Economic impact analysis of marker-assisted breeding for resistance to pests and post-harvest deterioration in cassava

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Abstract

Marker-assisted breeding could have a major impact in relieving productivity constraints that cannot as easily or rapidly be relieved by conventional breeding alone. This paper estimates the benefits of using marker-assisted breeding, as compared to conventional breeding alone, in developing cassava varieties resistant to cassava mosaic disease, green mite, whitefly and post-harvest physiological deterioration in Nigeria, Ghana and Uganda. Marker-assisted breeding is estimated to save at least four years in the breeding cycle for varieties resistant to the pests and to result in incremental net benefits over 25 years in the range of $34 to $800 million depending on the country, the particular constraint and various assumptions. Benefits may reach as high as $3 billion for resistance to post-harvest physiological deterioration, as conventional breeding is not projected to solve the problem within a reasonable time frame.

Keywords: marker-assisted breeding; impact assessment; cassava; green mite, whitefly, cassava mosaic disease, post-harvest physiological deterioration

La sélection assistée par marqueur pourrait plus facilement ou rapidement réduire les contraintes de la productivité qu'en utilisant uniquement la sélection traditionnelle. Au niveau économique, cela pourrait avoir un impact majeur. Cet article évalue les bénéfices de l'utilisation de la sélection assistée par marqueur, opposée à la simple utilisation de la sélection traditionnelle, grâce au développement de variétés de manioc résistantes à la maladie de la mosaïque du manioc, à l'acarien vert, à la mouche blanche et à la détérioration physiologique post récolte au Nigeria, au Ghana et en Ouganda. On estime que la sélection assistée par marqueur fait gagner au moins quatre années au cycle de reproduction des

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variétés résistantes à la maladie, aux insectes et à la détérioration avec, comme résultat, des bénéfices additionnels nets sur une période de 25 ans, allant de 34 à 800 millions US$ selon le pays, les contraintes particulières et les diverses suppositions. Les bénéfices peuvent atteindre les 3 milliards US$ dans les cas de résistance à la détérioration physiologique post récolte, alors que la sélection traditionnelle ne prévoit pas de résoudre le problème dans un délai raisonnable.

Mots-clés : *sélection assistée par marqueur ; évaluation de l'impact ; manioc ; acarien vert ; mouche blanche ; maladie de la mosaïque du manioc ; détérioration physiologique post récolte*

1. Introduction

Cassava (*Manihot esculenta* Crantz) is an important root crop, especially in sub-Saharan Africa, where it is estimated that 250 million people use it to obtain half their daily calories (FAO, 2008). Despite being adapted to a wide range of agro-ecological conditions, including poor soil fertility and erratic rainfall, cassava is susceptible to a number of diseases such as cassava mosaic disease (CMD) and insect pests such as green mite and whitefly, and in its raw form deteriorates rapidly after harvest (Reilly et al., 2007). Conventional breeding (CB) can be used to deal with these constraints, but with cassava it is a long process and difficult to use when the goal is simultaneously incorporating multiple traits. Consequently, alternative approaches such as marker-assisted breeding (MAB) are currently being explored. While MAB is more expensive than CB alone, it is potentially more cost effective if it speeds up the breeding process and has a higher probability of success.

Scientists at the International Center for Tropical Agriculture (CIAT) in Colombia, in collaboration with others from national agricultural research institutions in Brazil, Nigeria, Ghana and Uganda, have evaluated wild cassava (*Manihot*) germplasm in Brazil (the center of origin for cassava) and have isolated germplasm with resistance to green mite, whitefly, CMD and post-harvest physiological deterioration (PPD). They are using this germplasm and MAB to more rapidly build resistance to CMD, green mite and PPD into popular cassava lines from Nigeria and Ghana, and resistance to CMD, green mite, whitefly and PPD into lines from Uganda.

This paper presents the results of an ex ante economic assessment of using MAB as compared to CB alone to develop cassava varieties with resistance to the problems of pests and PPD in the target countries. It first describes the potential benefits of MAB, the research being undertaken in the MAB cassava program, and the pathway through which technologies are developed and eventually reach producers. Describing this pathway helps to identify the relationship between MAB cassava research and other research, the likely outputs from the MAB cassava program, and the timing of the outputs in different geographic areas. The paper then discusses data on cassava production, prices and trade in Nigeria, Ghana and Uganda, after which it describes the economic surplus and benefit cost methods used for the impact assessment and the means for obtaining information on assumptions about yield and cost changes, probability of research success, research adoption lags, rates of adoption, elasticities, research costs and discount rate. It concludes by presenting the results of the economic surplus and benefit cost analyses and discussing the implications for cassava breeding programs in Africa.

2. What is MAB and what are its potential advantages?

With MAB, marker genes are found on a chromosome in close proximity to the gene of a desired trait. The marker gene is placed on a genetic map which indicates its recombination frequency relative to other genes (Okogbenin et al., 2006). Genes that are close in a genetic map are usually carried over in breeding crosses. Marker genes are used to determine whether a breeding cross has transferred the desired trait. If the marker gene is present, it is highly probable that the desired trait will be present in the progeny (Ribaut & Hoisington, 1998). Disease resistance in plants is often controlled by relatively few genes (Young, 1999), but some traits are genetically complex, involving many genes, or quantitative trait loci.[1]

MAB has several potential advantages over CB. Molecular markers can reduce the number of generations required for backcrossing, saving time in the breeding process. CB requires 12 to 16 years to develop a new cassava variety with the desired traits. One reason it takes so long is that backcrosses are needed to eliminate unwanted traits (linkage drag) that come along with the desired traits during the breeding process. With the use of genetic markers, breeding is more precise, thereby eliminating several backcrosses and time consuming phenotypic (visual) evaluations. Undesirable traits are often difficult to eliminate using CB alone (Collard & Mackill, 2008). With minimal linkage drag, MAB facilitates stacking of genes or combining (introgressing) genes for multiple desirable traits without introducing undesirable ones. An additional benefit of MAB is that it does not experience the regulatory hurdles and delays associated with genetically modified organisms because in most cases genes are not transferred from one species to another.

The success of MAB depends on several factors, such as the number of target genes to be transferred, the number of genotypes selected in each breeding generation, and the biology of the plant. Among the situations in which scientists prefer to use marker assistance to identify traits are those where (1) the desired trait is expressed late in plant development, (2) the target gene is recessive, (3) special conditions must be present for expression of the target gene, (4) the genes are unstable in different environments, (5) there are multiple unrelated genes affecting the targeted trait and (6) multiple traits are targeted at the same time (Servin et al., 2004). Each of these situations is problematic for CB alone. A key aspect of using MAB is that traits can be identified, isolated and transferred without being in a specific agro-ecology. The high level of uncertainty related to CB is that even if one believes a trait is present, confidence is only established after many field trials. Markers reduce the amount of germplasm a breeder needs to carry at every stage of breeding and evaluation.

While MAB has many potential benefits, it is a more expensive process than CB because of the equipment and consumables for the lab and the initial cost of developing the markers (Dreher et al., 2003; Morris et al., 2003). Although there have been widespread economic assessments of the benefits and costs of conventional and transgenic breeding programs, relatively few have been done of MAB programs, ex post or ex ante. Those that have been done (Moreau et al., 2000; Dreher et al., 2003; Morris et al., 2003; Brennan & Martin, 2007) have focused primarily on the cost side of breeding, with less emphasis on quantifying benefits. Kaye-Blake et al. (2007) compared the economics of four biotechnologies in New Zealand, but with limited detail. Brennan and Martin made careful estimates of the costs of MAB as compared to CB for a wheat breeding program at CIMMYT (the International Maize

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[1] Quantitative trait loci (QTL) are stretches of DNA within plant genomes that are closely linked to the genes of interest (Collard et al., 2005).

and Wheat Improvement Center) in Mexico. They also estimated that an MAB technology that reduced the breeding time from nine to seven years in a wheat breeding program in Mexico could increase benefits by 12%, obtaining a relatively rough estimate of the benefits. For a crop such as cassava, for which CB is more difficult, the savings in breeding time and benefits may be significantly larger.

3. Technology impact pathway

The breeding stages for resistance to CMD, green mite, whitefly and PPD using MAB as compared to CB are presented in Table 1. By using MAB, a breeding program can achieve results at least four years earlier than with conventional methods. Preliminary and advanced yield trials are skipped as these are unnecessary once the genes of interest have been identified. The uniform or regional trial periods are reduced from two to four years, because in these stages with MAB only the presence of the genes of interest and its performance are tested. Some of the other breeding stages can be shortened, such as clonal evaluation, which could potentially be completed in 12 to 16 months.

Table 1: Cassava breeding stages with conventional and MAB technologies

Activity	Conventional breeding	Marker-assisted breeding
Female x male	Year 0	Year 0
F1 and clone evaluation	Year 1–2	Year 1–2
Preliminary yield trials	Year 3	Skipped
Advanced yield trials	Year 4	Skipped
Uniform/Regional trials	Years 5–8	Years 3–4
On farm trials	Year 9	Year 5
Variety release	Year 10	Year 6
Multiplication[a]	Years 11–15	Years 7–11
Total number of years	15	11

Source: Rudi, 2008.

a. At present multiplication takes five years on average, but this could be cut to two years if managed by breeders with additional resources.

The cassava molecular breeding program at CIAT has generated 60 new lines with resistance, 11 of which are ready for uniform trials. In Nigeria and Ghana, several regional and on-farm trials have been completed for CMD and green mite resistance. The first varietal release is expected soon. In Uganda, regional trials have not yet been completed, but should be within two years for CMD, green mite and whitefly resistance.

While CMD is the most devastating cassava disease in Africa, and green mite and whitefly are serious problems, the greatest benefit from using MAB in cassava may be the identification of a way to delay PPD. The delayed PPD is in the in-vitro propagation stage at CIAT and the markers are expected to be available for some of the breeding programs in Africa in the near future. These markers will be evaluated in Nigeria, Ghana and Uganda, under local environmental conditions. At present only a small fraction of fresh cassava production is marketed beyond the local farmers' market. Delayed PPD could bring fundamental improvements to cassava markets in Africa.

According to local scientists, it is difficult to multiply seedlings of any improved variety because resources for public extension in the target countries are limited. Because cassava spreads by cuttings, a concerted outreach effort is needed if adoption is to take place rapidly once a variety is released. On average, a cassava plant can produce six to eight seedling stakes per year. As a result, multiplication of improved varieties is projected to take about five years in each country.

4. Production, prices and trade

Value of production and the nature of the market are key factors influencing the size and distribution of the economic benefits of improved cassava technologies. Prices and production were gathered from the FAOSTAT database, IFPRI and local sources. For Nigeria, the 2008 local farm level price of fresh cassava roots was estimated at $60 per ton. For Uganda, there was no price information in FAOSTAT, so government data were used, which suggest an average price of $75 per ton of fresh cassava roots. For Ghana, we used the price provided by FAOSTAT of about $85 per ton. The cassava quantities produced for the last four years are presented in Table 2. Very little cassava is traded in Africa because it is bulky and difficult to store well unless processed.

Table 2: Total production of cassava in Nigeria, Ghana and Uganda (000 tons)

Year	Nigeria	Ghana	Uganda
2002	34,120	9,731	5,373
2003	36,304	10,239	5,450
2004	38,845	9,739	5,500
2005	41,565	9,567	5,031

Source: FAO, 2008

5. Methods

Economic surplus analysis was used to project the economic contribution of the cassava MAB program based on the situation with and without the new technologies and with and without CB alone. Impacts were calculated over a period of 20 years, taking into account (1) base production and prices in each of the three countries as described above, (2) the nature of cassava markets, (3) projected yield and cost changes, (4) estimated time for discovery, development and deployment of the marker technologies and associated germplasm, (5) estimated time to breed, test and disseminate the improved cultivars, (6) the probabilities if the research meets with success, (7) the rate at which the variety is adopted by farmers and (8) the discount rate for benefits and costs. These parameters were assumed to be the same for MAB and CB except for items (4), (5) and (6).

Because little cassava is traded internationally by the three countries, a closed economy economic surplus model was assumed. The change in total economic surplus (TS) for a closed economy with linear demand and supply and a parallel research induced supply shift is measured as: $\Delta TS = P_0 Q_0 K (1 + 0.5Z\eta)$, where P_0 and Q_0 are initial equilibrium price and quantity, respectively; $Z = K\varepsilon/(\varepsilon + \eta)$ is the relative reduction in price due to the supply shift; ε = supply elasticity; η = demand elasticity (absolute value), and K = shift of the supply curve as a proportion of the initial price. The latter is calculated as

$$K = \left(\frac{E(Y)}{\varepsilon}\right) - \left(\frac{E(C)}{1 + E(Y)}\right) p\ A\ (1\text{-}d),$$

where E(Y) is the expected proportionate yield increase per hectare after adoption of the new technology, E(C) is the expected proportionate change in variable input cost per hectare, p is the probability of success with the research, A is the adoption rate for the new technology and d is its depreciation rate (Alston et al., 1995).

Economic benefits were calculated as the change in total economic surplus for each year, and the costs were the expenditures involved in developing and disseminating the new varieties. Using a 5% discount rate to reflect the real rate of return on alternative public investments, economic benefits were combined with R&D costs to obtain the net present value (NPV) using the formula

$$NPV = \sum_{t=1}^{T} \frac{R_t - C_t}{(1+i)^t}$$

where R_t = the benefits in year t, C_t = the costs in year t, and i = the discount rate. Comparisons were made in which the new technologies for managing CMD, green mite, whitefly and PPD were (a) developed with MAB as compared to not being developed at all and (b) developed with MAB as compared to CB breeding alone.

6. Key assumptions

Data on yields and input costs were gathered from previous field trials, previous surveys of cassava farmers, and the opinions of seven scientists and other local experts in the three countries, gathered in structured interviews. The data were combined with output prices and per hectare budgets were constructed for each location. The expected percentage yield increase for improved cassava over current varieties was 50% for the base scenario with CMD/ green mite resistance in Nigeria and Ghana. Twenty-five percent was expected for varieties with combined CMD/ green mite and whitefly resistance in Uganda. For varieties with delayed PPD, an additional 25 to 30% gain was expected depending on the country. The scientists and other experts estimated a 5% increase in labor costs for the higher yielding varieties with pest resistance, with other costs being about the same. Labor costs may be reduced for PPD resistant varieties, although experts declined to project a specific amount and none was assumed.

Few reliable estimates of cassava price elasticities for sub-Saharan countries are available, but Tsegai and Kormawa (2002) estimated a cassava price elasticity of demand in northern Nigeria of -0.46. This elasticity was used in the study and a sensitivity analysis was run. No supply elasticities for cassava were available for Nigeria, Ghana and Uganda, but a value of 1 was assumed based on the growth period for cassava and the suggestion in Alston et al. (1995:322).

The timing of adoption of the new varieties was projected to differ by technology and also by country because of differences in the stage of field trials. For Nigeria and Ghana, the scientists and other experts expect the time of release and adoption patterns will be similar. Varieties developed through MAB with CMD and green mite resistance were expected to be released in 2009, while varieties with delayed PPD were expected to be released by 2014. As compared to MAB, varieties developed through CB were expected to be released four years later for CMD and green mite resistance, but never (at least over the 20 years) for delayed PPD. For Uganda, varieties developed through MAB with CMD and green mite resistance were expected to be released in 2012, and varieties with whitefly resistance two years later. Similar varieties developed through CB were expected to be released four years later. A summary of timing and other key assumptions is presented in Tables 3a and 3b. Because the new cassava varieties are in the development stage, these predictions about their adoption were made using data from the interviews mentioned above. The level of adoption is expected to depend on the success of the new technology in providing resistance to the target constraints and therefore higher yields.

Table 3a: Summary of key parameters used as baseline assumptions in economic surplus models for MAB

Parameter	Nigeria CMD, GM[a]	Ghana CMD, GM	Uganda CMD, GM, WF[b]	Nigeria CMD, GM, PPD	Ghana CMD, GM, PPD	Uganda CMD, GM, WF, PPD
Year of release	2009	2009	2012	2014	2014	2018
Max. (%) adoption rate	40	40	40	60	60	60
Supply elasticity	1	1	1	1	1	1
Demand elasticity	-0.46	-0.46	-0.46	-0.46	-0.46	-0.46
Yield change (%)	50	50	25	80	65	45
Cost change (%)	5	5	5	5	5	5
Probability of success (%)	90	90	90	67	67	67
Base price ($/MT)	60	85	75	60	85	75
Base quantity (1000 MT)	40,000	9,000	5,500	40,000	9,000	5,500
Total research & dissemination costs ($1000s)	1490	1490	1490	1690	1690	1690

Source: Rudi, 2008
a. green mite; b. whitefly

Table 3b: Summary of key baseline parameters in economic surplus models for CB that differ from parameters used for MAB

Parameter	Nigeria CMD, GM[a]	Ghana CMD, GM	Uganda CMD, GM, WF[b]	Nigeria CMD, GM, PPD	Ghana CMD, GM, PPD	Uganda CMD, GM, WF, PPD
Year of release	2013	2013	2016	–	–	–
Probability of success (%)	50	50	50	–	–	–
Total research & dissemination costs ($1000s)	1350	1350	1350	–	–	–

Source: Rudi, 2008
a. green mite; b. whitefly

Nweke (2004) found that approximately 60% of the villages he surveyed in Nigeria had partially planted improved varieties of cassava. In Ghana, the adoption rate was less than 10%. In Uganda, both the government and various aid agencies showed increased interest in cassava as a result of the severe CMD that devastated the crop in the 1990s. Several improved cultivars with partial resistance are currently available besides the local varieties in all three countries. For example, variety TMS 30572, developed by the IITA (International Institute of Tropical Agriculture), is now the most common variety planted by farmers in Nigeria. Farmers in each of the three countries have found improved varieties superior to local ones because of their higher yield, resistance to insects and diseases, earliness of bulking or speed of root growth. Johnson et al. (2006) estimated that from 1989 to 1991, 70% of farmers in the humid zone in Nigeria had adopted improved varieties, but only 34% in the sub-humid zones. The figure was only 4% in sub-humid Ghana, and data were not available for Uganda.

Scientists and other experts interviewed felt that the maximum adoption rate for new cassava varieties would be 40% for CMD, green mite and whitefly resistance in each country. While this rate is higher for Ghana than in the earlier study, the previous lower rate was likely because the improved varieties were released later here than in the other countries. Varieties with a delayed PPD were assumed to have higher adoption. We assume adoption will increase for the first six years after release, remain constant for four years, and then decline for five years.

On the basis of the interviews with scientists, and the nearness of variety release, the probability of success with MAB was set at 90% for varieties with resistance to CMD, green mite and whitefly. CB was estimated to have a probability of success rate of 50%. For the varieties with delayed PPD, the probability of success was reduced to 67% with MAB breeding and to zero for CB.

Research and development costs (before discounting) totaled roughly $1.5 million per new variety developed through MAB. These costs were less for CB at approximately $1.35 million. Although MAB was more expensive in the early years, CB involved added expenses in later years because of the longer breeding period. The cost difference between MAB and CB was therefore only about 15% overall, although the initial investment was higher for MAB. These MAB cost data were obtained from records of expenses incurred on the GCP (Generation Challenge Program) that supported the cassava MAB research plus estimates of local costs not covered by the project related to field trials and varietal dissemination. The estimated costs are only approximate as there were some fixed project costs at CIAT that had to be apportioned over the three target countries. The costs for CB in all three countries were based on the estimated costs of the trials and varietal dissemination in Nigeria.

7. Results

The economic benefits were first assessed by comparing the new MAB varieties with current varieties grown by farmers, and secondly by comparing MAB breeding with varieties developed in a CB program (Table 4). A comparison between the MAB and CB for incorporating delayed PPD is not shown because breeding for this trait with CB methods alone is not expected to achieve success in the foreseeable future, according to cassava breeders. Different timelines for development and release and different target stresses were considered for the target countries. In Nigeria and Ghana resistance to CMD and green mite was considered first and in Uganda resistance to CMD, green mite and whitefly. PPD is a universal problem and therefore delayed PPD was considered for all three countries. The gains from adding PPD resistance are especially large, as much as $2,900 million in Nigeria, because (a) current losses are large and pervasive and (b) the problem is not likely to be solved using CB over the next 20 years. Therefore the counterfactual is the current set of varieties. Even in Uganda, economic gains are projected to be $280 million.

Table 4: Benefits of resistance to mosaic disease, green mites, whitefly and PPD

Constraint and country	Year of cassava variety release with MAB[c]	Net present value (NPV) over current varieties (million$)	Incremental NPV over conventional breeding (CB) (million$)
CMD, GM[a]			
Nigeria	2009	1493	817
Ghana	2009	676	371
CMD, GM, WF[b]			
Uganda	2112	53	34
CMD, GM, WF, PPD			
Nigeria	2014	2899	NA
Ghana	2014	855	NA
Uganda	2018	280	NA

a. green mite; b. whitefly
c. Year of release is assumed to be four years later for conventional breeding, except for PPD resistance, for which no release is assumed.

8. Sensitivity analysis

Several sensitivity analyses were completed that estimated the net economic benefits when projected yields, timing of variety release, adoption rates, and elasticities were allowed to vary. Scientists and other experts were asked their opinions on the least likely, most likely, and highest likely yield increases resulting from the improved varieties. For example, the lowest expected yield increase in Nigeria for a CMD and green mite resistant variety was 30% rather than 50%, and the highest was 60%. For the 50% yield change for Nigeria, the NPV was $1,493 million more for MAB than for current varieties and $817 million more for MAB than for CB. The NPV for the 30% yield change was 44% lower, and for the 60% yield increase about 22% higher, than it was for the 50% change. The same pattern held for yield changes for the other countries and for PPD. In other words, the percentage drop in NPV was greater than the percentage yield change, since the yield dropped because research costs are fixed (and the opposite was the case when the yield increased). The patterns for changes in factors such as probability of success and adoption rate were the same as for change in yield.

Key sensitivity analyses were done to compare the differences in the time required to release the varieties using MAB and those using CB. The base scenario for Nigeria includes a time period four years longer for CB than for MAB, with an incremental benefit of $817 million for MAB as compared to CB (for resistance to CMD and green mite). If the time difference is only three years, the incremental benefit drops to $784 million; if it is five years, it rises to $850 million. In fact, the time lag has to drop to less than one year before the benefits of CB exceed those of MAB. A similar pattern is observed for other countries and constraints.

When maximum adoption rates were allowed to vary based on expert opinion of most likely, highest expected and least likely rates, for any given percentage drop in the rate of adoption the benefits dropped by a smaller percentage because of the time pattern of benefits and costs combined with discounting. Likewise, higher maximum adoption rates are associated with proportionally smaller net benefits. For example, with a 30% maximum adoption rate for a variety resistant to CMD and green mite, as compared to a 40% rate (a 25% reduction in the assumed maximum rate), net benefits were reduced by 14%. Under the range of adoption rates suggested by experts, benefits ranged from a high of $3,220 million for pest resistance and delayed PPD in Nigeria for MAB compared to current varieties, to a low of $29 million for pest resistance without delayed PPD in Uganda for MAB compared to CB.

Supply and demand elasticities were also allowed to vary. Varying demand elasticities had a minimal effect on estimated benefits, but varying the supply elasticities from 1.2 to 0.8 caused benefits for MAB over current varieties to vary from 18% lower to 27% higher in Nigeria for CMD and green mite resistance, with similar percentage changes for the other countries and resistance traits.

9. Conclusion

Economic analysis in this paper demonstrates that MAB can significantly improve the efficiency of the cassava breeding process and have major economic benefits. The incremental net benefits of MAB over CB for developing varieties with resistance to CMD, green mite and whitefly are estimated at $817 million for Nigeria, $371 million for Ghana and $34 million for Uganda. These incremental benefits result mainly from earlier release of new varieties and the fact that the costs of MAB are relatively low compared to the benefits. MAB is estimated to save four years in the breeding process as compared to CB, but could potentially save as much as seven years. These results provide strong evidence that MAB is a highly productive investment in sub-Saharan Africa, especially in coordination with international agricultural research centers. The net benefits of MAB over *current* varieties for the management of CMD, green mite and whitefly are of course even higher, and total approximately $1.5 billion for Nigeria, $676 million for Ghana and $53 million for Uganda. The total benefits for varieties including delayed PPD are approximately $2.9 billion for Nigeria, $855 million for Ghana and $280 million for Uganda. Subtracting the incremental benefits of MAB over CB from those of MAB compared to current varieties indicates that the benefits from CB for managing these cassava constraints are roughly half those of MAB.

Previous economic analysis of the costs of MAB as compared to CB found that MAB was more expensive. The results in this paper demonstrate that the incremental benefits for cassava are so great that the cost difference pales in comparison, giving a significant boost to the argument that MAB makes sense in breeding programs in sub-Saharan Africa, at least for cassava. While the advantage is great for the pest problems considered, it is even higher for a trait such as PPD resistance, which cannot be developed though CB in a foreseeable timeframe, especially when it needs to be combined with the other resistance traits.

This paper did not directly compare MAB with another alternative biotechnology approach for building resistance into cassava, the development of transgenic varieties. However, there are some hints at the results from such a comparison when one considers the additional time lags that would be involved with meeting regulatory rules for approval of transgenic varieties, especially since these rules are still under development in these countries. Even if the direct costs of meeting the rules are high, those costs may be less of an issue than the time lags involved. Therefore, at least while regulatory processes are being refined to make them efficient with respect to time, MAB would appear to be an excellent means of improving the efficiency of the breeding program.

Another implication of this study is that any means that can be found to increase the adoption of improved varieties for a major crop such as cassava in Nigeria, or shorten the delays, can have extraordinary benefits. When a significant production constraint is relieved in a country that produces 40 million metric tons of cassava annually, every year sooner that benefits are realized will lead to major benefits, even with a discount rate of 3 to 5%.

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