is currently adapted. This is largely because of its combined high temperature and drought tolerance, even in some areas where these changes will create severe stress for other crops. In fact cassava is likely to expand into new areas of the subtropics that become more suitable as temperatures rise, and into areas where more-sensitive crops decline or disappear.

On the whole, cassava is tolerant of very high temperatures compared to many crops. This is in part because there is no critical stage, such as flowering, when brief periods of high temperatures will cause drastic yield losses. Increasing temperatures may not have a large direct effect on cassava production. On the other hand, areas that become too hot for other crops could create new growing areas for cassava to fill the gap. Some climate models show that India could be especially affected by rising temperatures, with broad shifts away from grains and pulses in some areas (Ceballos et al., 2011).

Possibly the most significant effect of temperature rise on cassava's adaptation will be to allow it to move into higher-altitude and higher/lower-latitude regions. Currently, cassava's limit at the Equator is at about 2000 masl, and this just for a narrow range of germplasm accessions from the Andean zone of the Americas, especially Colombia. These extended new highland areas for cassava are likely to be most important in East Africa, and in the Andes of Colombia and Ecuador. Currently cassava can be grown in latitudes near the Tropics of Cancer and Capricorn. Global warming may extend this range, as winters become milder. This is of particular interest in China, which is looking for options to expand planted area but has a

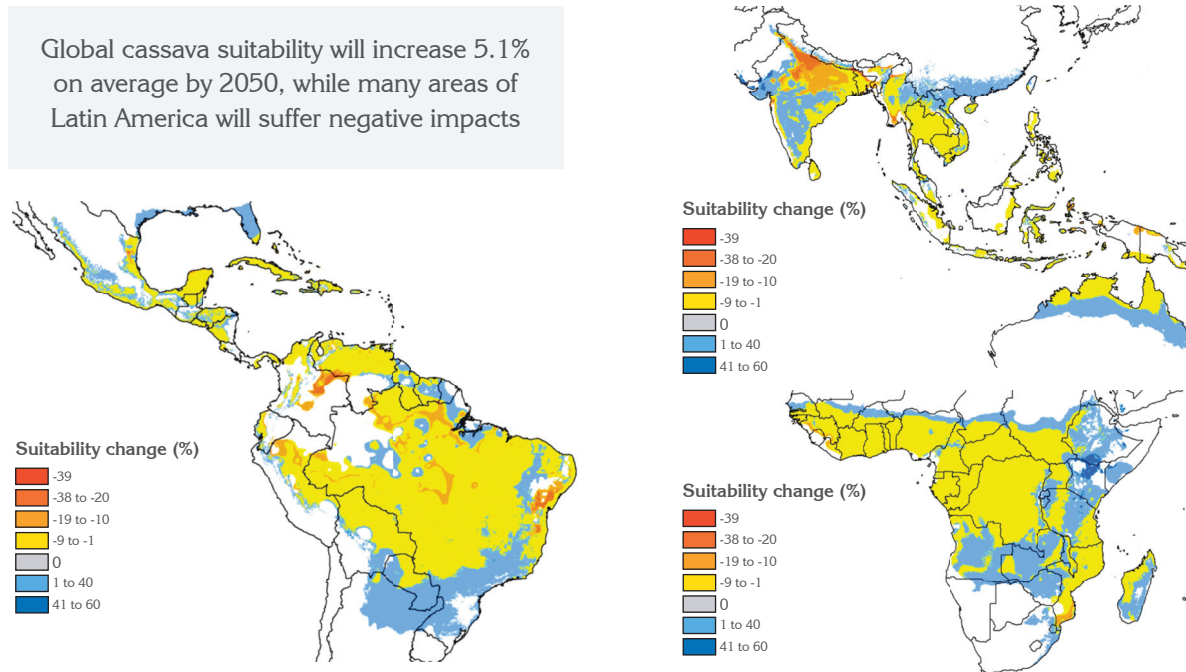


Figure 2. Impact of climate change on cassava suitable environments.

SOURCE: Decision and Policy Analysis (DAPA) Research Area, CIAT.

relatively limited region within the subtropics that is suitable for cassava. This is not to say that global warming will have overall positive effects on agriculture, but there will be opportunities for farmers to adapt with new crops and new practices if science can provide the appropriate technological support.

Drought promises to be one of the most widespread negative impacts of climate change on crop production in general. Lower overall rainfall and greater uncertainty both come into play in climate change scenarios. Therefore, it is logical that breeding programs in many crops have begun to take into account major efforts to select for drought tolerance. Cassava models appear to indicate a different strategy.

First, cassava will likely move into areas where other crops are constrained, especially grain crops, with their susceptibility to drought during certain development stages, such as flowering and early grain filling. But cassava is broadly drought tolerant already, so it will do quite well in areas where other crops cannot succeed. But the question remains about the advisability of stressing selection for drought tolerance in traditional cassava-growing areas that are already

dry, and will become drier with climate change. Although breeding for drought tolerance has been limited, there are clear indications from physiological studies that selection for even better tolerance could succeed. So it is a matter of comparing returns on investment from alternative breeding goals. Climate change models and crop models suggest that other constraints brought about by climate change, and especially the effects of pests and diseases, are likely to be more severe, and often more amenable to management through breeding for resistance/tolerance than is drought.

The other side of the rainfall issue is excess water. Cassava typically does not tolerate waterlogging. Root rots can become common if soils are waterlogged even for relatively short periods of time. Breeding has shown little promise, and in most cases management practices are probably more appropriate as an adaptation strategy.

Increase of atmospheric CO₂

Atmospheric CO₂ is one of the major causes of climate change and has increased by 40% from a pre-industrial revolution baseline. Confined-environment studies indicate that increases in atmospheric CO₂ concentration could result in a

reduction in root production. Concentration of cyanogenic glucosides in the roots was not affected by increases in CO₂. On the other hand, there was a large increase of glucosides in the leaves of plants grown in higher CO₂ concentrations (Gleadow and Woodrow, 2002; Gleadow et al., 2009). These results contradict earlier ones reported by Imai et al. (1984). Free-Air CO₂ Enrichment (FACE) methods allow field evaluation of crops under elevated CO₂ concentrations which simulate the predicted levels for the decades to come (El-Sharkawy, 2009). These studies suggest that photosynthetic efficiency would increase more in C₃ (like potatoes and cassava) than in C₄ crops (like maize and rice) (Long et al., 2004; 2006). Modeling and FACE results could guide the molecular optimization of the photosynthetic apparatus to maximize carbon gains without increasing crop inputs (Rosenthal and Ort, 2012).

Pest and pathogen response to climate change

There are several reasons why risks are increasing for introduction and spread of pests and pathogens into new areas. These include:

- More international travel
- Greater interest in introducing new materials by uninformed travelers, e.g., businessmen or women managing cassava plantations or processing plants
- Greater potential for introduced pests or pathogens to encounter host plants (increasing area planted to cassava globally, e.g., larger contiguous cassava plantings that allow pests to spread quickly)
- Climate change that transforms less suitable environments into more suitable ones for introduced pests or pathogens
- The interest in new crops, such as *Jatropha* (also a member of the Euphorbiaceae family) which can be a reservoir of pests and diseases that can also affect cassava. The recent interest in this crop has resulted in vast and unregulated exchange of germplasm.

The first defense against pest and pathogen spread to new areas is the double-pronged approach of education and regulation. The

principle audience needs to be the general public – about the risks of moving uncontrolled plant materials and agricultural products across national borders. This is not to downplay the importance of official channels. Most countries have strict quarantine regulations on the books, but lack personnel and budget for enforcement. Understanding the risks is the primary motivation for investing in better enforcement.

Climate change modeling, layered with pest adaptation maps, illustrates the potential spread to new areas in the context of climate change. This allows the application of resources in hotspot areas for monitoring, diagnosis, and management. It is expected that pests affecting cassava will evolve into more dynamic pattern, particularly as a result of increased temperatures that reduces the relevance of diapause and/or shortens their life cycle (Ceballos et al., 2011).

Figures 3 and 4 illustrate areas where cassava green mite and whitefly, respectively, are likely to increase or decrease in severity due to climate change by 2020. For both species, there will be widespread effects in the Americas and Africa, but less so in Asia.

Effective pest and pathogen monitoring and diagnosis systems are essential to early detection and effective management. Fortunately, such systems may be implemented across a number of crops, and do not need to be re-invented for each individual crop. The *PlantWise* system of CABI, for example, may be a good model to incorporate cassava data and take advantage of a system that is applicable for a broad range of crops. A pilot system is being established for Southeast Asia, which should develop into globally applied systems for information exchange about pests and diseases.

Soil degradation

Some of the new soil-related challenges likely to be exacerbated by climate change are: more rapid loss of organic matter due to higher soil temperatures; planting in areas more vulnerable to erosion (e.g., further up hillsides as temperatures rise); and greater nutrient leaching in areas where rainfall has increased.

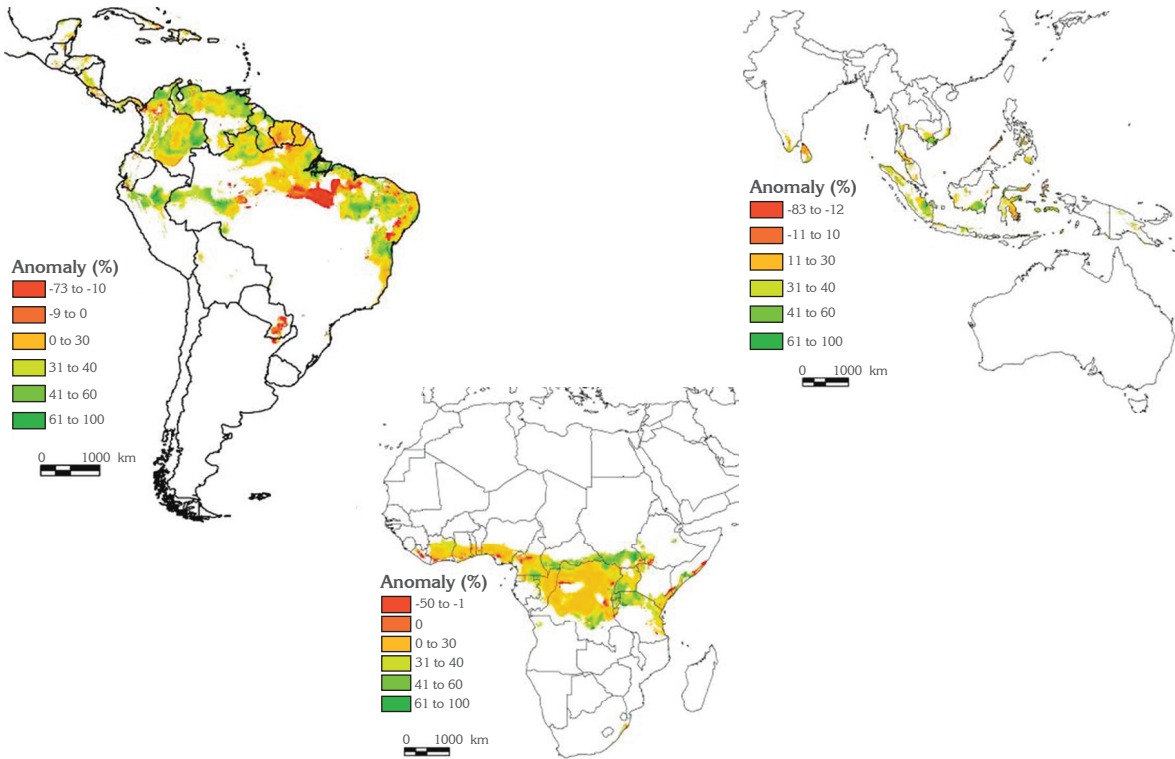


Figure 3. Climate change impacts on cassava green mite (*Mononychellus tanajoa*) by 2020.
 SOURCE: Decision and Policy Analysis (DAPA) Research Area, CIAT.

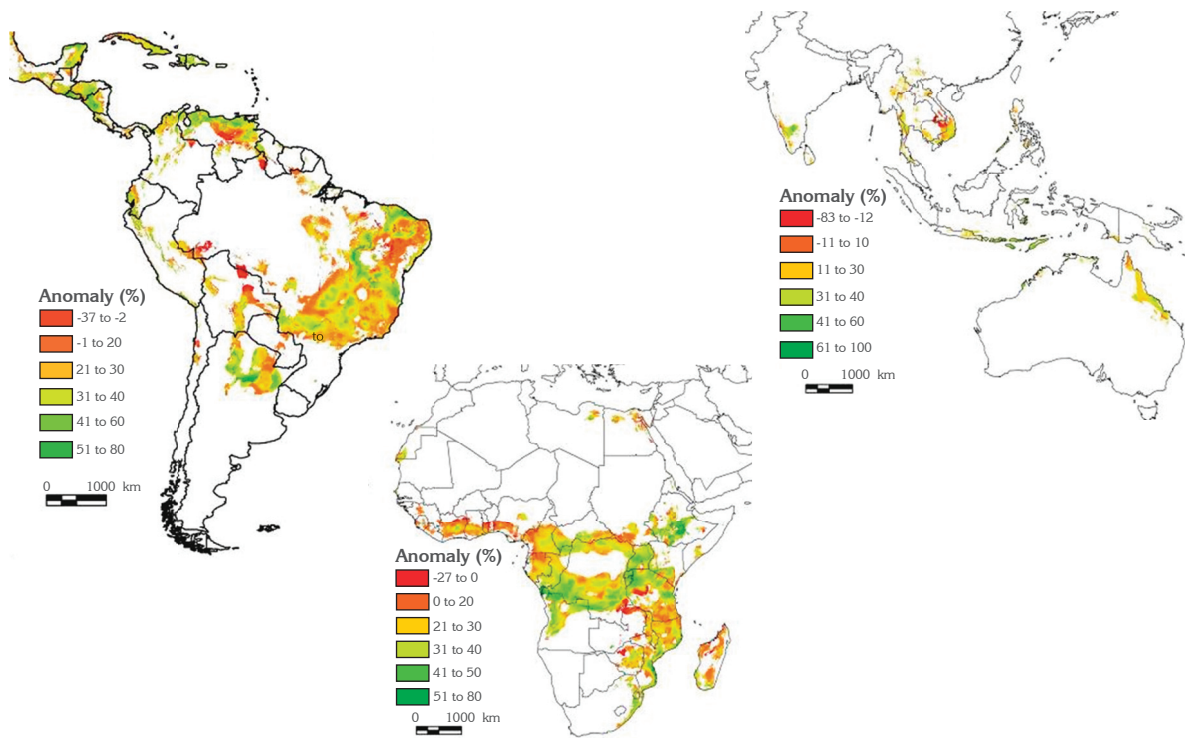


Figure 4. Climate change impacts on cassava whitefly by 2020.
 SOURCE: Decision and Policy Analysis (DAPA) Research Area, CIAT.

For cassava in an era of climate change, one of the great challenges for sustainable soil management is in areas where the crop expands to replace species that are less adapted to drier conditions. Unless this expansion into new areas is accompanied by appropriate management and technologies, there is a risk that growers without the experience of growing the crop will use practices that exacerbate erosion. Certainly there should also be attempts to introduce diversification programs, such as the planting of perennial crops/pastures/trees in the most vulnerable areas.

Conservation tillage or no-tillage systems have had relatively little application in cassava. Alternatives to conventional tillage will be important both in areas of reduced and increased rainfall. In reduced rainfall, conservation tillage conserves soil water. Under heavy rainfall, it reduces erosion and improves soil structure for better drainage. These advantages need to be weighed against the possibility of sacrificing yield or income as a result of adoption of these practices. The development of herbicide-tolerant genotypes would greatly facilitate the adoption of reduced-tillage practices. Technically, this should be relatively easy through transgenic methods, but the licensing, regulatory, and consumer acceptance issues would be huge hurdles to ultimate success. There need to be intensified efforts at the discovery of herbicide tolerance that is not transgenic. The most likely approaches are through screening of a broad genetic base of progeny from selfed genebank accessions, and through mutation and selection at the cellular level.

The Key Role of Partnerships

Little is accomplished in isolation. Science and its successful application require partnerships among a range of public and private organizations. There is a need for concerted capacity building and interchange to assess and develop eco-efficiency goals and methods for cassava technologies (see Chapter 14, this volume). The new CGIAR structure takes a step in that direction through capitalizing on the potential synergies among

centers working on several vegetatively propagated crops, and by bringing together the wide range of partners that can collaborate toward common goals. This new CGIAR Research Program on Roots, Tubers and Bananas (CRP-RTB) continues many of the same goals and activities as previously carried out by CIAT and IITA for cassava. However, there is now greater emphasis on linking research to development outcomes and on realizing the synergies among the various root, tuber, and banana crops and the centers that work on them (see www.rtb.cgiar.org/). The long history of collaboration between CGIAR centers and other entities working on cassava will be further enhanced under the new system.

Gender and Eco-Efficient Cassava Systems

There is a wide contrast on the use of cassava ranging from a key element in subsistence farming in Africa to mostly a cash crop to be used by different processing industries in Southeast Asia. CIAT is aware that in many cases well-intentioned interventions result in undesirable unforeseen impacts. A major thrust in our research is toward the gradual transformation of cassava from subsistence farming into income-generating crop. However, it has to be acknowledged that whenever this occurs, some gender-related issues may arise. In many resource-limited farming households, it is women who stay in the farm attending to the different chores, while men go to the villages in search of income-generating activities. If cassava becomes a cash crop, it is likely that the role women and men play will change. Many social scientists have expressed their concern that some of these changes may be negative, but also could result in positive trends, such as “the return of men to the farm for a reunited family.” The impact of turning cassava into a cash crop from the gender perspective is difficult to predict, not to mention to modulate, from a research position. It is important, however, to monitor them and make whatever intervention may be required to maximize the positive impacts while minimizing the negative ones.

Researchers need to monitor potential gender-related impact. Moreover, we actively search for potential areas where gender plays an important role. For instance, it has been recognized for many years that it is typically women who are in charge of weeding cassava fields in many regions of Africa. This implies that very often, women will invest the first two months of the crop in weed-control activities. Development of herbicide tolerance is therefore one such issue. It is envisioned that, in principle, this trait should benefit women as they could redirect their effort to other more-productive endeavors. Whenever the trait is identified or induced, however, careful analysis of its expected advantages will be tested through participatory approaches to make sure that the technology is well appreciated by the women we are targeting to benefit.

Another activity typically linked to women and children is the peeling of cassava, for example, in the production of *farinha* in Northeast Brazil or *gari* and *fufu* in Western Africa. It is known that peel thickness is another trait that may offer a gender bias. Awareness of such a situation is relevant for orienting research in the right direction. A thin peel is desirable for those industries where the entire root is processed, since it maximizes the proportion of valuable tissue. On the other hand, a thick peel facilitates the operation of manual peeling reducing the overall cost of such operations, thus maintaining its competitiveness.

Most importantly, study of gender biases need to be part of research design from the outset, rather than an afterthought after a technology is already developed and disseminated.

Key Lessons and Opportunities for Policy Interventions

Policies aimed specifically at eco-efficiency of crop research are nearly non-existent in developing countries. The scientific community has a major challenge to educate, inform, and advocate for such policies. We present a few examples here, although this is not by any means a comprehensive list.

Policy on food security and equity

Developing countries that support technological and economic progress as a means of addressing food security and equity will find that cassava, where it is adapted, can often play significant food security and equity roles.

Policy on market development

Policies that favor new industries can open opportunities for cassava markets. The broad range of products that can derive from cassava provides an ideal vehicle for new industry development. Multiple industries can evolve from the many cassava end-uses, to the advantage of cassava growers. Multiple market opportunities for farmers mean that there are likely to be better prices and lower swings in the market prices. A key example of this kind of intervention is the policy to mix 10% cassava flour with wheat flour for the baking industry. However, as discussed during the West Africa Root and Tuber Crops Conference (Accra, Ghana, 12–16 Sept 2011) (Dixon, 2011), policies need to be turned into laws for an effective impact.

Trade policy

Open versus protectionist trade policies will impact the kinds of markets where cassava can be competitive. Certainly the global tendency is toward more open markets, but there are many exceptions. Strong policies that protect local agricultural and industrial development are often a necessary short- to medium-term strategy in order to develop a competitive global position. On the other hand, protectionist policies tend to promote inefficiencies and, ultimately, higher prices for consumers. In any case, trade policies will rarely be developed specifically with the cassava market in mind, but rather with a broad agricultural or industrial vision.

Policy on biofuels

China is leading the way in biofuels from cassava, as a result of a dual policy that aims, on the one hand, to reduce reliance on fossil fuels and, on the other hand, to keep staple foods from competing in the biofuels market. Thus, cassava, as an efficient energy producer and with a very minor role as a food in China, is an ideal option.

In Africa the situation is more complex, where cassava for biofuels is likely to compete with food markets, and where most of those who rely on cassava for food are not able to absorb cost increases even of small levels without suffering serious consequences.

Policy on agriculture in fragile ecosystems

Thailand attempted for many years to support crop diversification in the northeast of the country, to prevent the continued spread of cassava into fragile soils. The policy had limited success because cassava is so much better adapted than most other crops that can provide a profit to farmers. These types of policies are, however, rather rare on a global basis. In order to succeed, they need to either strictly prevent the growing of cassava in inappropriate environments, or provide equal or better alternatives through technology support and/or subsidies that give farmers attractive options. In fact, effective policies that address the use of fragile landscapes are sorely needed in many countries. Along with policy, education of growers and the offering of eco-efficient technologies are needed for positive impact.

Policy on research and extension support

Until recent times, there was nearly no private sector support to cassava research. This is changing, but slowly. In Thailand, for example, the private sector provides modest support for development of specialty starch varieties, provides extension services in the form of advice on management practices, and provides growers with biological control organisms for the cassava mealybug, a newly emerging pest problem. There are examples elsewhere as well of important but quite limited industry support to technology development. This means that public support for research is the main determinant of the success of cassava research in any given country. CIAT and IITA have strong multidisciplinary research programs, but they also rely on the capacity of national partners to jointly develop that technology and deliver it to farmers or to industry. Policy that supports a sustainable research and extension system is essential to the ability of cassava to play

its full role as a vehicle for eco-efficient development.

The public sector for cassava research is seriously underfunded in most countries. In Africa, donor support in the last few decades has made a dent, but the long-term consequences of donor-dependent funding of research are uncertain. On the one hand, it seems to be a necessary intermediate step, while local public and private support and capacity are developed. All too often, however, this support is not prioritized, leading to programs falling by the wayside when donor funding diminishes or dries up. There needs to be much more support from studies illustrating the impact of investment in research by national and local governments.

Policy on credit and crop insurance

The long cycle of cassava from planting to harvest often implies a heavy burden for the farmers because of the long time required to recover their investments. It is becoming a common practice for governments through different banking systems to provide soft credits to farmers, particularly in cases where they have some sort of agreement with the processing sector and after it has been demonstrated that proper inputs and management practices will be used in growing the crop. This practice offers several advantages as it promotes linkages between the production and processing sector and encourages the adoption of technologies for the sustainable and competitive production of cassava. Within the same policies, farmers can also have access to crop insurance. For insurance to have more widespread impact, however, more data on production risks are necessary.

Summary: Approaches to Eco-Efficient Research for Cassava

CIAT works with partners to develop technologies that are more productive, profitable and competitive, sustainable, resilient as well as more sustainable. The following summarizes how this relates to CIAT's cassava research for development.

- **More productive:** *Providing inexpensive and nutritious food for poor consumers.* This is largely the CIAT legacy of its first 40 years, by

producing clones with high and stable productivity, and giving special consideration to dry-matter content (Kawano, 2003; Kawano and Cock, 2005).

- **More profitable and competitive:** *Creating new opportunities for growers to increase their incomes.* New or expanded markets are needed for cassava farmers to pull themselves out of poverty. Without markets to absorb increased productivity, moving beyond subsistence is only a dream for many. High-value traits such as the *waxy* and small-granule starches (Ceballos et al., 2007; 2008; Sánchez et al., 2009) and enhanced carotenoids contents are examples of traits that can move into new specialty markets.
- **More sustainable:** *Environmentally, economically, and socially.* Pest and disease management strategies fit mainly in this area (but also in others). Genetic resistance and biological control are the central elements of integrated pest management. Managing soil erosion and maintaining/improving soil fertility are probably the most critical needs to achieve sustainability in many cassava-growing regions.
- **More resilient:** *Reversing land degradation and adapting to the new conditions caused by climate change.* Cassava is already one of the world's most resilient crops, and it has the potential to be even more resilient through a combination of genetic and management approaches. Its inherent drought tolerance, adaptation to high temperatures, efficient use of soil nutrients, and tolerance to highly acid soil conditions make it a popular crop where these conditions already exist. And with climate change, it will replace other crops as these conditions are newly created in some regions.
- **More equitable:** *Providing new opportunities for the rural poor.* Equity issues that cassava can help address include income generation for the poor, and technologies that are pro-women. The very nature of traditional cassava production by smallholders and processing at the local level has contributed to equity issues. The challenge is to continue to address equity issues as scale of production increases and more sophisticated markets are developed.

Specialty cassavas, such as waxy-starch varieties, should lead not only to increased value and higher incomes to farmers, but also should promote a closer association between farmers and processors (e.g., contract farming) which can favor both layers of the value chain.

While biofuels are often seen as working against equity issues, examples in cassava illustrate other options. CLAYUCA is developing a model for cassava based on decentralized small plants at the village level that produce 50% ethanol, which is then shipped to a more sophisticated central plant for dehydration to 99%.

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