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Strategic Assessment of Research Priorities for Cassava

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1. Introduction and background

Following its official launch in 2012, the CGIAR Research Program on Roots, Tubers and Bananas (RTB)[1] embarked on a strategic assessment of research priorities for five of its major crops (banana, cassava, potato, sweet potato, and yams). The objective of this exercise was to determine the expected impact each research options would generate in terms of economic benefits, poverty reduction, food security, nutrition and health, gender equity, and environmental sustainability. The priority assessment was a collaborative study conducted by RTB members and partners using a common methodology across all five crops.

This report documents the procedure and results of the priority assessment for key cassava research options (steps 3–5 of the RTB priority assessment). The results of the priority assessment exercise are presented and discussed to shed light on the implications for cassava research priorities. Similar reports summarizing the process and results of the strategic assessment are available for the other four crops included in the RTB priority assessment. The results are directly feeding into RTB strategic priority setting. Collated information and estimates obtained have been used to quantify intermediate development indicators (IDOs) supporting the RTB flagship cases and the results can guide budget allocation decision across RTB research areas, crops and regions.

The rest of the report is organized as follows. The next section explains the process of selecting research options to be included in the assessment as well as an overview of methods used in the assessment. The report continues with a detailed description of the research options assessed, the parameter elicitation process, and an overview of parameters and assumptions used in the assessment. Finally, the results of the cassava priority assessment are presented in section 5. The document concludes with a discussion of results, lessons learnt, and suggested follow-up activities to complete the exercise.

illustrates the methodological framework, which is organized as a six-step process[2]. The first step involved defining agro-ecological zones and mapping of crop production for different geographic regions aimed at identifying target areas for RTB research interventions. Best suited for research interventions are "hot spots" which are defined as geographic regions and/or production systems characterized by a large number of small-scale producers and/or high dependency of poor consumers on the respective RTB crop, the presence of major constraints or opportunities (suitable to be addressed by research) as well as high incidence of poverty and food insecurity. Overlays of different maps (e.g. crop production,

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[1] The CGIAR Research Program on Roots, Tubers and Bananas (RTB) is a broad alliance of research-for-development stakeholders and partners. Their shared purpose is to tap the underutilized potential of root, tuber, and banana crops for improving nutrition and food security, increasing incomes and fostering greater gender equity – especially amongst the world's poorest and most vulnerable populations (www.rtb.cgiar.org). CGIAR is a global agriculture research partnership for a food-secure future. Its science is carried out by the 15 research centers who are members of the CGIAR Consortium in collaboration with hundreds of partner organizations. www.cgiar.org

[2] The steps are not necessarily carried out in chronological order, and the exact execution of the process may vary slightly across crops.

biotic or abiotic constraints, and poverty and food security indicators) point to areas where targeted RTB research can lead to high impact[3].

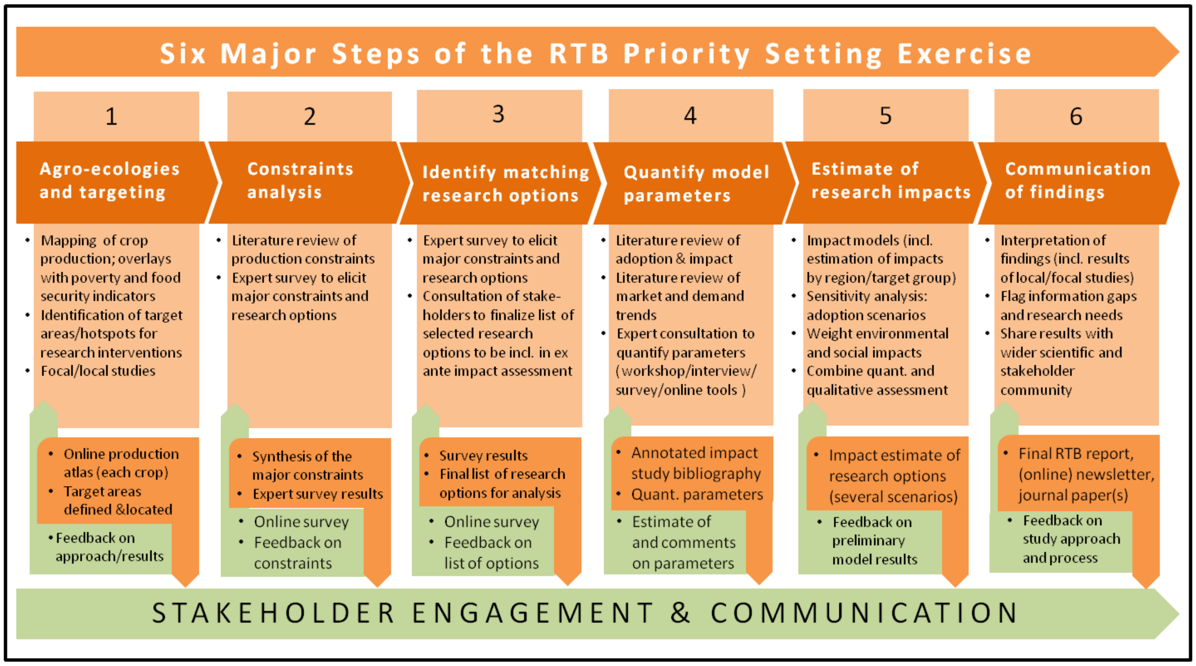
In the second step, a constraint analysis was conducted to identify major production and marketing constraints of the RTB mandate crops and assessing the relative importance of these constraints to select high priority research interventions. As part of the constraint analysis and identification of priority research options (see step 2 and step 3 in Figure 1), expert surveys were carried out in mid-2012 to early 2013 for each of the five crops included in the RTB priority assessment.

One major purpose of the expert surveys was to engage the global scientific/stakeholder community in identifying research options to be included in a participatory way. The process and results of the global expert surveys are presented in separate reports, one for each crop[4]. The selection of the research options in step 3 was largely based on the expert survey results and complemented with focus group discussions with selected experts for each of the crops. The data and parameter estimates for the quantitative assessment (step 4) were derived from (inter)national statistics or elicited from experts knowledgeable on specific research fields, regions, and crop agro-ecologies.

[3] The outcome of this mapping exercise is manifested in two online mapping resources called "RTB Maps" (http://www.rtb.cgiar.org/RTBMaps) and "Banana Mapper" (www.crop-mapper.org/banana). Building and populating the tools, however, took longer than initially anticipated and thus neither RTB Maps nor the Banana Mapper were used for targeting in the priority assessment exercise.

[4] The reports are available under http://www.rtb.cgiar.org/category/resources/working-papers/

Figure 1. Graphical presentation of the RTB strategic assessment of research priorities



Potential research impacts were assessed in step 5 using the economic surplus model, which has been used extensively to quantify expected economic impacts of technical change in agriculture (Alston et al. 1995). The model was extended to estimate the potential number of beneficiaries and poverty reduction effects. Cost-benefit analyses were undertaken to estimate the economic returns to planned investments on the development of each of the research options analyzed. The results also provide a regional breakdown of the benefits and potential adoption area. The effects of different assumptions regarding the pace and ceiling of adoption were tested using a sensitivity analysis under two different adoption scenarios.

More specifically, the ex-ante impact assessment addressed the following research questions:

- What is the expected impact of research options considering standard economic indicators?
- (How) do the expected impacts of assessed research options differ?
- Which research options are likely to reach the largest number of beneficiaries?
- What are the poverty reduction impacts of the selected research options?

A novel method was proposed to establish weights for technology options according to impact on gender equity. This was tested out in an expert workshop but proved problematic to operationalize as gender relevance is context specific. Gender specialists on the team subsequently opted to use a case study approach as a follow up to the main study to determine gender relevance and outcomes of technological choices.

The results of the analyses are being shared with the wider scientific and stakeholder community (step 6) and the feedback will be incorporated and, where necessary, parameter estimates, and assumptions will be modified.

This report documents the procedure and results of the priority assessment for key cassava research options (steps 3–5 of the RTB priority assessment). The results of the priority assessment exercise are presented and discussed to shed light on the implications for cassava research priorities. Similar reports summarizing the process and results of the strategic assessment are available for the other four crops included in the RTB priority assessment[5]. The results are directly feeding into RTB strategic priority setting. Collated information and estimates obtained have been used to quantify intermediate development indicators (IDOs) supporting the RTB flagship cases and the results can guide budget allocation decision across RTB research areas, crops and regions.

The rest of the report is organized as follows. The next section explains the process of selecting research options to be included in the assessment as well as an overview of methods used in the assessment. The report continues with a detailed description of the research options assessed, the parameter elicitation process, and an overview of parameters and assumptions used in the assessment. Finally, the results of the cassava priority assessment are presented in section 5. The document concludes with a discussion of results, lessons learnt, and suggested follow-up activities to complete the exercise.

2. Methodology and data

2.1 Constraints analysis and identification of research options

Expert surveys were carried out to guide the constraints analysis and the identification of research options for each of the included RTB crop[6]. The surveys engaged stakeholders from a broad range of disciplines and backgrounds and this exercise served several purposes: first, the cassava expert community was involved in the selection of research options assessed in the priority assessment exercise through survey participation. Second, consulting a broad range of experts with different fields of expertise increased the chance to capture key constraints irrespective of institutional priorities and capacity. Last, the surveys led to empirically founded and ranked lists of constraints and associated

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[5] The reports are available under http://www.rtb.cgiar.org/category/resources/working-papers/

[6] The basic tool for the expert surveys was a structured questionnaire with questions about the major constraints for each crop. To facilitate the participation of national and local level experts, the questionnaires were provided in English for all crops and in the additional following languages: Spanish for all crops except yam; French for potatoes and cassava; Chinese for potatoes and sweet potatoes; Russian for potatoes; and Portuguese for cassava. Besides conducting the surveys in several regional meetings relevant to each crop or online through personal invitations and individualized links, all surveys were also available online through a link on the RTB webpage. A total of 1,681 respondents from more than 50 different countries completed the survey across all five crops.

research options. These lists have informed the selection of research options to be included in the ex-ante impact assessment in the subsequent steps of the priority assessment exercise.

Defining cassava research options for the economics surplus analysis involved a series of activities described in Table 1. The research options that were identified as being important globally are presented in Table 2.

Table 1: Activities for defining the research options for the economic surplus analysis

Process	Activity	Dates
Constraint analysis	Geographical targeting project	Aug.–Nov. 2011
	Literature review	2012
Technology supply side consultation	Written expert survey	June 2011
	Online expert survey	Sept. 2012–Mar. 2013
Demand side consultation	Stakeholder consultation, LAC	Apr. 2013
	Stakeholder consultations, Asia	July, Nov. 2013
	Stakeholder consultation, Africa	June-Aug. 2013
Synthesis of the information	Meeting with cassava scientists at CIAT	July 2013
	RTB CRP flagship and IDOs review	Oct.–Nov. 2013
	Meeting with cassava scientists at IITA	Nov. 2013
Elicitation of analysis parameters	Meetings with scientists, surveys	Oct.–Dec. 2013

The identification of cassava research options started with analysis of the data obtained from the global expert survey in which a sample of 343 cassava experts identified the priority constraints to cassava production, processing, and marketing. The opinions of scientists who are closely involved in research on cassava production, processing, and market constraints served as the major source of information for identifying research options to address those constraints. For this objective, a global survey instrument was designed in consultation with scientists at CIAT and IITA in Spanish, English, French, and Portuguese. A global online survey of cassava experts was conducted in 2012 using the online Survey Monkey tool; 60 questionnaires were completed. In addition, questionnaires were administered to cassava experts who attended international events. A total of 282 responses were obtained at the Second Scientific Conference of the Global Cassava Partnership for the 21st Century, held on 18–22 June 2012, in Kampala, Uganda. At the 16th Triennial Symposium of the International Society for Tropical Root Crops held on 23–28 September 2012 in Abeokuta, Nigeria, 29 questionnaires were completed. Finally, cross-country surveys of the national cassava programs and expert consultations conducted in 2013 in Africa as well as in Latin America and the Caribbean (LAC) and Asia and provided more responses. A total of 343 valid questionnaires were accounted for in the analysis. The results of the survey are presented in Annex 1 for the first 55 ranked technologies/options.

On the basis of the analysis of the expert survey data, potential research options were identified for further formal evaluation using the economic surplus model (Alston et al. 1995). These research options included those that address the constraints relating to (1) root yields, (2) production costs, (3) postharvest processing and utilization, (4) sustainable production, and (5) nutritional quality. Overall, 12 research options were identified and analyzed for cassava, but economic analysis of the research option relating to nutritional quality was beyond the scope of this study and was thus not part of the priority assessment. Assessing potential impacts of research options that aim to increase nutritional quality of staple crops generally requires a different methodology (e.g. Disability Adjusted Life Years approach) and different datasets. The initial list of research options was presented and discussed with the scientists from IITA and CIAT, and later at the RTB priority assessment task force workshop held on 12–16 August 2013, in Lima, Peru. These research options were later linked with CIAT and IITA research outputs. The research options were selected to match selected research options associated with RTB flagships,[7] which contribute to the required attainment of Intermediate Development Outcomes (IDOs). The final set of research options was then developed and agreed upon at the final workshop held on 12–14 November 2013, also in Lima. Table 2 presents the final list of research options, the average scores and ranks of related technology options from the global expert survey, and links to related RTB flagships.

Table 2: List of cassava research options included in the ex-ante impact assessment

Research option	Link to RTB flagships	Global score and rank based on expert survey		
		Score	**Constraint**	**Rank**
Efficient and massive high- quality planting material production and distribution systems	LS4: Framework for analyzing and intervening in RTB seed systems	4.13	Improving production and distribution of elite planting materials	#5
		3.99	Mass propagation methods, including tissue culture & hydroponics	#23
High-yielding, drought-resistant varieties and increased water-use efficiency	CA2: Varieties for improved profitability and sustainability in traditional food markets	4.16	High yield	#4
		4.09	Drought tolerance / water use efficiency	#8
High-yielding varieties with dual resistance to cassava mosaic disease/cassava brown streak disease (CMD/CBSD)	CA5: Farmer cassava yields boosted through effective management of CBSD, CMD, and whiteflies	4.16	High yield	#4
		4.04	Cassava mosaic disease management	#16
		4.02	Cassava mosaic disease breeding	#20
		3.81	Cassava brown streak disease	#37
		4.21	Phenotypic/molecular screening of landraces	#2
High-yielding varieties with high dry matter and starch	CA1: Varieties with added value in new and high growth industrial markets for cassava	4.16	High yield	#4
		4.17	Developing cassava products for industrial applications flour and starch	#3
		3.95	High dry matter	#26

[7] Since the completion of the priority setting exercise, the structure of RTB and the terminology used to describe the structure have changed somewhat. For example, what are referred to as "Flagships" in this report are now called "Clusters of Activity." For an up-to-date overview of RTB structure, see http://www.rtb.cgiar.org/.

Research option	Link to RTB flagships	Global score and rank based on expert survey		
		Score	Constraint	Rank
High-yielding varieties with longer shelf life	CA1: Varieties with added value in new and high- growth industrial markets for cassava	4.23	Improving shelf life of cassava roots	#1
		4.16	High yield	#4
		3.98	Tolerance to postharvest physiological deterioration	#24
Integrated pest and disease management practices, including resistant varieties	CA5: Farmer cassava yields boosted through effective management of CBSD, CMD, and whiteflies	Biotic stresses such as CMD (#16, 20), CBSD (#37, 45), whiteflies (#28, 39), bacterial blight (#29, 30), mites (#40), and root rots (#50) are ranked among the first 55 constraints.		
Processing technologies for value addition	CA6: Improved technology and knowledge for small- to medium-scale cassava processing centers also CC3 (improved postharvest)	4.17	Developing cassava products for industrial applications flour and starch	#3
		4.04	Improving small scale processing of cassava for human consumption	#15
		3.97	Development of competitive cassava value chains	#25
Strategies to prevent introduction of exotic pests and diseases	CA4: Preemptive, emergency and ongoing response capacity to manage emergent biological constraints in Asia and the Americas (Cassava mealybug, whiteflies, frogskin, and witches broom)	4.08	Assess impact of cassava research and development	#9
		Biotic stresses such as CMD (#16, 20), CBS (#37, 45), whiteflies (#28, 39), bacterial blight (#29, 30), mites (#40), and root rots (#50) are ranked among the first 55 constraints.		
Sustainable crop and soil fertility management practices	CA2: Varieties for improved profitability and sustainability in traditional food markets	4.21	Phenotypic/molecular screening of landraces	#2
		4.03	Improving soil fertility	#18
		4.0	Improving cassava cropping systems	#21
		3.89	Weed management and control	#32
		3.77	Soil management and erosion control	#41

Additionally, two research options described in **Error! Reference source not found.** were included in the a nalysis due to special considerations and suggestions by scientists.

Table 3. List of special cases for cassava research options

Research option	Link to RTB flagships	Global score and rank based on expert survey		
		Score	Constraint	Rank
High-yielding varieties with cold tolerance	CA2: Varieties for improved profitability and sustainability in traditional food markets	4.16	High yield	#4
		2.71	Low temperature/winter hardiness	>55
		4.03	Germplasm enhancement and pre-breeding	#17
High-yielding varieties with improved nutritional quality	CA3: Farmer and consumer-accepted high vitamin A cassava	4.16	High yield	#4
		4.12	Phenotypic/molecular screening of landraces	#5

The links between the selected research options, the IDOs for the RTB CRP, and the system level outcomes (SLOs) are presented in Table 4.

Table 4: Links of the research options to IDOs

IDO	Indicator	Research option
1) Improved productivity in pro-poor RTB food systems (SLOs 1, 2, & 4)	• Change in on-farm yield disaggregated by per capita household income for x households in y countries/region • Changes in cropping system patterns and yield gaps (maps) for x households in y countries/region • Changes in total factor productivity (labor, energy, water and nutrients)	• Sustainable soil fertility management • Integrated pest and disease management • Drought resistant/water-use efficiency • Planting material systems
2) Increased and stable access to food commodities by rural and urban poor (SLOs 2 & 3)	• Change in mean and variance calorific gap • Decrease in annual price variance in y region • Increase in aggregate supply in x countries	• Integrated pest and disease management • Drought resistant/water-use efficiency • Cold tolerance • Dual resistance to CMD/CBSD • Processing technologies for value addition • Longer shelf life • High dry matter and starch • Improved nutritional quality
3) Improved diet quality of nutritionally vulnerable populations, especially women and children (SLO 3)	• Improvement in frequency of consumption of nutritious foods by children under 5 years and women of reproductive age for x households in y countries/region • Improvement in dietary diversity indices of target households for x households in y countries/region	• Sustainable soil fertility management • Integrated pest and disease management • Drought resistant/water-use efficiency • High dry matter and starch • Improved nutritional quality • Prevent introduction of exotic pests and diseases
4) Increased and more gender-equitable income for poor participants in RTB value chains (SLOs 1 & 2)	• % change in farmer revenue from marketing improved RTB varieties for x households in y countries/region • % changes in RTB income among different types of farmers and other relevant value chain actors differentiating women and men for x households in y countries/region	• Integrated pest and disease management • Prevent introduction of exotic pests and diseases
5) Improved ecosystem services for enhanced food system stability and sustaining novel genetic diversity for future use (SLOs 2 & 4)	• Total number of LR cultivars preserved in situ and ex situ per hotspot in x hotspots in y regions	• Sustainable soil fertility management • Integrated pest and disease management

2.2 Economic surplus model and cost-benefit analysis

Several impact studies of agricultural technologies have estimated aggregate economic benefits through extrapolation of farm-level yield or income gains using partial equilibrium simulation models such as the economic surplus model (Alston et al., 1995).

The economic surplus model is the most widely used method for economic evaluation of expected benefits and costs of a new agricultural technology. Agricultural research can lead to technological change mainly through increased yield, reduced yield losses, or reduced cost of production. If the new technology is yield increasing, adoption leads to lower per-unit costs of production as well as a higher quantity of goods sold on the markets. This will shift the supply function of the commodity and lead to an increase in the quantity sold and a fall in the price for that good assuming the demand function is downward-sloping and the market for the commodity is perfectly competitive. As a result, consumers benefit from a price reduction and producers benefit from selling larger quantities of the product.

A closed economy[8] economic surplus model was used to derive summary measures of the potential impacts of different cassava research options for a period of 25 years (2014-2039). The benefits were measured based on a parallel downward shift in the (linear) supply curve. We estimated the change in economic surplus (defined as the total benefits that accrue to consumers and producers when a good or service is exchanged)[9] using formulas presented in Alston et al. (1995). Annex 3 provides details of the basic formulas used in the ex-ante impact analysis of cassava research options.

For the cost-benefit analysis, the estimated annual flows of gross economic benefits from each technology and target country were aggregated, and each year's aggregate benefits and estimated R&D costs were discounted to derive the present value (in 2014) of total net benefits from the research interventions. The key parameters that determine the magnitude of the economic benefits are the following: (1) the expected technology adoption in terms of area under improved technologies, (2) expected yield gains (or avoided losses) following adoption, and (3) pre-research levels of production

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[8]Despite the presence of global and regional integration arrangements that aim to facilitate trade on global markets, commodities such as cassava are mostly produced and consumed domestically and not easily traded on the global markets especially in less developed countries due to lack of processing technologies, high perishability of cassava, and trade rules and regulations that hinder free trade. As such, a closed economy model best represents the market for cassava.

[9] The consumer surplus is the difference between the maximum price consumers are willing to pay and the actual price they do pay. If a consumer would be willing to pay more than the current asking price, then she is getting more benefit from the purchased product than she spent to buy it. The producer surplus is the benefit a producer receives from providing a good/service at a market price higher than what she would be willing to sell. Through economic modeling of supply and demand equations, the related quantities of consumer and producer surplus are determined. The consumer surplus (individual or aggregated) is the area under the (individual or aggregated) demand curve and above a horizontal line at the actual price (in the aggregated case: the equilibrium price). The producer surplus (individual or aggregated) is the area above the (individual or aggregated) supply curve and below a horizontal line at the actual price (in the aggregated case: the equilibrium price).

and prices. To ensure comparability across the five crop studies, the same set of assumptions and data sources were used for all crop studies conducted under the RTB priority assessment.

2.3 Estimation of poverty effects

Extending the results of the conventional economic surplus and cost-benefit analysis, the impact of each of the cassava research options on rural poverty reduction was estimated following the approach in Alene et al. (2009). It weighs the economic surplus results according to the poverty levels in each of the countries, the share of agriculture in total GDP, and the agricultural growth elasticity of poverty. The impact of each research option on rural poverty reduction was estimated by first estimating the marginal impact on poverty reduction of an increase in the value of agricultural production using poverty reduction elasticities of agricultural productivity growth. The reduction in the total number of poor was then calculated by considering the estimated economic benefits as the additional increase in agricultural production value. Thirtle et al. (2003) found that a 1% growth in agricultural productivity reduces the total number of rural poor by 0.72% in Africa, 0.48% in Asia, and 0.15% in Latin America and the Caribbean (LAC). Under the assumption of constant returns to scale, a 1% growth in total factor productivity leads to a 1% growth in agricultural production. For each country, the number of poor lifted above the $1-a-day poverty line was thus derived as follows:

$$\Delta N_p = \underbrace{\underbrace{\underbrace{\left(\frac{\Delta \text{ES}}{\text{Agriculture value added}} \times 100\%\right)}_{\text{Gains from R\&E as \% of agricultural production}} \times \underbrace{\frac{\partial \ln\left(\frac{N_p}{N}\right)}{\partial \ln(Y)}}_{\text{Poverty elasticity}}}_{\text{Poverty reduction as \% of the poor}} \times N_p}_{\text{Number of poor escaping poverty}}$$

where ΔN_p is the number of poor lifted above the poverty line, N_p is the total number of poor, N is the total population, Y is agricultural productivity, and ΔES is the change in economic surplus. The poverty elasticity is interpreted as the marginal impact of a 1% increase in agricultural productivity in terms of the number of poor reduced as a percentage of the total poor (N_p), and not of the total population.

2.4 Estimation of the number of potential beneficiaries

Data on average crop area per household and average household size were used to estimate the numbers of beneficiaries, following a procedure and dataset developed to estimate total number of RTB poor beneficiaries (CGIAR, 2011). Data for individual countries were obtained mostly from FAO statistical database, published sources of information, or expert opinion when needed. Estimated area under two adoption scenarios (high and low adoption) was divided by the average area per household to estimate the number of adopting households, and then multiplied by household size to estimate total number of beneficiaries.

3. Description of the research options

3.1 Efficient and massive high-quality planting material production and distribution systems

This research option focuses on improved quality and access to cassava planting material, rapid multiplication, mass propagation methods, alternatives for micro-stakes from disease-free stocks and on-farm management of planting material, and decentralized multiplication with improved management practices (i.e., capacity building for farmers to produce their own high-quality, clean[10] planting material). This option attempts to address the shortage of high quality cassava planting materials. It increases availability of the stems from distribution agencies of government, private sector, and other partners. With respect to the RTB research dimension, this option includes formal and informal technologies for improving farmer-based production and distribution of planting materials, methods for mass propagation of planting materials, alternatives for stem cuttings from disease-free stocks, and production of hybrids from inbred progenitors.

Several efforts to address the problem of clean cassava planting materials are ongoing. The Alliance for a Green Revolution in Africa (AGRA) is currently funding several projects on cassava germplasm improvement and dissemination in Eastern and Southern African countries. In coastal Kenya, there is a project on multiplication of high-yielding and disease-tolerant cassava clones and creation of distribution channels for planting materials. In Tanzania (mainland) there is a project that aims to develop varieties that combine high root-yielding ability along with high dry matter and high starch content for the humid and sub-humid lowlands. In the Lake Zone of Tanzania, AGRA is funding a project with a component addressing improved access to germplasm, including that of cassava. In Malawi, AGRA is funding two projects on cassava breeding aimed at developing improved sweet cassava varieties and promoting improved cassava and sweet potato varieties. In Mozambique, AGRA is funding a project on multiplication and dissemination of improved cassava varieties resistant to CBSD. The GLCI project, funded by the Bill and Melinda Gates Foundation (BMGF), has also been building the capacity of local partners and farmers to address the CMD and emerging CBSD pandemics that threaten food security and income of cassava-dependent farm families. It has targeted the distribution of clean planting material to millions of households in six countries of East and Central Africa: the Democratic Republic of the Congo (DRC), Kenya, Rwanda, Burundi, Uganda, and Tanzania. The research has been implemented since 2007 and more than 70% of the work has been accomplished.

CIAT scientists have made advances in the generation of cassava "micro-stakes" technology, which will ensure clean planting material. Of particular interest is an attempt to produce synthetic seeds that will help to prevent transmission of pests and diseases while multiplying by many-fold the propagation rate relative to other rapid propagation systems.

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[10] "Clean planting materials" are cassava planting materials that have been screened and certified to be physiologically sound and with a minimum of any pests and/or disease infestation.

The adoptable innovations resulting from the research include improved multiplication methodologies and clean cassava planting materials/varieties that minimize attack by pests and diseases. The timely availability of good planting materials constitutes a decisive factor for the dissemination and use of new cassava varieties.

Among the expected benefits, clean, high-quality planting material is expected to increase productivity by 20% under normal conditions, regardless of the geographic situation. For the most important pests and diseases (witches broom, cassava bacterial blight [CBB], mealybug, CMD, frogskin disease, and CBSD), a clean seed system will help to reduce losses by up to 50% in extreme cases. This is especially important in locations where diseases are widespread (e.g., CMD and CBSD in Africa, or CBB in LAC). In Africa, the likelihood of research success is estimated at about 60%; in LAC and Asia, it is closer to 80%.

3.2 High-yielding, drought-tolerant varieties and increased water-use efficiency

This research option includes breeding for high-yielding, drought-tolerant varieties with high water-use efficiency. Water stress at any time in the early growth period (first few months) significantly reduces the growth of roots and shoots, and impairs subsequent development of the storage roots. Once well-established cassava rarely dies due to drought, but yields can be severely reduced. Droughts have become more frequent and severe in many parts of Africa. In certain regions of Asia, Central America, and the Caribbean, on top of reduced rainfall, increased population and economic growth will increase the water demand for agriculture. In the RTB research dimension, this option is on breeding for high-yielding, early-maturing varieties that can escape drought, and varieties with high water use efficiency. The complementary agronomic dimensions include studies on improved irrigation systems.

A breeding program to combat CBSD in Eastern and Southern Africa also uses marker-assisted breeding and biotechnology tools to improve yield and drought tolerance, especially through increased water-use efficiency. Since the initiation of the program in 2009, 40% of the work has been accomplished. It is expected that adoptable innovations from this research option will be high-yielding, drought-tolerant varieties with high water-use efficiency. Also included is improved and better irrigation management. These will result in farmers having cassava varieties with high-yielding ability and increased water-use efficiency leading to increased production and reduced food insecurity and poverty. Benefits will be bigger for countries with long summer periods (i.e., more than 6 months without rain). With new varieties, yields could increase production by up to 25% in most seasonally dry cassava-growing areas of sub-Saharan Africa (SSA) and drier countries in LAC and Asia. The probability of research success is expected to be high because some promising varieties have been identified among both landrace and improved varieties.

3.3 High-yielding varieties with cold tolerance

This research option will develop varieties with high yields and tolerance to cold temperatures. This will expand production areas to the highlands with year-round low temperatures (above 1,500 masl), or with seasonally low temperatures where there is high risk of frost[11] (i.e., regions that are in higher latitudes). Currently it is unknown whether there is any relationship between tolerance to year-round low temperatures in highland situations and tolerance to seasonal low temperatures. This option is addressed with the research dimension related to breeding for high-yielding varieties with tolerance to cold weather and frost. Local cassava varieties that can be tolerant to cold weather and frost are grown in natural environments such as north of Argentina, south of Brazil and Paraguay, and southern China. CIAT has developed a range of highland-adapted varieties, but for a limited area of the Andes of southern Colombia. Southern Brazil and China have had strong breeding programs, but with limited attempts to introduce new genetic diversity to further the range of cassava into higher latitudes.

Breeding for these traits will result in farmers having cassava varieties with high-yielding ability and tolerance to cold temperatures, which will allow cassava to be produced in new regions in the world to increase production and food security. Countries in higher latitudes (e.g. China, Argentina, Brazil, Paraguay, Bolivia and South Africa) and high altitudes (Andean countries and East Africa highlands) would benefit from this option. As with the case of drought tolerance, the probability of research success is expected to be high because some promising varieties have been identified in the field that have tolerance to cold weather and frost.

3.4 High-yielding varieties with dual resistance to CMD/CBSD

This research option involves breeding for high yield combined with dual resistance to both CMD and CBSD. It addresses the problem of low-yielding varieties and combats the CMD and CBSD pandemics. CMD is the most severe and widespread, limiting production of the crop in SSA. CMD produces a variety of foliar symptoms that include mosaic, mottling, misshapen and twisted leaflets, and an overall reduction in size of leaves and plants. CBSD is especially damaging in East Africa, where it reduces yields by more than 50%. It was first identified in 1936 in Tanzania and has spread to other coastal areas of East Africa, from Kenya to Mozambique. There are many research dimensions with respect to this option, including breeding for high yields, early harvest, drought tolerance, and resistance to CMD and CBSD. High yielding resistant varieties should also include other key traits such as improved shelf life of roots; nutrient-use efficiency; better nutritional qualities like pro-vitamins; and resistance to other biotic and abiotic stresses. Efforts should be directed toward integrated breeding using both molecular and conventional approaches.

This research option has been pursued since 2007 and efforts are underway on molecular and conventional breeding for high yield with dual resistance to CMD and CBSD as well as improved agronomic practices. The focus countries are Tanzania, Mozambique, Kenya, Uganda, Malawi, Zambia, Congo, DRC, and Cameroon. IITA does not have technologies from this option; efforts to develop adoptable technologies are ongoing. The breeding program is complemented with integrated crop management practices such as improved management options for CMD and CBSD; soil fertility with

[11] Cassava is highly frost-sensitive, and must be harvested or pruned prior to frost occurrence.

micronutrients, fertilizer, and organic matter; better cropping systems, harvest methods, and machinery for planting and harvesting. The adoption of the technologies from this research is expected to result in increased yield and good quality cassava with enhanced resistance to CMD and CBSD that offer farmers better market value. The technologies are expected to be gender equitable and environmentally friendly. For East Africa, the focus is on both CMD and CBSD, and for West Africa the research will curb the CMD pandemic and offer preemptive options in the case of introduction of CBSD. Adoptable innovations expected from this option are high-yielding varieties with dual resistance to CMD and CBSD.

3.5 High-yielding varieties with high dry matter and starch

This research option involves breeding for cultivars with high-yielding varieties combined with high dry matter and starch. Dry matter production is an important determinant for storage root yield in cassava and is an important criterion in breeding programs for enhanced yield. On average about 85% of dry matter in roots is from starch, so these terms (*starch yield* and *dry matter yield*) are used nearly interchangeably. High starch content is an important component of yield and quality for almost all uses of cassava (starch, flour, chips, and industrial raw material). In the RTB research dimension, this research component option includes breeding for high yields, high dry matter content, and good quality starch. The complementary agronomic practices include fertilization, correct plant spacing, and improved use of organic matter.

Efforts are underway to breed for high-yielding varieties with high dry matter and starch in Africa (e.g., evaluation and selection of cassava for high starch content and yield in Tanzania). To date three varieties with the high starch content have been developed in Tanzania. In Nigeria, IITA and the Nigerian Root Crops Research Institute (NRCRI) have released two improved cassava varieties for starch and dry matter. In LAC, CIAT's cassava team has also developed novel starch quality traits such as the waxy-starch and small-granule mutations that promise to strengthen the crop's appeal to industrial markets. For this research option, the adoptable innovations resulting from research include varieties with high dry matter and starch for food and industrial use. This technology will lead to cassava varieties with high yield, dry matter, and starch for increased incomes, enhanced food security, and reduced poverty. An increase in starch content, at the same fresh root yield levels, means a relative increase in economic yield but also entails a small increase in production costs.

3.6 High-yielding varieties with improved nutritional quality

This research option involves breeding for varieties with high nutritional quality such as vitamin A, high protein content, and low cyanide content. Cassava varieties with high vitamin A are expected to reduce significantly dietary constraints to millions of people depending on cassava. The research component options include breeding for high yields and better nutritional qualities like protein, pro-vitamins, and minerals. Nonetheless, to date there is limited evidence on breeders' capacity to improve protein and mineral content of cassava.

Efforts to address nutritional deficiencies through cassava have seen progress through breeding in both SSA and the Americas. Research on this option started in Cameroon in 1990 and in Tanzania in 1996. Research is now ongoing in several SSA countries, including Tanzania, Zambia, Mozambique, Malawi, Uganda, Cameroon, and Kenya. In the DRC, there are some high pro-vitamin A varieties on the ground—for example, Liyayi (like egg yolk), which is known and adopted by farmers. In Nigeria, three pro-vitamin A (or yellow) cassava varieties bred by IITA and NRCRI, with support from HarvestPlus, have been released to provide more vitamin A in the diets of more than 70 million Nigerians who eat cassava every day. Improved varieties resulting from this work will offer large nutritional benefits for poor consumers as well as significant advantages for the animal feed industry. The adoptable innovations are expected to increase yield and improve cassava with better nutritional characteristics such as pro-vitamin A and minerals. The impact of this research option is realized mainly in terms of improvements in health and nutrition.

3.7 High-yielding varieties with longer shelf life

This research option comprises breeding for high-yielding varieties with longer shelf life. One of the major constraints facing the large-scale production and commercialization of cassava is rapid postharvest physiological deterioration (PPD). Given the high perishability of harvested cassava, there is need for rapid processing of the storage roots into more stable products. In this research option, the breeding program aims to increase yield and shelf life. The adoptable innovations resulting from breeding are high-yielding varieties with longer shelf life.

There are actually postharvest technologies that help slow PPD, such as the case of plastic bags for wrapping fresh cassava products. However, there has been little success in identifying cassava varieties with longer shelf life. The research involves new varieties with slower PPD and postharvest technologies to preserve fresh cassava for longer periods for price stabilization and reduction of postharvest losses and transaction costs.

3.8 Integrated pest and disease management practices, including resistant varieties

The integrated pest and disease management practices, including resistant varieties, option addresses the constraint of reducing yield due to pests and diseases pandemics and aims to reduce crop losses from important pests and diseases. In different areas of the cassava production zones of Africa, one or more pests are important. Major pests reported in cassava-producing countries include cassava green mites (CGM), white flies, mealybug, and CBB. In Asia, the most important pest is the mealybug (*P. Manihoti*) and the predominant disease is witches broom disease. In LAC, on the other hand, there is no particular species that causes major losses in the region. Although the subterranean sucker (*Cyrtomenusbergi Froeschner*) has been singled out as an important pest in certain places, the biggest pest in LAC is the mite. While not well-documented, the largest losses from diseases in LAC appear to correspond to those caused by CBB (E. Alvarez, pers. comm.).

In Africa, research dimensions with respect to this option include breeding for resistance to pests and diseases such as whiteflies, CBB, super-elongation disease, and cassava green mites. Complementary agronomic management options include integrated management of pests and diseases. For LAC, it is important to further develop varieties that are resistant to CBB and super-elongation, and to initiate breeding for resistance to the frogskin disease. Biological control options have been developed for mites in LAC and the mealybug in Asia. Varieties resistant to CMD are needed in Asia as a preemptive strategy in case the virus pathogen is introduced from Africa or India.

One of the most successful integrated pest and disease management programs is the biological control of CGM. In 1983, IITA initiated a classical biological control program against CGM in collaboration with partner institutions in Africa, South America, and Europe. A phytoseiid predator, *Typhlodromalus aripo*, was identified and imported from South America to Africa and proved to be very effective (80%) in controlling CGM in Africa (Herren and Neuenschwander 1992). Yield assessment trial results showed that biological control by *T. aripo* increased yields by 30% in infested fields while reducing the CGM population some 30–90% (with an average of 50%) (Herren and Neuenschwander 1992). For the mealybug in both Africa and Asia, biological control is applied, whereas witches broom disease is so far more efficiently controlled with appropriate seed management. In the LAC region, mite control is done through better crop management and resistant varieties. Application of pesticides is discouraged, as a matter of safety and the side effects of destroying beneficial organisms. CBB is controlled by an improved management of planting materials and varietal resistance. These pests and diseases are yet to be contained fully in either Africa or LAC despite the major breakthrough in biological control. Efforts to control pests and diseases must be ongoing due to their continual evolution as well as changes in their environment due to changes in management practices and climate change. For cassava mealybug, the parasitoid *E. lopezi*, which was found in Paraguay and successfully introduced in Africa in the 1980s, has proven to be an effective control. It was introduced into Thailand, with plans to extend its application to other cassava-growing Asian countries.

Work on the development of new varieties resistant to CGM, white flies, frogskin disease, and CBB is either ongoing or is expected in the near future. The methodologies for better management of planting material in order to stop witches broom, CBB, frogskin, CGM, white flies, mealybug, CBB, and subterranean sucker need to be studied. In Africa, LAC, and Asia, expected benefits of pest and disease management programs include increased crop yields, large reductions in mite populations, and environmental benefits due to the non-use of persistent chemical insecticides. In Asia, crop losses due to the mealybug are expected to be reduced to 5% from potential values of 70%. While loss estimates from witches broom are preliminary, it is believed that improved seed management can substantially reduce losses (K. Fahrney, pers. comm.). For the LAC region, losses attributable to CBB in areas of high incidence could drop from 30% to near zero, and the damage from mites, which is estimated at 20–30% of production under high incidence, could be reduced to 10–20%, depending on the site (CIAT Cassava Program).

3.9 Processing technologies for value addition

This option focuses on developing new products from cassava; producing new processing technologies for facilitating starch processing, adding value, and developing and marketing quality products; and reducing environmental pollution due to processing. Emphasis is on the inclusion of small farmers, and the addition of value along the cassava value chain. The option is also expected to facilitate postharvest utilization and marketing of cassava. Production of new processed cassava products and processing equipment entails improving small-scale processing of cassava for human consumption and industrial uses. It also includes the development of cassava products for human consumption, cassava products for industrial applications (e.g., flour and starch), and alternative on-farm utilization/processing for value addition. This requires value chain changes to improve the quality and reliability of production by farmers and increasing interaction among actors in the marketing chain in order to improve access of farmers to value-adding markets. It also involves processing technologies that ensure consistency in product quality and economies of scale. None of these research dimensions is a substitute for another. They are all complementary.

There are several efforts by particular countries to develop cassava value chains through research and extension. “Cassava processing technologies for value addition” is a project funded by the Common Fund for Commodities and led by IITA, working with a wide range of partners in Tanzania, Malawi, Madagascar, and Zambia. More research efforts to modify and upscale existing processing technologies to minimize cost are ongoing. CIAT has been collaborating with the Latin American and Caribbean Consortium to Support Cassava R&D (CLAYUCA) to develop processing technologies and machinery for small and medium cassava farmers, and to develop new products for human consumption (e.g., bakery products) and animal feed (utilization of waste and sub-products of industrial processes).

The adoptable innovations expected to emerge from these research options are different forms of cassava chips, cassava flour, cassava frozen chunks and *personal size* root pieces for export. Novel products incorporating cassava starch or flour are cassava bread, cassava biscuits, cassava flour for pizza, ice cream, and instant noodles. The increase in sales of cassava products is anticipated to lead to increased adoption of high-yielding, disease-resistant and improved cassava varieties. So far, IITA has developed technologies from this option; research is ongoing on production of more adoptable technologies. Similarly, CIAT–CLAYUCA has developed various products and processes that are suitable for the LAC and Asian regions. The innovations from this option are expected to significantly reduce waste and postharvest losses. They will add value to cassava and improve handling of cassava along the value chain, and will lead to export of cassava products to non-cassava growing areas of the world. Processing technologies will be adopted by small farmers so that they obtain better prices for their product and expand their operations. There is the potential of creating new starch industries in regions where this was unfeasible until now. Moreover, the technologies expected are gender and environmentally friendly. The adoptable innovations resulting from this research option include new processing technologies. Therefore, value addition technologies are expected to increase distribution of benefits among value chain actors through proper marketing arrangements in all countries. The research will be conducted in all cassava-growing countries as these technologies, or similar ones, have been tested already.

3.10 Strategies to prevent introduction of exotic pests and diseases

There is the danger of diseases and pests “jumping” natural obstacles such as mountains or bodies of water, and reaching new regions, creating new hazards to cassava production. Indeed, mealybug has recently been reported to have crossed the ocean and been spotted in Indonesia, or CMD finding its way in the past decades from Africa to India. For Asia, this research option should prevent the introduction of green mites to parts of SE Asia, a pest that is already present in Africa and LAC. Strategies should be devised to impede the expansion of the CMD to the rest of Asia.

The white fly (*Benicia tabaci*) needs to be halted from crossing from Africa into LAC and Asia. Although there are white flies in LAC, the existing *B. tabaci* biotype does not thrive on cassava. CMD and CBSD are diseases from Africa that could cause significant damage in LAC or Asia. Development of technologies is needed for pests and risk assessment with large data and from reliable sources, in order to devise strategies and actions to prevent the introduction of exotic pests and diseases. This research option should be promoted for national agricultural research systems (NARS) on the political level. This is a new type of research as preventive measures are hard to devise without enough information about the potential risks. Adoptable innovations include development of diagnostic kits, risk prediction maps, and quarantines. The benefits of this technology translate into stemming potential yield losses if any important pest or plague reaches a new region. This research option involves much uncertainty, and the combined probability of success will be highly variable, depending on the commitment of the countries in question.

3.11 Sustainable crop and soil fertility management practices

This option involves management practices such as application of appropriate and site-specific organic and mineral nutrients, integration of legumes into cassava systems, use of bio-fertilizer, weed control, and system- and site-specific improved varieties. There are two interrelated components: sustainable soil fertility management practices and sustainable crop management practices.

3.12 Sustainable soil fertility management practices

This research option aims so improve soil nutrient status for long term high productivity and sustainability. It involves such management practices as application of appropriate and site-specific organic and mineral nutrients, integration of legume intercrops or rotation crops, use of bio-fertilizer, and reduced soil losses through erosion control practices. The increasing rate of population growth and consequent pressures from competing socioeconomic demands in most African countries have led to soil erosion and nutrient depletion, which have reduced agricultural productivity and degraded the environment.

Research on soil management started many years ago in most African countries and continues today in all the countries. CIALCA (www.cialca.org) is a research-for-development consortium led by the Tropical Soil Biology and Fertility Research Area of the International Center for Tropical Agriculture (TSBF-CIAT), IITA, and Bioversity International. It involves a diverse range of partners across the research-to-development continuum. Its major goal is to improve the livelihoods of rural households in Central Africa through the identification, evaluation, and promotion of technological options to enhance the productivity of cassava, banana, maize, and legume-based systems and creation of an enabling environment for their adoption. CIALCA has been operating since late 2005 in 10 mandate areas in Burundi, Rwanda, and DRC to promote combined application of organic and mineral inputs to lessresponsive soils. To a large extent, adoption is market-driven as commodity sales provide incentives and cash income to invest in soil fertility management technologies.

In West Africa, IITA uses a stepwise approach, first determining the most limiting nutrient(s), followed by elaborating the correct quantity required and the construction of recommendations for optimal nutrient composition and quantities. Along with other integrated soil fertility options, IITA is currently working with the International Fertilizer Development Center on testing special fertilizer blends for cassava and addressing the augmentation of neglected nutrients such as sulphur, magnesium, zinc, and boron. There are no recent fertilizer response curves for cassava in West Africa; hence, farmers do not know the composition and amounts of fertilizer to apply. The nutrient(s) most limiting to cassava production in West Africa have not been quantitatively determined. The replenishment of the most limiting nutrient would lead to substantial yield increases. Today, with more options available and a stronger and earlier involvement of farmers in research for development, such approaches are worth reconsidering. More research efforts are expected to benefit farmers in all cassava-growing areas of Africa where soil fertility is a problem.

CIAT's approach has been more on the application of eco-efficient principles to soil fertility and crop management. Eco-efficiency takes into account agronomic, social, environmental and economic dimensions. The focus is on maximizing the agronomic efficiency of inputs, with enhanced productivity and profitability and minimized losses to the environment as direct consequences. Since 2001, the TSBF of CIAT has been working on a combination of improved germplasm, adequate application of fertilizers, and better agronomic practices. This process has been complemented with the collection of information and mapping of soil properties and ecosystem health at landscape level. Efficient systems that combine crop-pasture-fallow to improve productivity are being tested in the savannas and hillsides.

The adoptable innovations expected from this option are land-enhancing technologies such as different and diverse types of organic and inorganic fertilizers as well as mechanization of cassava production operations such as planting and harvesting. Adoptable technologies should also include different types of herbicides and other chemicals for weed controls. Innovations for managing soil acidity and salinity as well as erosion control will be explored via this option. CIAT has some proven technologies available and new ones are being tested. We are making special efforts to gather spatial information that can render knowledge to apply soil fertility and crop management technologies strategically and effectively. Eco-efficient integrated soil fertility management encompasses green manure, animal manure, fertilizer, and soil erosion preventing practices. The adoptable technologies from this option are expected to be gender and environmentally friendly. Innovations from this option are expected to improve yields, increase farmer household incomes, and enhance their livelihoods. Yield increase is expected to be higher for improved varieties (up to 60%) than for native varieties (up to 40%); therefore, Asian farmers are expected to realize bigger increases in yield, while their LAC counterparts will see a smaller increase in yield. Overall, yields could be increased by at least 55%. The technologies generated as a result of this option are expected to benefit all cassava-growing farmers in all the regions. The research option is expected to take place in all the agro-ecological zones of LAC, most of Asia, and West, East, and Central

Africa. On the basis of responses from experts interviewed, the probability of research success in this area is at least 50% in most African countries. Owing to the existence of many successful cases, there is high probability of success in LAC and Asia.

3.13 Sustainable crop management practices

This option involves such management practices as weed control, system- and site-specific improved varieties, land preparation, plant densities, harvest of foliage, associated crops, mechanization of planting and harvesting, integration of legume in cassava, and use of bio-fertilizer. The research dimensions of this option include research on production technology; agronomy; and crop management. It also includes production of technologies on improving cassava-cropping systems, harvesting methods or machinery for planting and harvesting, weed management and control, and water management in crop production. The research option began many years ago in most African countries. It is ongoing in all the countries.

The adoptable innovations expected from this option are soil-enhancing technologies such as organic and inorganic fertilizers; mechanization of planting and harvesting, and different types of herbicides and other chemicals, or mechanical means for weed control. Innovations for managing soil acidity and salinity as well as erosion control will be developed within this option. Some varieties suitable for different locations have been identified at CIAT, improving the crop management options of farmers in LAC and Asia. The adoptable technologies from this option are expected to be gender equitable and environmentally friendly.

4. Parameter estimates and data sources

Expert opinions served as the major source of information for the economic surplus analysis of cassava research options. A structured questionnaire was developed to guide consultations with IITA and CIAT scientists as well as with NARS partners in Africa, LAC, and Asia who are working on particular cassava production and market constraints to elicit key parameter estimates for the research options addressing those constraints. Expert consultations at IITA involved 12 scientists: cassava breeders (6), agronomists (3), virologists (2), and processing and utilization specialists (1). The cross-country survey in Africa involved 30 experts from NARS partners in Africa: Benin (1), Cameroon (1), DRC (1), Ghana (4), Kenya (1), Mozambique (3), Nigeria (2), Togo (3), Uganda (3), Tanzania (9), and Zambia (2). In CIAT, a group of 14 scientists (breeders, agronomists, postharvest processing experts, molecular biologists, entomologists, plant physiologists, and virologists) working in LAC and Asia was consulted. Also, an online survey was conducted and 46 responses were obtained. For each research option identified, scientists were asked to estimate the values of the following key parameters: maximum adoption rate, year of beginning of adoption, years to maximum adoption rate, expected yield increase (%), area affected by the constraint (%), cost change due to inputs (%), and probability of research success (%). The values of some parameters such as research costs were assembled from several sources, such as RTB program proposal and past empirical work (e.g., Thirtle et al. 2003; Alene et al. 2009; FAO 2013; World Bank 2013). Table 5 presents the description of the key project, technology, and market-related parameters used and the corresponding data sources.

Table 5: Assumptions and data sources for key parameters used in the economic surplus analysis

Parameter	**Assumption/Source**
Time period	25 years (2014–2039); 10 years for research investment—research lag (maximum time period for RTB). Most of the R&D investments will run for 10 years, though other research options may either be longer or shorter.
Elasticities of supply and demand	Elasticities of supply and demand were assumed to be 1 and 0.5 respectively across technologies and for all countries due to limited availability of information.
Productivity effects	Expert estimates for a particular technology supported by field trial data.
Input cost changes	Expert estimates for a particular technology supported by farm-level surveys; changes in costs for particular inputs estimated in terms of relative share in overall production costs.
Probability of research success	Maximum value of 0.8 for quick wins was assumed and lower values if uncertainty of research success is higher (or implementation uncertain—e.g., GM crops). Success probabilities should be different across technologies, allowing for differences at least across regions for the same technology. Country-level success probabilities were not available, but these could be included in subsequent assessments.
Depreciation rate	1% across all technologies and countries
Discount rate	10% (World Bank 2013)
Production	National average annual production for 2009–2011 from FAOSTAT (2013). Where data were missing, we used data from previous years.
Prices	National average annual production and prices for 2009–2011 from FAOSTAT (2013). Where data were missing, we used data from previous years.
Adoption profile	Logistic adoption curve; adoption ceiling (A_{max} or At_3) based on expert estimates (as share of total area in potential adoption domain); time to reach adoption ceiling (in years = t_3); adoption rate in first year of adoption (At_1) is 1% of adoption ceiling for all technologies; year of first adoption (t_1); disadoption based on timeframe and expert assessment. Two adoption scenarios: (1) adoption scenario based on expert assessment and (2) conservative adoption scenario: 50% of expert assessment.
R&D and dissemination costs	1. Research costs estimated as the sum of: (1) RTB budgets as presented in the program proposal by thematic area (some themes actually matching the research options identified); (2) bilateral projects at IITA and CIAT (assumed to be equal to RTB budgets); and (3) NARS costs, which are assumed to be equal to IITA and CIAT budgets combined. 2. Dissemination costs for new variety is (US$50/ha) and (US$80/ha) for other knowledge-intensive technologies, such as crop management interventions.
Poverty	Poverty incidence (% living on less than US$1.25/day), the number of poor people, and agricultural value added from World Bank's World Development Indicators database (World Bank 2013).
Agricultural value added	World Bank's World Development Indicators database (World Bank 2013).
Number of beneficiaries	Country-specific estimates prepared for RTB proposal: crop area per HH for specific crop and number of persons per HH.

4.1 Socioeconomic parameters

Table 6 presents the data on the key socioeconomic parameters used in the economic surplus analysis of cassava research options for individual countries in Africa, Asia, and LAC. Data on annual harvested area, production, and producer prices were obtained from the FAOSTAT database (FAO 2013). We used three-year national averages for each country for the period 2010–2012. In cases where FAO data were not available for particular countries and years (e.g., producer prices), we used data obtained from the respective ministries of agriculture and offices of statistics. Data on the incidence of poverty, the number of poor, and agricultural value added were obtained from the World Bank's World Development Indicators database (World Bank 2013).

We also used poverty elasticities of 0.72, 0.48, and 0.15 for Africa, Asia, and LAC, respectively (Thirtle et al. 2003). The data on cassava area per household and household size that were used for the estimation of the numbers of beneficiaries were taken from a dataset put together for the estimation of the potential number of beneficiaries of the RTB program (CGIAR 2011).

Table 6: Data on the socioeconomic parameters used in the economic surplus analysis

Country	**Price** (US$/ton)	**Quantity** ('000 tons)	**Area harvested** ('000ha)	**Household size** (persons)	**Area per farm** (ha)	**Poverty incidence** (%)	**Number of poor** (million)	**Agricultural Value Added** (US$ billion)
Angola	350	13,673	936	6	0.50	56	10.7	10.6
Benin	470	3,611	251	5	0.50	45	4.0	2.5
Burkina Faso	268	4	3	5	0.50	45	7.4	3.5
Burundi	374	564	65	5	0.50	81	6.8	0.9
Cameroon	357	3,744	263	5	0.50	9	1.8	4.9
Chad	698	230	22	5	0.50	45	5.0	1.5
Congo	330	1,177	135	5	0.50	53	2.2	0.5
Cote d'Ivoire	243	2,309	347	5	0.50	24	4.7	6.2
DRC	330	15,224	1,960	5	0.50	86	56.8	8.1
Ghana	163	13,325	883	4	0.50	25	6.0	9.2
Guinea	354	1,065	129	6	0.50	42	4.2	1.5
Kenya	130	608	64	4	0.50	41	16.4	11.0
Liberia	295	494	62	6	0.50	83	3.3	0.9
Madagascar	171	3,173	473	5	0.50	78	16.2	2.9
Malawi	333	4,028	194	4	0.50	67	10.0	1.3
Mozambique	201	8,501	1,267	5	0.50	60	13.9	4.4
Nigeria	259	43,920	3,449	4	0.50	68	107.2	85.9
Rwanda	299	2,325	196	4	0.50	67	7.1	2.3
Senegal	328	164	26	9	0.50	25	3.1	2.1
Sierra Leone	295	446	84	6	0.50	45	2.6	2.2

Country	Price (US$/ton)	Quantity ('000 tons)	Area harvested ('000ha)	Household size (persons)	Area per farm (ha)	Poverty incidence (%)	Number of poor (million)	Agricultural Value Added (US$ billion)
Togo	174	934	148	5	0.50	39	2.3	1.2
Uganda	120	5,073	417	5	0.50	43	14.3	4.7
Tanzania	210	5,037	898	5	0.50	67	41.5	7.8
Zambia	240	1,193	200	5	0.50	66	8.6	4.0
Argentina	116	182	18	4	0.40	1	0.4	49.1
Bolivia	299	249	29	4	0.50	16	1.6	3.1
Brazil	125	24,907	1,761	5	0.75	6	12.1	123.8
Cambodia	263	4,038	189	4	0.50	19	2.7	4.7
China	127	4,528	277	4	0.25	12	158.6	732.2
Colombia	310	2,166	204	5	0.40	8	3.8	23.5
Costa Rica	238	500	34	5	1.00	3	0.1	2.5
Cuba	62	402	71	5	1.00	2	0.2	3.0
Ecuador	245	57	19	5	1.00	5	0.7	7.8
Haiti	160	573	140	5	0.20	62	6.2	1.9
India	160	8,586	245	5	0.60	33	399.1	337.1
Indonesia	198	23,322	1,180	12	0.50	16	39.5	127.0
Jamaica	449	18	1	5	0.75	0.21	0.01	1.0
Laos	160	465	20	5	0.50	34	2.2	2.6
Malaysia	231	48	3	5	0.50	1	0.2	34.6
Paraguay	63	2,563	180	4	0.45	7	0.5	5.5
Peru	165	1,174	100	4	0.40	5	1.5	10.6
Philippines	132	2,118	218	4	0.50	18	17.5	29.2
Thailand	60	24,669	1,210	4	0.50	0.38	0.3	41.5
Venezuela	922	498	36	4	0.50	7	2.0	19.0
Vietnam	112	9,008	521	4	0.50	17	14.8	27.2

Source: FAOSTAT (http://faostat.fao.org/) and World Bank (http://data.worldbank.org/indicator).

4.2 Technology development, dissemination, and adoption parameters

The economic surplus model employed for the ex-ante impact analysis typically uses market-related data on socioeconomic parameters and technology-related data on technology development, dissemination, and adoption parameters (Alston et al. 1995). Therefore, in addition to the socioeconomic parameters such as production and prices, the economic surplus model uses a number of parameters that relate to the research and dissemination process and includes those that relate to the expected effects of new technology adoption on yield gains (or reduced yield losses) and production costs. In addition to parameters relating to expected yield gains and production cost changes following technology adoption by farmers, other technology-related parameters of importance include (1) the research lag defined as the number of years it takes until an adoptable innovation will be available to farmers; (2) adoption ceiling defined as the maximum adoption rate as a proportion of total cropped area; (3) adoption lag defined as the number of years until maximum adoption is reached; (4) the costs required to conduct R&D (i.e., R&D costs); (5) the dissemination costs for each technology (either US$80 or US$50 for every new hectare of adoption depending on the type of technology); and (6) the probability of research success. Tables 1–10 in Annex 2 present detailed technology-related data by country and research option.

Since the outcomes of research investments cannot be realized for many years, ex-ante technology generation and adoption parameters can only be based on the opinions of R&D experts who draw on a wealth of experience and knowledge in making informed predictions. Most of the data relating to cassava technology development, dissemination, and adoption were obtained primarily through expert surveys and consultations. Expert estimation of the values of some of these parameters involved a number of steps designed to facilitate the elicitation process. For example, estimation of the adoption ceiling involved estimation of the area affected by the underlying constraint as a proportion of the total cropped area and the expected adoption rate as a proportion of the affected area. For Africa, the affected area was thus used only to facilitate the estimation of the ultimate value of adoption as a proportion of the total cropped area. That is, adoption as a proportion of total cassava area is estimated as the product of adopting a proportion of the affected area and the affected area as a proportion of total area. For almost all research options, however, cassava experts working especially in Africa argue that much of the cassava area has been (or is expected to be) affected by the underlying constraints, such as low yield potential, poor resistance to pests and diseases, shorter shelf life, and lack of clean planting material multiplication and distribution system. Consequently, the experts argue that improved seed systems and improved varieties with high-yield attributes would be appropriate for almost all recommendation domains. Varieties with resistance to pests and diseases, however, should be developed not only for those areas that are currently affected by the diseases, but also for all areas that will be affected in the many years to come (including pre-emptive measures). Indeed, using currently affected area as a recommendation domain for adoption would understate potential adoption of those technologies. Looking at the nature of most of our research options that make explicit mention of "high yield," they also say that much of the cassava area should be a relevant adoption domain, especially because wider geographic adaptation is also one of the key criteria of varietal release.

Similar arguments could be used for the case of LAC and Asia, with the exception that the measure of the crop area affected by the constraint or the technology was not included in the assessment of the adoption of technology, and the values used may overestimate the impact of the technologies. It is important to note that in some cases these values can be important, such as in the case of drought-resistant cassava, which will have a real impact only in a small fraction of crop areas in Asia and LAC. Another example is the case of some pests that affect only specific regions of countries and continents due to geographic or climatic barriers. Overall, this parameter was left out of this research to maintain consistency across all regions. It needs to be revisited in future analysis.

On the other hand, R&D costs were estimated as the sum of (1) CRP-RTB investments in cassava research disaggregated by research theme (CGIAR 2011); (2) bilateral project funding for IITA (mainly for Africa) and CIAT (mainly for Asia and LAC), which was estimated to be approximately equal to the CRP-RTB funding; and (3) NARS partner costs, which were assumed to be equal to the total of CRP-RTB and bilateral funding through IITA and CIAT. Aggregating the costs across countries for each research option gives the global R&D costs needed for calculating the global NPVs and IRRs. The CRP-RTB costs were estimated based on the figures in the RTB program proposal (Table 8.2, p. 166). The annual cassava budget was allocated across the research options. For some options such as "planting materials," allocation was already made and only required little adjustment to reallocate the overheads and CRP management costs. Dissemination costs were estimated to be US$50 per hectare of adopted area for new varieties and US$80 per hectare of adopted area for other knowledge-intensive technologies, such as crop management interventions.

Table 7 provides an overview of the parameters related to cassava research and technology dissemination process. The year when the respective research started was included as an indicator of how much of the research has been completed. Cassava research in Africa dates back to 1936, when scientists started doing research to address major production constraints such as CMD. However, efforts to address CBSD by developing varieties with dual resistance to both CMD (including the new Uganda variant) and CBSD started recently. In this assessment, we treat all past research costs as sunk costs—that is, costs excluded from the computation of research costs. Thus the information on how much of the research has already been completed puts the result of the assessment in perspective as one would expect higher NPVs and IRRs for research options with much of the R&D cost not accounted for. Clearly, the IRR measure favors such research options due to shorter research lags and higher probability of research success.

Table 7: Overview of parameters related to cassava research and technology dissemination process

Technology	Duration of Research Phase (years)		Year when Research Started		Number of Countries Targeted		R&D Costs (US$ million/year)			Dissemination Cost (US$/ha)	
	Africa	**LAC/Asia**	**Africa**	**LAC/Asia**	**Africa**	**LAC/Asia**	**Africa**	**LAC/Asia**	**Total**	**Africa**	**LAC/Asia**
High-yielding varieties with resistance to major diseases (CMD/CBSD)	8		2007		24		3.88		3.88	50	
High-yielding varieties with high dry matter and starch	6	4	2007	1980	24	21	3.88	3.88	7.76	50	50
High-yielding varieties with longer shelf life	7	6	2014	2014	24	21	3.88	3.88	7.76	50	50
High-yielding, drought-tolerant varieties and increased water-use efficiency	7	8	2009	2010	24	21	3.88	3.88	7.76	50	50
Sustainable crop and soil fertility management practices	4	1	1980	1980	24	21	3.88	3.88	7.76	80	80
Integrated pest and disease management practices, including resistant varieties	5	8	1983	1998	24	21	3.88	3.88	7.76	80	80
Efficient and massive high-quality planting material production and distribution systems	3	1	2007	1995	24	21	4.39	4.39	8.78	80	80
Processing technologies for value addition	6	1	2003	2003	24	21	4.19	4.19	8.38	80	80
Strategies to prevent introduction of exotic pests and diseases		5		2014		21		3.88	3.88		80
High-yielding varieties tolerant to cold weather and frost		5		2014		21		3.88	3.88		50

Note: The research option "high-yielding varieties with improved nutritional quality" was not included in the analysis.

4.3 Parameter estimates for individual research options

The estimates of the parameters used in the economic surplus analysis such as maximum adoption rate, research lag, years to maximum adoption rate, percentage yield increase, cost changes due to inputs, and probability of success that are specific to each research option and country are presented in Annex 2 (Tables 1–10). This section provides an overview of the parameter estimates for each research option.

1. High-yielding varieties with dual resistance to CMD and CBSD: (1) maximum adoption rate of 30–50%; (2) research lag of 5–10 years; (3) adoption lag of 12 years; (4) yield increase of 30%; (5) input cost change of 20%; and (6) probability of success of 50%.
2. High-yielding varieties with high dry matter and starch: (1) maximum adoption rate of 8–90%; (2) research lag of 3–8 years; (3) to adoption lag of 12 for all African countries and 10 for all LAC and Asian countries; (4) yield increase of 15–30%; (5) input cost change of 15–20%; and (6) probability of success of 50–70%.
3. High-yielding varieties with longer shelf life: (1) maximum adoption rate of 8–90%; (2) research lag of 5–8 years; (3) adoption lag of 10–14 years; (4) yield increase of 6–65%; (5) input cost change of 5–20%; and (6) probability of success of 50–80%. Expected reduction in postharvest losses as a proportion of total production following adoption of varieties with longer shelf life was taken as the yield loss avoided and was estimated as the product of (1) current postharvest losses as a proportion of total production and (2) expected reduction in postharvest losses (as a proportion of current losses) following adoption of varieties with longer shelf life.
4. High-yielding, drought-tolerant varieties and increased water-use efficiency: (1) maximum adoption rate of 8–90%; (2) research lag of 5–8 years; (3) adoption lag of 12 years; (4) yield increase of 15–35%; (5) input cost change of 10–20%; and (6) probability of success of 65–80%.
5. Sustainable crop and soil fertility management practices: (1) maximum adoption rates of 20–50%; (2) research lag of 1–5 years; (3) adoption lag of 8–12 years; (4) yield increase of 15–55%; (5) input cost change of 5–30%; and (6) probability of success of 75–80%. This research option generally has short research lags because of the advanced stage of development of the components of the technological packages. In view of significant yield responses of cassava to crop and soil fertility management practices, the experts also estimated a relatively higher yield increase of 15–55% as compared to the rest of the research options.
6. Integrated pest and disease management practices, including resistant varieties: (1) maximum adoption rate of 8–90%; (2) research lag of 5–8 years; (3) adoption lag of 12 years; (4) yield increase of 25–70%; (5) input cost change of -30 to 20%; and (6) probability of success of 50–80%.
7. Efficient and massive high-quality planting material production and distribution systems: (1) maximum adoption rate of 20–50%; (2) research lag of 1–4 years; (3) adoption lag of 5–12 years; (4) yield increase of 30–50%; (5) input cost change of 5–25%; and (6) probability of success of 50–80%. This research option has the shortest research lag of one year for many countries in LAC and Asia.
8. Processing technologies for value addition: (1) maximum adoption rate 10–34%; (2) research lag of 2–8 years; (3) adoption lag of 8–12 years; (4) yield increase of 15–35%; (5) no production cost change due to inputs—that is, a postharvest technology involving no varietal change; and (6)

probability of success of 50–80%. The expected yield gains were estimated indirectly based on the supply response to price increases attributable to value addition through processing. With a unitary price elasticity of supply, cassava price changes due to processing and value addition translate into equivalent production increases. As the area under cassava can be reasonably assumed to be fixed in the short run, production increases in response to price increases can only be achieved through equivalent yield increases.

9. Strategies to prevent introduction of exotic pests and diseases: (1) maximum adoption rate of 10–60%; (2) research lag of 5 years; (3) adoption lag of 10 years; (4) no yield increase—that is, impact of intervention realized through production cost reductions; (5) input cost change of -35 to -10%; and (6) probability of success of 50%.
10. High-yielding varieties tolerant to cold weather and frost: (1) maximum adoption rate of 10% in Colombia to 100% in Argentina; (2) research lag of 8 years; (3) adoption lag of 12 years; (4) yield increase of 20%; and (5) probability of success of 50%.

5. Results of the ex-ante impact assessment using economic surplus model

The ex-ante analysis was undertaken under two alternative maximum adoption scenarios: (1) “higher adoption” scenario using adoption rates of technologies estimated by experts who are usually optimistic about the prospects of the technologies they are developing, and (2) a more conservative “lower adoption” scenario with expert estimates of adoption reduced by 50%. The summary measures of the ex-ante economic benefits of cassava technologies are presented in Table 8, whereas Table 9 presents the number of beneficiaries and poverty reduction impacts. The discussion in this section focuses on the results under the basic “higher adoption” scenario, but Tables 8–10 also present the results under the conservative “lower adoption” scenario for comparison. As expected, halving adoption ceiling estimates of technologies only reduces the size of expected benefits and impacts on poverty reduction, but does not alter the relative importance and impacts of the various research options.

The results show that each of the cassava technologies generates large NPVs of benefits, indicating the profitability of investments in the respective cassava research options. There is considerable variation in NPVs across options ranging from US $194 million for high yielding varieties tolerant to cold weather and frost to US $16.7 billion for sustainable crop and soil fertility management practices. However, because of the substantial variation in the R&D investments needed to generate the estimated benefits, the NPVs cannot be used to rank the research options. The IRRs are a preferred measure for ranking alternative technologies.

The results of the ex-ante analysis of the IRRs further show that, even under the lower adoption scenario with expert estimates of adoption reduced by 50%, the IRRs for each of the cassava research options are much higher than the standard 10% interest rate. There is, however, considerable variation in the return on investment across research options. For the higher adoption scenario, for example, the

IRRs range from 30% for high-yielding varieties tolerant to cold weather and frost to 641% for high-quality planting material production and distribution systems. Similarly, for the lower adoption scenario, the IRRs range from 23% for high-yielding varieties tolerant to cold weather and frost to 416% for high-quality planting material production and distribution systems. The results confirm the fact that lack of an efficient planting material multiplication and distribution system is a major constraint to cassava production. As such, the research option addressing this constraint can have very high returns on investment by unlocking the huge potential for a cassava-planting material system that promotes large-scale adoption of improved varieties.

Table 8 also presents the estimated area on which the new technology will be adopted under both the lower and higher adoption scenarios. As per definition of the scenarios, the adoption ceiling reached under the lower adoption scenario is half of the area under the higher adoption scenario. The estimated adoption area is an additional indicator to be considered when making funding decisions as it translates into the likely number of beneficiaries of the new technology. Similar to the NPV results, however, the adoption ceiling information should be interpreted with caution because of the different levels of investments required for each of the research options to achieve the respective maximum adoption rates. Table 9 shows the estimated number of households and persons who will benefit from each of the research options. These figures are determined by the adoption ceilings and the total area under cassava in Africa, Asia, and LAC. The estimated number of beneficiaries of the various research options offers an alternative perspective of their respective potential impacts. The estimates show that between 1 million and 16 million households (or 6 million–73 million people) will benefit from the different research options. High-yielding varieties with drought tolerance and water-use efficiency, high-yielding varieties with high dry matter and starch, integrated pest and disease management practices, and high-yielding varieties with longer shelf life can reach the largest number of beneficiaries because of the largest area coverage in all the regions.

Table 8: Results of ex-ante assessment of cassava technologies—adoption ceilings and benefits

Technology	Adoption Ceiling		All Benefits			
			Lower adoption		Higher adoption	
	Lower adoption (million ha)	**Higher adoption** (million ha)	**NPV** (US$ million)	**IRR** (%)	**NPV** (US$ million)	**IRR** (%)
High-yielding varieties with resistance to major diseases	2.61	5.22	1,189	57	2,408	69
High-yielding varieties with high dry matter and starch	3.73	7.47	2,143	71	4,345	89
High-yielding varieties with longer shelf life	3.70	7.40	1,167	44	2,386	53
High-yielding, drought-tolerant varieties and increased water-use efficiency	3.99	7.98	3,025	61	6,127	73
Sustainable crop and soil fertility management practices	3.27	6.54	8,284	210	16,743	301
Integrated pest and disease management practices, including resistant varieties	3.82	7.64	3,732	60	7,625	71
Efficient and massive high-quality planting material production and distribution systems	3.38	6.77	7,585	416	15,299	641
Processing technologies for value addition	2.20	4.41	3,345	120	6,768	158
Strategies to prevent introduction of exotic pests and diseases	1.18	2.36	1,529	71	3,103	86
High-yielding varieties tolerant to cold weather and frost	0.32	0.63	83	23	194	30

Source: Model estimation results.

The last two columns in Table 9 show the estimated poverty reduction effects of the different research options. Although the expected impacts on poverty reduction do not account for the differing R&D and extension investments across the research options, the high and low priorities implied by the poverty reduction measure are generally consistent with those based on the economic IRR. The estimated impacts on poverty reduction range from some 100,000 people for cold weather and frost tolerance research and 220,000 people for research on prevention of introduction of exotic pests and diseases to over 4 million people for efficient planting material production and distribution system and over 5 million people for sustainable crop and soil fertility management practices. As noted earlier, sustainable crop and soil fertility management practices and efficient planting material production and distribution systems also have the highest IRR, whereas developing high-yielding varieties tolerant to cold weather and frost generates the lowest IRR of 30%. The results show that an integrated approach involving sustainable crop and soil fertility management practices and an efficient planting material production and distribution system would greatly reduce poverty among the poor cassava-growing households. The expected number of poor people lifted out of poverty depends largely on the size of the total economic benefits, national poverty rates, and region-specific elasticities of poverty reduction with respect to agricultural productivity growth.

Table 9: Results of ex-ante assessment of cassava technologies—beneficiaries and poverty reduction

Technology	Number of Beneficiaries				Poverty Reduction	
	Lower adoption		Higher adoption		Lower adoption	Higher adoption
	Households (millions)	Persons (millions)	Households (millions)	Persons (millions)	Persons (millions)	Persons (millions)
High-yielding varieties with resistance to major diseases	5	24	10	48	1.00	2.01
High-yielding varieties with high dry matter and starch	7	34	15	69	1.27	2.54
High-yielding varieties with longer shelf life	8	35	15	69	0.84	1.69
High-yielding, drought-tolerant varieties and increased water-use efficiency	8	36	16	73	2.00	4.03
Sustainable crop and soil fertility management practices	6	32	13	63	2.66	5.36
Integrated pest and disease management practices, including resistant varieties	7	35	15	70	1.18	2.38
Efficient and massive high-quality planting material production and distribution systems	7	33	13	66	2.10	4.22
Processing technologies for value addition	4	23	9	45	0.92	1.85
Strategies to prevent introduction of exotic pests and diseases	2	16	5	32	0.11	0.22
High-yielding varieties tolerant to cold weather and frost	1	3	1	6	0.00	0.01

Source: Model estimation results.

With Africa having the highest poverty rates as well as poverty elasticity, the poverty reduction measure thus favors research options generating much of the global economic benefits that accrue to Africa. This partly explains why the two options targeting Asia and LAC only (i.e., strategies to prevent introduction of exotic pests and diseases and high-yielding varieties tolerant to cold weather and frost) have the lowest expected poverty reduction effects. The relative impacts of research options on poverty reduction thus depend not only on the total economic benefits but also on the regional shares of total economic benefits. Research options generating comparable global economic benefits may actually have different poverty reduction impacts depending on Africa's share of the total benefits. High-yielding, drought-tolerant varieties and increased water-use efficiency have lower global economic benefits than does integrated pest and disease management, but the poverty reduction impacts are greater (over 4 million vs. 2.4 million people) because Africa accounts for much of the global economic benefits from drought tolerance.

Table 10: Regional breakdown of adoption of cassava technologies

Technology	Adoption Ceiling (higher adoption scenario)						
	Africa		LAC		Asia		Total
	(million ha)	Share (%)	(million ha)	Share (%)	(million ha)	Share (%)	(million ha)
High-yielding varieties with dual resistance to CMD/CBSD	5.22	100					5.22
High-yielding varieties with high dry matter and starch	5.45	73	0.37	5	1.65	22	7.47
High-yielding varieties with longer shelf life	5.22	71	0.37	5	1.81	25	7.40
High-yielding, drought-tolerant varieties and increased water-use efficiency	5.41	68	0.92	12	1.65	21	7.98
Sustainable crop and soil fertility management practices	3.97	61	1.15	18	1.42	22	6.54
Integrated pest and disease management practices, including resistant varieties (whiteflies, CBB, super elongation, and green mites)	4.94	65	1.05	14	1.65	22	7.64
Efficient and massive high-quality planting material production and distribution systems	4.54	67	0.92	14	1.30	19	6.77
Processing technologies for value addition	2.49	57	0.75	17	1.17	27	4.41
Strategies to prevent introduction of exotic pests and diseases			0.60	25	1.76	75	2.36
High-yielding varieties tolerant to cold weather and frost			0.39	62	0.24	38	0.63

Source: Model estimation results.

Table 8 presents information on the regional distribution of the adoption area for the different research options. For most research options, Africa accounts for over 50% of the cassava area that will be under improved varieties when maximum adoption is reached. More specifically, Africa's area share under improved varieties ranges from 57% for processing technologies for value addition to 73% for high-yielding varieties with high dry matter and starch and 100% for high-yielding varieties with dual resistance to the major diseases CMD and CBSD. Globally, the adoption ceilings for improved cassava technologies ranges from a little over 0.5 million ha of cassava for high-yielding varieties tolerant to cold weather and frost to nearly 8 million ha for high-yielding, drought-tolerant varieties and increased water-use efficiency.

6. Conclusions and gaps

The results of the strategic assessment of cassava research options show considerable potential for impact of investments in cassava research. There are also important differences in the potential benefits from different research options. The major conclusions and observations emerging from the ex-ante analysis of potential impacts of cassava research options are the following:

- All cassava research options generate positive economic impacts in terms of both NPVs and IRRs, indicating the social profitability of investments in cassava research to address a whole range of production and market constraints.
- The research options with the greatest potential impacts in terms of both IRR and poverty reduction are (1) efficient planting material production and distribution systems and (2) sustainable crop and soil fertility management practices. Efficient planting material production and distribution systems can go a long way in addressing the observed low adoption of improved varieties due to lack of clean planting materials. Similarly, sustainable crop and soil fertility management practices play a key role in closing the observed yield gaps, especially in Africa. Clearly, research options that lead to greater technology adoption and increased root yields should have greater economic and poverty reduction impacts.
- The relative impacts of research options on poverty reduction depend not only on the total economic benefits but also on the regional shares of total economic benefits. As both poverty rates and poverty reduction elasticities are the highest in Africa, research options generating comparable global economic benefits may actually have different poverty reduction impacts depending on Africa's share of the total benefits. For example, high-yielding, drought-tolerant varieties and increased water-use efficiency have lower global economic benefits than does integrated pest and disease management. However, the poverty reduction impacts are greater because Africa accounts for much of the global economic benefits from drought tolerance.
- The regional distribution of the adoption area for most research options shows that Africa accounts for over 50% of the cassava area that will be under improved varieties when maximum adoption is reached.
- It should be noted that the economic benefits or poverty reduction estimates for the different cassava research options cannot be aggregated. This is because the assumption underlying the strategic assessment is that the research options are mutually exclusive, with only one option pursued at a time rather than all options at the same time.

Although these are important findings providing key insights into the prospects of alternative research options, there is considerable scope for improvement of the strategic assessment. Possible areas for improvement include the following:

- Increased harmonization of expert consultation procedures across regions—Africa, Asia, and LAC—for refining the values of key technology-related parameters such as adoption ceilings, yield gains, production cost changes, and probability of success. This will require, first, sharing the preliminary results with the same experts who provided the information and then seeking further inputs and refinements based on a shared understanding and realistic assessment of the prospects for development and dissemination of the different technologies across regions and countries. For example, adoption ceiling estimates can be refined through a more formal assessment of the expected size of the technology recommendation domains as a proportion of the total cassava area based on the incidence and severity of the constraints to be addressed by each research option. The present analysis relies on the assumption that the technologies resulting from each of the research options will have wider geographical adaptation and the results may thus overestimate the actual benefits if these technologies turn out to have only local adaptation and effectiveness.

- The analysis of poverty reduction is an important contribution of this study, but it reflects only partially the dynamics of the most vulnerable populations in Asia and LAC, underestimating the social impact of the new technologies. To accrue for the real impacts of improved cassava production and processing technologies in these regions, other important factors, such as the vulnerability of low- to medium-income families to economic shocks, or the increasing concentration of poor populations in big cities, need to be considered in future studies.
- The producer prices of cassava appear to be too high for fresh roots in a number of countries, and this affects the calculations of economic impacts. Therefore, further validation against producer price information that may be available with national statistics offices or ministries of agriculture is required.
- For research options such as processing for value addition or varieties with longer shelf life that generate economic benefits mainly through demand shifts rather than supply shifts, further efforts should be made to refine the models to fully account for economic gains due to shifts in the demand function and the resulting price changes.
- For research options such as breeding for nutritional quality (e.g., pro-vitamin A, etc.) that generate nutritional and health benefits, more appropriate models such as Disability Adjusted Life Years should be developed and applied. In a similar way, cold-resistant cassava could open vast areas in developing countries to the production of cassava with consequent positive impact. Further efforts should also be made to translate the resulting nutritional and health benefits, or the new markets and opportunities from new technologies, into economic IRR measures for ease of comparison with all other research options on the same economic criteria.
- For cassava processing and other value addition technologies, the economic surplus model used in this study only captures the economic benefits associated with increased productivity and supply in response to higher derived demand—i.e. demand shift for processed cassava also leading to demand shift for fresh roots—and market opportunity for fresh cassava roots. As the model does not account for the more direct benefits associated with the demand shift and the value-added farmers earn from selling the processed product, there is need to develop and apply a unified framework involving both demand and supply shifts to measure the direct and indirect economic benefits associated with processing technologies for value addition.

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Annex 1: Results of the expert survey

Rank	Constraint	LAC	Asia	Africa	Regional	Global	Total
1	Improving shelf life of cassava roots	4.20	4.33	4.10	4.21	4.29	4.23
2	Phenotypic/molecular screening of landraces in search of high-value traits/new sources/ tolerance/resistance to stress	4.63	4.04	3.97	4.21	4.20	4.21
3	Developing cassava products for industrial applications (flour and starch)	4.39	4.10	4.05	4.18	4.13	4.17
4	High yield	4.18	4.28	4.02	4.16	4.17	4.16
5	Improving production and distribution of elite planting materials	4.17	4.00	4.16	4.11	4.20	4.13
6	Collection, characterization, evaluation, documentation (ex situ)	4.43	4.12	3.86	4.13	4.06	4.12
7	Improving technologies for farmer-based production and distribution of planting materials (informal)	4.29	4.15	3.96	4.13	4.05	4.11
8	Drought tolerance/water-use efficiency	4.14	4.28	3.98	4.13	3.97	4.09
9	Assess impact of cassava research and development	4.32	4.18	3.86	4.12	3.98	4.08
10	Developing cassava products for human consumption	4.53	4.00	3.87	4.13	3.93	4.08
11	Assessment of small farmer access to new technologies	4.25	4.07	3.93	4.08	4.04	4.07
12	Early harvest (6–8 months after planting)	4.10	4.14	4.02	4.09	4.00	4.07
13	Alternative on-farm utilization/processing for value addition	4.47	4.07	3.85	4.13	3.84	4.06
14	Assessment of cassava technology adoption	4.26	4.14	3.80	4.07	4.01	4.06
15	Improving small-scale processing of cassava for human consumption (e.g., gari, fufu, farinha, sago, kokonte, casabe, gaplek, etc.)	4.35	3.86	4.04	4.08	3.92	4.04
16	CMD (disease management)	3.84	3.89	4.34	4.02	4.08	4.04
17	Germplasm enhancement and pre-breeding	4.20	4.25	3.84	4.10	3.82	4.03
18	Improving soil fertility (micronutrients and fertilizer)	4.23	4.17	3.96	4.12	3.74	4.03
19	Development of farmer organizations and farmer clusters linked to markets	4.42	3.90	3.87	4.06	3.88	4.02
20	CMD (breeding for biotic stress resistance)	3.58	4.22	4.15	3.98	4.11	4.02
21	Improving cassava cropping systems	4.14	4.03	3.96	4.04	3.87	4.00
22	Improving policy framework for cassava planting materials (distribution, regulations, IPRs)	4.26	3.96	3.82	4.01	3.93	3.99
23	Mass propagation methods, including tissue culture and hydroponics	4.22	3.89	4.01	4.04	3.84	3.99
24	Tolerance to postharvest physiological deterioration	4.05	3.88	3.87	3.93	4.14	3.98
25	Development of competitive cassava value chains	4.37	3.81	3.82	4.00	3.89	3.97
26	High dry matter	4.05	4.07	3.89	4.00	3.81	3.95
27	Harvesting methods or machinery for planting/harvesting	4.35	4.07	3.68	4.03	3.68	3.94
28	White flies	3.71	4.07	3.95	3.91	4.03	3.94
29	CBB (*Xanthomonas* spp.)	4.35	3.96	3.54	3.95	3.82	3.92

Rank	Constraint	LAC	Asia	Africa	Regional	Global	Total
30	CBB	4.19	3.96	3.78	3.98	3.67	3.90
31	Alternatives for micro-stakes from disease free stocks	4.16	4.12	3.53	3.94	3.75	3.89
32	Weed management and control	4.20	3.93	3.83	3.99	3.59	3.89
33	Developing cassava products for animal feed	4.33	4.04	3.49	3.95	3.63	3.87
34	Others (transport, agricultural insurance, capacity building to farmers, fabrication of cassava-processing equipment, developing cassava chips for export market)	3.67	3.44	4.61	3.91	3.71	3.86
35	Processing quality	4.05	3.76	3.76	3.86	3.71	3.82
36	Weed	4.21	3.96	3.64	3.94	3.44	3.81
37	CBSD (disease management)	3.39	3.42	4.30	3.70	4.11	3.81
38	Assess health and environmental risks of herbicide and pesticide use in cassava systems	3.89	3.71	3.72	3.78	3.81	3.78
39	Whiteflies	3.53	3.84	3.82	3.73	3.92	3.78
40	Mites	3.81	3.89	3.73	3.81	3.67	3.77
41	Soil management and erosion control	3.95	4.07	3.64	3.89	3.43	3.77
42	In-situ genetic resource management	4.17	3.60	3.57	3.78	3.68	3.75
43	Nutrient-use efficiency	3.94	3.70	3.72	3.79	3.65	3.75
44	Gender-friendly labor-saving tools	4.11	3.77	3.56	3.81	3.55	3.75
45	CBSD (breeding for biotic stress resistance)	2.93	3.67	4.22	3.61	4.12	3.74
46	Water management in crop production	3.62	4.00	3.75	3.79	3.53	3.73
47	Other specific producer-preferred traits	3.79	3.71	3.68	3.72	3.72	3.72
48	Starch quality traits	3.82	3.50	3.63	3.65	3.84	3.70
49	Mechanization	4.05	3.57	3.63	3.75	3.52	3.69
50	Root rots	3.94	3.92	3.47	3.78	3.44	3.69
51	Research on more gender equitable value chains	4.17	3.38	3.61	3.72	3.60	3.69
52	Others (long underground storage, vitamin E, starch modification, early bulking, leaf quality, early bulking and maturing)	4.00	3.00	4.02	3.67	3.71	3.68
53	Pro-vitamin A (beta-carotene)	4.00	3.22	3.78	3.67	3.68	3.67
54	Research on food and agricultural policies affecting cassava	3.84	3.68	3.49	3.67	3.59	3.65
55	Assess health effects of bio-fortified cassava varieties	3.88	3.70	3.40	3.66	3.53	3.63

Annex 2: Values of technology-related parameters for individual research options

Table 1: High-yielding varieties with dual resistance to CMD/CBSD

Country	Maximum Adoption Rate	Research Lag (years)	Adoption Lag (years)	Yield Increase	Input Cost Change	Probability of Success
Angola	30%	10.00	12.00	30%	20%	50%
Benin	40%	7.00	12.00	30%	20%	50%
Burkina Faso	30%	10.00	12.00	30%	20%	50%
Burundi	30%	10.00	12.00	30%	20%	50%
Cameroon	40%	7.00	12.00	30%	20%	50%
Chad	30%	10.00	12.00	30%	20%	50%
Congo	30%	10.00	12.00	30%	20%	50%
Cote d'Ivoire	30%	10.00	12.00	30%	20%	50%
DRC	40%	7.00	12.00	30%	20%	50%
Ghana	50%	5.00	12.00	30%	20%	50%
Guinea	30%	10.00	12.00	30%	20%	50%
Kenya	40%	7.00	12.00	30%	20%	50%
Liberia	30%	10.00	12.00	30%	20%	50%
Madagascar	30%	10.00	12.00	30%	20%	50%
Malawi	40%	7.00	12.00	30%	20%	50%
Mozambique	40%	7.00	12.00	30%	20%	50%
Nigeria	50%	5.00	12.00	30%	20%	50%
Rwanda	30%	10.00	12.00	30%	20%	50%
Senegal	30%	10.00	12.00	30%	20%	50%
Sierra Leone	30%	10.00	12.00	30%	20%	50%
Togo	40%	7.00	12.00	30%	20%	50%
Uganda	50%	5.00	12.00	30%	20%	50%
Tanzania	40%	7.00	12.00	30%	20%	50%
Zambia	40%	7.00	12.00	30%	20%	50%

Source: Expert consultations with IITA and NARS scientists in Africa.

Table 2: High-yielding varieties with high dry matter and starch

Country	Maximum Adoption Rate	Research Lag (years)	Adoption Lag (years)	Yield Increase	Input Cost Change	Probability of Success
Angola	30%	8.00	12.00	30%	20%	50%
Benin	40%	5.00	12.00	30%	20%	50%
Burkina Faso	30%	8.00	12.00	30%	20%	50%
Burundi	30%	8.00	12.00	30%	20%	50%
Cameroon	40%	5.00	12.00	30%	20%	50%
Chad	30%	8.00	12.00	30%	20%	50%
Congo	30%	8.00	12.00	30%	20%	50%
Cote d'Ivoire	40%	5.00	12.00	30%	20%	50%
DRC	50%	3.00	12.00	30%	20%	50%
Ghana	50%	3.00	12.00	30%	20%	50%
Guinea	30%	8.00	12.00	30%	20%	50%
Kenya	40%	5.00	12.00	30%	20%	50%
Liberia	30%	8.00	12.00	30%	20%	50%
Madagascar	30%	8.00	12.00	30%	20%	50%
Malawi	40%	5.00	12.00	30%	20%	50%
Mozambique	40%	5.00	12.00	30%	20%	50%
Nigeria	50%	3.00	12.00	30%	20%	50%
Rwanda	30%	8.00	12.00	30%	20%	50%
Senegal	30%	8.00	12.00	30%	20%	50%
Sierra Leone	30%	8.00	12.00	30%	20%	50%
Togo	40%	5.00	12.00	30%	20%	50%
Uganda	50%	3.00	12.00	30%	20%	50%
Tanzania	40%	5.00	12.00	30%	20%	50%
Zambia	40%	5.00	12.00	30%	20%	50%
Argentina	28%	4.00	10.00	22%	15%	70%
Bolivia	19%	4.00	10.00	22%	15%	70%
Brazil	10%	4.00	10.00	22%	15%	70%
Cambodia	68%	4.00	10.00	22%	15%	70%
China	8%	4.00	10.00	22%	15%	70%
Colombia	30%	4.00	10.00	22%	15%	70%
Costa Rica	20%	4.00	10.00	22%	15%	70%
Cuba	19%	4.00	10.00	22%	15%	70%
Ecuador	23%	4.00	10.00	22%	15%	70%
Haiti	15%	4.00	10.00	22%	15%	70%
India	33%	4.00	10.00	22%	15%	70%
Indonesia	8%	4.00	10.00	22%	15%	70%
Jamaica	17%	4.00	10.00	22%	15%	70%
Laos	80%	4.00	10.00	22%	15%	70%
Malaysia	26%	4.00	10.00	22%	15%	70%
Paraguay	21%	4.00	10.00	22%	15%	70%
Peru	26%	4.00	10.00	22%	15%	70%
Philippines	10%	4.00	10.00	22%	15%	70%
Thailand	90%	4.00	10.00	22%	15%	70%
Venezuela	26%	4.00	10.00	22%	15%	70%

Country	Maximum Adoption Rate	Research Lag (years)	Adoption Lag (years)	Yield Increase	Input Cost Change	Probability of Success
Vietnam	38%	4.00	10.00	22%	15%	70%

Source: Expert consultations with IITA, CIAT, and NARS scientists in Africa, LAC, and Asia.

Table 3: High-yielding varieties with longer shelf life

Country	Maximum Adoption Rate	Research Lag (years)	Adoption Lag (years)	Yield Increase	Input Cost Change	Probability of Success
Angola	30%	8.00	12.00	32%	20%	50%
Benin	40%	7.00	12.00	28%	20%	50%
Burkina Faso	30%	8.00	12.00	32%	20%	50%
Burundi	30%	8.00	12.00	32%	20%	50%
Cameroon	40%	7.00	12.00	28%	20%	50%
Chad	30%	8.00	12.00	32%	20%	50%
Congo	30%	8.00	12.00	32%	20%	50%
Cote d’Ivoire	30%	8.00	12.00	32%	20%	50%
DRC	40%	7.00	12.00	28%	20%	50%
Ghana	50%	5.00	12.00	24%	20%	50%
Guinea	30%	8.00	12.00	32%	20%	50%
Kenya	40%	7.00	12.00	28%	20%	50%
Liberia	30%	8.00	12.00	32%	20%	50%
Madagascar	30%	8.00	12.00	32%	20%	50%
Malawi	40%	7.00	12.00	28%	20%	50%
Mozambique	40%	7.00	12.00	28%	20%	50%
Nigeria	50%	5.00	12.00	24%	20%	50%
Rwanda	30%	8.00	12.00	32%	20%	50%
Senegal	30%	8.00	12.00	32%	20%	50%
Sierra Leone	30%	8.00	12.00	32%	20%	50%
Togo	40%	7.00	12.00	28%	20%	50%
Uganda	50%	5.00	12.00	24%	20%	50%
Tanzania	40%	7.00	12.00	28%	20%	50%
Zambia	40%	7.00	12.00	28%	20%	50%
Argentina	28%	8.00	14.00	22%	5%	80%
Bolivia	19%	8.00	14.00	30%	5%	80%
Brazil	10%	8.00	14.00	31%	5%	80%
Cambodia	68%	8.00	10.00	8%	5%	80%
China	70%	8.00	10.00	6%	5%	80%
Colombia	30%	8.00	14.00	12%	5%	80%
Costa Rica	20%	8.00	14.00	16%	5%	80%
Cuba	19%	8.00	14.00	23%	5%	80%
Ecuador	23%	8.00	14.00	18%	5%	80%
Haiti	15%	8.00	14.00	65%	5%	80%
India	33%	8.00	10.00	11%	5%	80%
Indonesia	8%	8.00	10.00	41%	5%	80%
Jamaica	17%	8.00	14.00	31%	5%	80%

Country	Maximum Adoption Rate	Research Lag (years)	Adoption Lag (years)	Yield Increase	Input Cost Change	Probability of Success
Laos	30%	8.00	10.00	16%	5%	80%
Malaysia	26%	8.00	10.00	13%	5%	80%
Paraguay	21%	8.00	14.00	34%	5%	80%
Peru	26%	8.00	14.00	19%	5%	80%
Philippines	10%	8.00	10.00	49%	5%	80%
Thailand	90%	8.00	10.00	6%	5%	80%
Venezuela	26%	8.00	14.00	31%	5%	80%
Vietnam	38%	8.00	10.00	16%	5%	80%

Source: Expert consultations with IITA, CIAT, and NARS scientists in Africa, LAC, and Asia.

Table 4: High-yielding, drought-tolerant varieties and increased water-use efficiency

Country	Maximum Adoption Rate	Research Lag (years)	Adoption Lag (years)	Yield Increase	Input Cost Change	Probability of Success
Angola	30%	8.00	12.00	35%	20%	65%
Benin	40%	7.00	12.00	35%	20%	65%
Burkina Faso	30%	8.00	12.00	35%	20%	65%
Burundi	30%	8.00	12.00	35%	20%	65%
Cameroon	40%	7.00	12.00	35%	20%	65%
Chad	30%	8.00	12.00	35%	20%	65%
Congo	30%	8.00	12.00	35%	20%	65%
Cote d'Ivoire	30%	8.00	12.00	35%	20%	65%
DRC	50%	5.00	12.00	35%	20%	65%
Ghana	50%	5.00	12.00	35%	20%	65%
Guinea	30%	8.00	12.00	35%	20%	65%
Kenya	40%	7.00	12.00	35%	20%	65%
Liberia	30%	8.00	12.00	35%	20%	65%
Madagascar	30%	8.00	12.00	35%	20%	65%
Malawi	40%	7.00	12.00	35%	20%	65%
Mozambique	40%	7.00	12.00	35%	20%	65%
Nigeria	50%	5.00	12.00	35%	20%	65%
Rwanda	30%	8.00	12.00	35%	20%	65%
Senegal	30%	8.00	12.00	35%	20%	65%
Sierra Leone	30%	8.00	12.00	35%	20%	65%
Togo	40%	7.00	12.00	35%	20%	65%
Uganda	50%	5.00	12.00	35%	20%	65%
Tanzania	40%	7.00	12.00	35%	20%	65%
Zambia	40%	7.00	12.00	35%	20%	65%
Argentina	30%	8.00	12.00	25%	10%	80%
Bolivia	30%	8.00	12.00	25%	10%	80%
Brazil	35%	8.00	12.00	25%	10%	80%
Cambodia	68%	8.00	12.00	25%	10%	80%
China	8%	8.00	12.00	25%	10%	80%
Colombia	40%	8.00	12.00	25%	10%	80%
Costa Rica	30%	8.00	12.00	25%	10%	80%
Cuba	40%	8.00	12.00	25%	10%	80%
Ecuador	40%	8.00	12.00	30%	10%	80%

Country	Maximum Adoption Rate	Research Lag (years)	Adoption Lag (years)	Yield Increase	Input Cost Change	Probability of Success
Haiti	40%	8.00	12.00	25%	10%	80%
India	33%	8.00	12.00	15%	10%	80%
Indonesia	8%	8.00	12.00	25%	10%	80%
Jamaica	30%	8.00	12.00	25%	10%	80%
Laos	80%	8.00	12.00	25%	10%	80%
Malaysia	30%	8.00	12.00	25%	10%	80%
Paraguay	30%	8.00	12.00	25%	10%	80%
Peru	40%	8.00	12.00	25%	10%	80%
Philippines	10%	8.00	12.00	25%	10%	80%
Thailand	90%	8.00	12.00	25%	10%	80%
Venezuela	30%	8.00	12.00	25%	10%	80%
Vietnam	38%	8.00	12.00	25%	10%	80%

Source: Expert consultations with IITA, CIAT, and NARS scientists in Africa, LAC, and Asia.

Table 5: Sustainable crop and soil fertility management practices

Country	Maximum Adoption Rate	Research Lag (years)	Adoption Lag (years)	Yield Increase	Input Cost Change	Probability of Success
Angola	20%	5.00	12.00	50%	25%	75%
Benin	30%	4.00	12.00	50%	25%	75%
Burkina Faso	20%	5.00	12.00	50%	25%	75%
Burundi	20%	5.00	12.00	50%	25%	75%
Cameroon	30%	4.00	12.00	50%	25%	75%
Chad	20%	5.00	12.00	50%	25%	75%
Congo	20%	5.00	12.00	50%	25%	75%
Cote d'Ivoire	20%	5.00	12.00	50%	25%	75%
DRC	30%	4.00	12.00	50%	25%	75%
Ghana	40%	3.00	12.00	50%	25%	75%
Guinea	20%	5.00	12.00	50%	25%	75%
Kenya	30%	4.00	12.00	50%	25%	75%
Liberia	20%	5.00	12.00	50%	25%	75%
Madagascar	20%	5.00	12.00	50%	25%	75%
Malawi	30%	4.00	12.00	50%	25%	75%
Mozambique	30%	4.00	12.00	50%	25%	75%
Nigeria	40%	3.00	12.00	50%	25%	75%
Rwanda	20%	5.00	12.00	50%	25%	75%
Senegal	20%	5.00	12.00	50%	25%	75%
Sierra Leone	20%	5.00	12.00	50%	25%	75%
Togo	30%	4.00	12.00	50%	25%	75%
Uganda	40%	3.00	12.00	50%	25%	75%
Tanzania	30%	4.00	12.00	50%	25%	75%
Zambia	30%	4.00	12.00	50%	25%	75%
Argentina	30%	1.00	8.00	55%	20%	80%
Bolivia	30%	1.00	8.00	55%	20%	80%
Brazil	50%	2.00	8.00	56%	20%	80%
Cambodia	30%	1.00	8.00	50%	20%	80%

Country	Maximum Adoption Rate	Research Lag (years)	Adoption Lag (years)	Yield Increase	Input Cost Change	Probability of Success
China	50%	1.00	8.00	40%	20%	80%
Colombia	45%	4.00	9.00	20%	15%	80%
Costa Rica	40%	1.00	8.00	50%	20%	80%
Cuba	30%	1.00	8.00	33%	20%	80%
Ecuador	30%	1.00	8.00	49%	20%	80%
Haiti	20%	3.00	6.00	30%	30%	80%
India	30%	1.00	8.00	17%	5%	80%
Indonesia	30%	1.00	8.00	50%	20%	80%
Jamaica	30%	1.00	10.00	43%	20%	80%
Laos	30%	1.00	10.00	50%	20%	80%
Malaysia	30%	1.00	8.00	50%	20%	80%
Paraguay	30%	1.00	8.00	55%	20%	80%
Peru	30%	1.00	8.00	49%	20%	80%
Philippines	30%	1.00	8.00	30%	20%	80%
Thailand	43%	1.00	8.00	15%	10%	80%
Venezuela	30%	1.00	8.00	20%	5%	80%
Vietnam	40%	1.00	8.00	50%	20%	80%

Source: Expert consultations with IITA, CIAT, and NARS scientists in Africa, LAC, and Asia.

Table 6: Integrated pest and disease management practices, including resistant varieties

Country	Maximum Adoption Rate	Research Lag (years)	Adoption Lag (years)	Yield Increase	Input Cost Change	Probability of Success
Angola	40%	5.00	12.00	25%	20%	80%
Benin	40%	5.00	12.00	25%	20%	80%
Burkina Faso	40%	5.00	12.00	25%	20%	80%
Burundi	40%	5.00	12.00	25%	20%	80%
Cameroon	40%	5.00	12.00	25%	20%	80%
Chad	40%	5.00	12.00	25%	20%	80%
Congo	40%	5.00	12.00	25%	20%	80%
Cote d'Ivoire	40%	5.00	12.00	25%	20%	80%
DRC	40%	5.00	12.00	25%	20%	80%
Ghana	40%	5.00	12.00	25%	20%	80%
Guinea	40%	5.00	12.00	25%	20%	80%
Kenya	40%	5.00	12.00	25%	20%	80%
Liberia	40%	5.00	12.00	25%	20%	80%
Madagascar	40%	5.00	12.00	25%	20%	80%
Malawi	40%	5.00	12.00	25%	20%	80%
Mozambique	40%	5.00	12.00	25%	20%	80%
Nigeria	40%	5.00	12.00	25%	20%	80%
Rwanda	40%	5.00	12.00	25%	20%	80%
Senegal	40%	5.00	12.00	25%	20%	80%
Sierra Leone	40%	5.00	12.00	25%	20%	80%

Country	Maximum Adoption Rate	Research Lag (years)	Adoption Lag (years)	Yield Increase	Input Cost Change	Probability of Success
Togo	40%	5.00	12.00	25%	20%	80%
Uganda	40%	5.00	12.00	25%	20%	80%
Tanzania	40%	5.00	12.00	25%	20%	80%
Zambia	40%	5.00	12.00	25%	20%	80%
Argentina	20%	8.00	12.00	37%	-15%	70%
Bolivia	30%	8.00	12.00	37%	-30%	70%
Brazil	40%	8.00	12.00	37%	-23%	50%
Cambodia	68%	8.00	12.00	70%	-15%	70%
China	8%	8.00	12.00	70%	-15%	70%
Colombia	40%	8.00	12.00	37%	-30%	50%
Costa Rica	30%	8.00	12.00	37%	-30%	70%
Cuba	30%	8.00	12.00	37%	-30%	70%
Ecuador	30%	8.00	12.00	37%	-30%	70%
Haiti	30%	8.00	12.00	37%	-30%	70%
India	33%	8.00	12.00	70%	-30%	70%
Indonesia	8%	8.00	12.00	70%	-30%	70%
Jamaica	10%	8.00	12.00	37%	-15%	70%
Laos	80%	8.00	12.00	70%	-15%	70%
Malaysia	10%	8.00	12.00	70%	-15%	70%
Paraguay	40%	8.00	12.00	37%	-30%	50%
Peru	40%	8.00	12.00	37%	-30%	50%
Philippines	10%	8.00	12.00	70%	-15%	70%
Thailand	90%	8.00	12.00	70%	-30%	70%
Venezuela	30%	8.00	12.00	37%	-30%	70%
Vietnam	38%	8.00	12.00	70%	-15%	70%

Source: Expert consultations with IITA, CIAT, and NARS scientists in Africa, LAC, and Asia.

Table 7: Efficient and massive high-quality planting material production and distribution systems

Country	Maximum Adoption Rate	Research Lag (years)	Adoption Lag (years)	Yield Increase	Input Cost Change	Probability of Success
Angola	20%	4.00	12.00	50%	25%	50%
Benin	30%	3.00	12.00	50%	25%	50%
Burkina Faso	20%	4.00	12.00	50%	25%	50%
Burundi	20%	4.00	12.00	50%	25%	50%
Cameroon	30%	3.00	12.00	50%	25%	50%
Chad	20%	4.00	12.00	50%	25%	50%
Congo	20%	4.00	12.00	50%	25%	50%
Cote d’Ivoire	30%	3.00	12.00	50%	25%	50%
DRC	40%	2.00	12.00	50%	25%	50%
Ghana	40%	2.00	12.00	50%	25%	50%
Guinea	20%	4.00	12.00	50%	25%	50%
Kenya	30%	3.00	12.00	50%	25%	50%
Liberia	20%	4.00	12.00	50%	25%	50%
Madagascar	20%	4.00	12.00	50%	25%	50%
Malawi	30%	3.00	12.00	50%	25%	50%

Country	Maximum Adoption Rate	Research Lag (years)	Adoption Lag (years)	Yield Increase	Input Cost Change	Probability of Success
Mozambique	30%	3.00	12.00	50%	25%	50%
Nigeria	50%	2.00	12.00	50%	25%	50%
Rwanda	20%	4.00	12.00	50%	25%	50%
Senegal	20%	4.00	12.00	50%	25%	50%
Sierra Leone	20%	4.00	12.00	50%	25%	50%
Togo	30%	3.00	12.00	50%	25%	50%
Uganda	40%	2.00	12.00	50%	25%	50%
Tanzania	30%	3.00	12.00	50%	25%	50%
Zambia	30%	3.00	12.00	50%	25%	50%
Argentina	30%	1.00	5.00	30%	5%	80%
Bolivia	30%	1.00	5.00	30%	5%	80%
Brazil	35%	1.00	5.00	30%	5%	80%
Cambodia	30%	1.00	5.00	30%	5%	80%
China	30%	1.00	5.00	30%	5%	80%
Colombia	40%	1.00	5.00	30%	5%	80%
Costa Rica	30%	1.00	5.00	30%	5%	80%
Cuba	40%	1.00	5.00	30%	5%	80%
Ecuador	40%	1.00	5.00	30%	5%	80%
Haiti	40%	1.00	5.00	30%	5%	80%
India	40%	1.00	5.00	30%	5%	80%
Indonesia	30%	1.00	5.00	30%	5%	80%
Jamaica	30%	1.00	5.00	30%	5%	80%
Laos	30%	1.00	5.00	30%	5%	80%
Malaysia	30%	1.00	5.00	30%	5%	80%
Paraguay	30%	1.00	5.00	30%	5%	80%
Peru	40%	1.00	5.00	30%	5%	80%
Philippines	30%	1.00	5.00	30%	5%	80%
Thailand	40%	1.00	5.00	30%	5%	80%
Venezuela	30%	1.00	5.00	30%	5%	80%
Vietnam	30%	1.00	5.00	30%	5%	80%

Source: Expert consultations with IITA, CIAT, and NARS scientists in Africa, LAC, and Asia.

Table 8: Processing technologies for value addition

Country	Maximum Adoption Rate	Research Lag (years)	Adoption Lag (years)	Yield Increase	Input Cost Change	Probability of Success
Angola	20%	8.00	12.00	25%	0%	50%
Benin	20%	5.00	12.00	25%	0%	50%
Burkina Faso	20%	8.00	12.00	25%	0%	50%
Burundi	20%	8.00	12.00	25%	0%	50%
Cameroon	20%	5.00	12.00	25%	0%	50%
Chad	20%	8.00	12.00	25%	0%	50%
Congo	20%	8.00	12.00	25%	0%	50%
Cote d'Ivoire	20%	8.00	12.00	25%	0%	50%
DRC	20%	5.00	12.00	25%	0%	50%
Ghana	20%	3.00	12.00	25%	0%	50%
Guinea	20%	8.00	12.00	25%	0%	50%
Kenya	20%	5.00	12.00	25%	0%	50%
Liberia	20%	8.00	12.00	25%	0%	50%
Madagascar	20%	8.00	12.00	25%	0%	50%
Malawi	20%	5.00	12.00	25%	0%	50%
Mozambique	20%	5.00	12.00	25%	0%	50%
Nigeria	20%	3.00	12.00	25%	0%	50%
Rwanda	20%	8.00	12.00	25%	0%	50%
Senegal	20%	8.00	12.00	25%	0%	50%
Sierra Leone	20%	8.00	12.00	25%	0%	50%
Togo	20%	5.00	12.00	25%	0%	50%
Uganda	20%	3.00	12.00	25%	0%	50%
Tanzania	20%	5.00	12.00	25%	0%	50%
Zambia	20%	5.00	12.00	25%	0%	50%
Argentina	16%	2.00	8.00	19%	0%	80%
Bolivia	18%	2.00	8.00	19%	0%	80%
Brazil	33%	2.00	8.00	22%	0%	80%
Cambodia	12%	2.00	8.00	20%	0%	80%
China	34%	2.00	8.00	23%	0%	80%
Colombia	30%	4.00	8.00	20%	0%	80%
Costa Rica	32%	2.00	8.00	22%	0%	80%
Cuba	23%	2.00	8.00	16%	0%	80%
Ecuador	25%	2.00	8.00	15%	0%	80%
Haiti	10%	2.00	8.00	16%	0%	80%
India	27%	2.00	8.00	35%	0%	80%
Indonesia	31%	2.00	8.00	25%	0%	80%
Jamaica	19%	2.00	8.00	25%	0%	80%
Laos	20%	2.00	8.00	25%	0%	80%
Malaysia	30%	2.00	8.00	24%	0%	80%
Paraguay	14%	2.00	8.00	22%	0%	80%
Peru	20%	2.00	8.00	20%	0%	80%
Philippines	20%	2.00	8.00	19%	0%	80%
Thailand	30%	2.00	8.00	27%	0%	80%

Country	Maximum Adoption Rate	Research Lag (years)	Adoption Lag (years)	Yield Increase	Input Cost Change	Probability of Success
Venezuela	12%	2.00	8.00	21%	0%	80%
Vietnam	40%	2.00	8.00	24%	0%	80%

Source: Expert consultations with IITA, CIAT, and NARS scientists in Africa, LAC, and Asia.

Table 9: Strategies to prevent introduction of exotic pests and diseases

Country	Maximum Adoption Rate	Research Lag (years)	Adoption Lag (years)	Yield Increase	Input Cost Change	Probability of Success
Argentina	10%	5.00	10.00	0%	-10%	50%
Bolivia	10%	5.00	10.00	0%	-10%	50%
Brazil	25%	5.00	10.00	0%	-18%	50%
Cambodia	50%	5.00	10.00	0%	-30%	50%
China	50%	5.00	10.00	0%	-30%	50%
Colombia	10%	5.00	10.00	0%	-10%	50%
Costa Rica	40%	5.00	10.00	0%	-25%	50%
Cuba	40%	5.00	10.00	0%	-25%	50%
Ecuador	10%	5.00	10.00	0%	-10%	50%
Haiti	40%	5.00	10.00	0%	-25%	50%
India	60%	5.00	10.00	0%	-35%	50%
Indonesia	60%	5.00	10.00	0%	-35%	50%
Jamaica	40%	5.00	10.00	0%	-25%	50%
Laos	50%	5.00	10.00	0%	-30%	50%
Malaysia	50%	5.00	10.00	0%	-30%	50%
Paraguay	10%	5.00	10.00	0%	-10%	50%
Peru	10%	5.00	10.00	0%	-10%	50%
Philippines	50%	5.00	10.00	0%	-30%	50%
Thailand	20%	5.00	10.00	0%	-15%	50%
Venezuela	10%	5.00	10.00	0%	-10%	50%
Vietnam	60%	5.00	10.00	0%	-35%	50%

Source: Expert consultations with CIAT and NARS scientists in LAC and Asia.

Table 10: High-yielding varieties tolerant to cold weather and frost

Country	Maximum Adoption Rate	Research Lag (years)	Adoption Lag (years)	Yield Increase	Input Cost Change	Probability of Success
Argentina	100%	8.00	12.00	20%	0%	50%
Brazil	20%	8.00	12.00	20%	0%	50%
China	50%	8.00	12.00	20%	0%	50%
Colombia	10%	8.00	12.00	20%	0%	50%
Vietnam	20%	8.00	12.00	20%	0%	50%

Source: Expert consultations with CIAT and NARS scientists in LAC and Asia.

Annex 3: Estimation of economic surplus, net present value, and internal rate of return

In a closed economy, economic surplus measures can be derived using the following formulas (Alston et al. 1995):

(1) change in economic surplus (ΔES) = $P_0Q_0K_t(1+0.5Z_t\eta)$;

(2) consumer surplus (ΔCS) = $P_0Q_0Z_t(1+0.5Z_t\eta)$; and

(3) producer surplus (ΔPS) = $(K_t–Z_t)P_0Q_0(1+0.5Z\eta)$,

where K_t is the supply shift representing the product of cost reduction per ton of output as a proportion of product price (K) and technology adoption at time t (A_t); P_0 represents pre-adoption price; Q_0 is pre-adoption level of production; η is the price elasticity of demand; and Z_t is the relative reduction in price at time t, which is calculated as $Z_t = K_t\varepsilon/(\varepsilon+\eta)$, where ε is the price elasticity of supply.

The research-induced supply shift parameter, K, is the single most important parameter influencing total economic surplus results from unit-cost reductions and is derived as

$K_t=[((\Delta Y/Y)/\varepsilon–(\Delta C/C))/(1+(\Delta Y/Y))]\times A_t$,

where ΔY/Y is the average proportional yield increase per hectare; ε is the elasticity of supply that is used to convert the gross production effect of research-induced yield changes to a gross unit production cost effect; ΔC/C is the average proportional change in the variable costs per hectare required to achieve the yield increase; and A_t is the rate of adoption of the improved technology at time t—the proportion of total cropped area under the improved varieties and practices. In the RTB priority assessment, annual supply shifts were then projected based on projected adoption profile for improved technologies (A_t) for the period 2014–2039 (25 years). Adoption (At) is assumed to follow a logistic diffusion curve.

For each country i (i=1, …, N), the changes in economic surplus (ΔES) and the research and extension costs (C_t) are discounted at a real discount rate, *r*, of 10% per annum to derive the net present values (NPV) as follows:

$$\text{NPV} = \sum_{t=1}^{25}\sum_{i=1}^{N}\left(\frac{\Delta \text{ES}_{i,t}}{(1+r)^t}\right) - \sum_{t=1}^{25}\left(\frac{\text{C}_t}{(1+r)^t}\right)$$

The aggregate internal rate of return (IRR) was also calculated as the discount rate that equates the aggregate NPV to zero as follows:

$$\sum_{t=1}^{25}\sum_{i=1}^{N}\left(\frac{\Delta \text{ES}_{i,t}}{(1+\text{IRR})^t}\right) - \sum_{t=1}^{25}\left(\frac{\text{C}_t}{(1+\text{IRR})^t}\right) = 0$$

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