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A prospective evaluation of biotechnology in semi-subsistence agriculture

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Abstract

The paper analyses ex ante the economic implications of transgenic virus- and weevil-resistant sweet potatoes in Kenya. These technologies are being developed within international projects, involving public and private organisations. It is expected that the resistant varieties will significantly reduce the crop losses in farmers' fields. Model calculations show that both innovations are likely to bring about substantial growth in economic surplus. The projected annual gross benefit is 5.4 mUS$ (million US$) for virus resistance and 9.9 mUS$ for weevil resistance. Due to the semi-subsistence nature of sweet potato, the producing households will be the main beneficiaries. However, market consumers will also capture about one-fourth of the aggregate welfare gains. The high profitability of the projects is confirmed by significantly positive returns on research investments. The examples demonstrate the viability of successful research partnerships between the public and private sectors. As most of the basic biotechnology tools available to date are patented by private companies in the North, which often do not have sufficient market incentives to develop end-technologies for the South, more interactions of this kind are required from a development policy perspective. Working with typical semi-subsistence crops is particularly appealing because it immediately targets the poor and avoids conflicts with the private sector's commercial interests. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Notwithstanding controversial debates, there is little doubt that biotechnology will be a key innovation for agricultural development in the 21st century. Crops that are genetically engineered to resist certain environmental stresses could especially benefit developing countries. Biotechnology applications, however, remain concentrated in the industrialised world, and the private sector usually determines the direction of related research (James, 2000). These efforts focus on areas with large market potentials so that research investments can be recovered and profits made. Many developing country crops — notably typical semi-subsistence crops — do not provide sufficient incentives for private sector research and development (R&D). Such crops have been termed 'orphan commodities'.

From a development policy perspective, public action is needed to help overcome these shortcomings in biotechnology R&D. Pure public research — for example by the international agricultural research centres — would be one option. But since the private biotechnology industry has a substantial lead over many public institutes in terms of facilities and experience, joint public–private sector research could be speedier and

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much more efficient than public research alone (Qaim et al., 2000). Moreover, basic biotechnology tools often apply to a diverse range of crops and problems. Because commercial enterprises hold the lions' share of these important patents, it would be difficult or impossible for public institutes to access the elementary tools needed for biotechnology research without interacting with the private sector. Viable models of public–private sector partnerships are required to effectively provide the poor in developing countries with promising biotechnology products.

Although a number of public research initiatives with private sector links have been launched in recent years, to date not a single transgenic orphan commodity has been developed into a commercial application. Hence, there is very little evidence on the economic implications — information which could assist decision-making and stimulate future co-operative research programs targeted to benefit developing countries. The present paper attempts to improve the information base. In an ex ante approach it analyses the potential economic impacts of two different recombinant sweet potato technologies — transgenic virus and weevil resistance — to be released in Kenya in the near future. Both innovations are being developed within international undertakings, involving public and private organisations.

The next section provides some background on the Kenyan sweet potato sector and the biotechnology projects analysed. The methodology applied for the economic evaluation is outlined in Section 3. For the quantification of potential technology benefits, an economic surplus model is refined which explicitly considers subsistence consumption. The empirical basis is explained in Section 4, and the model results are presented in Section 5. Section 6 discusses some conclusions and policy implications.

2. Background

2.1. The Kenyan sweet potato sector

In Kenya, like in other countries of Sub-Saharan Africa, sweet potato is predominantly grown by resource-poor women farmers. Sweet potato fulfils an important security function for producing households, because — under adverse climatic conditions and low-input regimes — it yields higher amounts of food energy and micronutrients per hectare than any other crop (Scott et al., 1992). On account of the increasing population pressure on land, the Kenyan area under sweet potato grew substantially during the last decades. Today, about 75,000 ha or 2% of the country's total arable land are cultivated with this crop (MALDM, 1998). In the farming systems of Kenya, sweet potato is usually part of a diversified cropping pattern. The average sweet potato holding of a farm has a size of 0.18 ha, and some 40% of the harvest is kept for own household consumption.

Sweet potato production conditions differ by location due to distinct agro-climatic and socio-economic factors. For the purpose of this study, Kenya is subdivided into two major sweet potato-producing regions: the West consisting of Nyanza and Western provinces, and the Central/East comprising Rift Valley, Central, Eastern and Coast provinces. 75% of all sweet potatoes are produced in the West, and the remaining 25% are produced in the Central/East. The western provinces are mostly humid or semi-humid. Although some of the producing areas in the Central and Coast provinces show humid conditions as well, the majority of them are classified as semi-arid. Quantitative information about the sweet potato farming systems could hardly be found in the literature. To get a better understanding of production characteristics a survey of 47 sweet potato farms in five different provinces was conducted by the author in 1998. Some variables describing regional conditions are shown in Table 1.

The average size of sweet potato-producing farms in the West is much smaller than in the Central/East.

Table 1
Average sweet potato production characteristics, by region[a]

	West	Central/East
Farm size (ha)	2.03	3.16
Sweet potato area (ha)	0.17	0.19
Home-consumed share of sweet potato (%)	41	37
Cost of sweet potato production (US$/ha)	348.16	321.81
Sweet potato yield (t/ha)	10.07	8.84
Per unit production cost (US$/t)	34.56	36.40
Net sweet potato income (US$/ha)	645.16	549.74

[a] Farm survey by the author (1998).

This reflects the higher population density in the Lake Victoria basin. Although no comprehensive information on overall household incomes was collected in the survey, own observations suggest that farms in the West are somewhat resource-poorer on average than those in the rest of the country.

The cost of sweet potato production is also shown in Table 1. Although Kenyan farmers usually grow sweet potato without purchased inputs, the households' own resources have been valued at their opportunity costs. Due to a higher labour intensity, the cost of production and the yields are somewhat higher in the West than in the Central/East. However, compared to other sweet potato-producing regions in the world, the yields obtained in Kenya are low. In spite of the crop's robustness, farmers suffer significant yield losses caused by pests and diseases, notably sweet potato weevils and viruses. Efficient methods to control these pathogens are not available, and conventional breeding programs to render genetic resistance have had only very limited success up till now. Although there are some sweet potato landraces with a certain degree of virus resistance, their use in breeding programs is difficult as the trait is negatively correlated with the yield performance. Genes encoding for weevil resistance are not known in the natural sweet potato germplasm.

2.2. *Biotechnology research projects*

A research project to advance non-conventional virus resistance in sweet potato was launched in 1992 in a collaborative effort between the private company Monsanto and the Kenya Agricultural Research Institute (KARI). Apart from the funds provided by Monsanto, the starting phase of the initiative was co-sponsored by the US Agency for International Development (USAID). Basic research components of the project — such as the development of suitable bio-transformation and plant regeneration protocols — were carried out in Monsanto laboratories in the USA in co-operation with KARI scientists (Wambugu, 1996). The most common sweet potato viruses in Africa are the sweet potato feathery mottle virus (SPFMV), transmitted by aphids, and the sweet potato chlorotic stunt virus (SPCSV), transmitted by whiteflies. Both viruses in combination are responsible for the so-called sweet potato virus disease (SPVD) which causes severe crop losses (Karyeija et al., 1998). The virus resistance mechanism is based on the SPFMV coat protein gene, and it is expected that this will render effective control of SPVD.

The transfer of the recombinant sweet potato technology from the USA to Kenya took place in 1999 under a royalty-free licensing agreement, which allows KARI to use the technology and to share it with other African countries in the future. Monsanto's contribution, therefore, can be looked upon as development aid. The next project phase (1999–2002) is sponsored through the Agricultural Research Fund (ARF) administered by the World Bank. This new phase is institutionally supported by Monsanto, the International Service for the Acquisition of Agri-biotech Applications (ISAAA) and the International Potato Center (CIP). It foresees the field-testing of virus-resistant sweet potatoes in Kenya as well as subsequent release of the transgenic varieties. The technology constitutes the initial experience with transgenic crops in Kenya. Thus, capacity building for safe technology application is an integral part of the project activities. The distribution of the first modified variety to Kenyan sweet potato farmers could start in 2002. In parallel, KARI plans to transform additional varieties for virus resistance in its newly refurbished biotechnology laboratory. The technology will be released as a public good.

Other research undertakings have been initiated more recently with the objective of developing transgenic weevil resistance for sweet potato to be used in Africa. These undertakings involve different public organisations in the USA, albeit the research builds on *Bacillus thuringiensis* (Bt) genes being patented by various private companies. Given the experience with the Monsanto/KARI project, it is expected that Kenya might be one of the first countries where the sweet potato weevil resistance technology will be used, possibly from 2004 onwards. Environmental and human health risks of both transgenic technologies are considered to be low. They are discussed in greater detail by Qaim (1999).

3. Methodology

This section describes the methodology for the ex ante economic analysis of transgenic sweet potato technology in Kenya. For the quantification of potential benefits, economic surplus changes are calculated in a partial equilibrium framework. This is the most common approach for the evaluation of commodity-related technological progress in agriculture (Alston et al., 1995). Nevertheless, it should be mentioned that this method can only capture the direct and immediate benefits of a technology for producers and consumers. Spillovers to other markets as well as indirect and dynamic effects are disregarded. For the biotechnology projects analysed such indirect effects could include:

- *Long-term benefits through capacity building*: The transgenic virus-resistant sweet potatoes will be the first recombinant crop technology developed by Kenyan scientists. The knowledge and experience gained by working with Monsanto and other project partners are expected to be sizeable. In addition, a national regulatory framework for the safe use of biotechnology is being established. These positive developments lay the ground for future technological progress in sweet potato and other crops.
- *Agricultural growth linkages*: Technology-related productivity gains lead to increasing purchasing power and thus to rising consumer demand for food and non-food commodities alike. Such a demand stimulus creates income gains in various sectors and generates employment and overall economic growth. Delgado et al. (1998) recently demonstrated the significance of such growth linkages due to innovations in agriculture for various Sub-Saharan African countries.

These indirect benefit potentials are hard to measure for individual technologies, so we confine the quantitative analysis to the direct effects. It should be kept in mind, however, that the welfare gains identified through the modelling approach will tend to undervalue the true long-term benefits of the biotechnology projects.

3.1. The model

As international trade in sweet potato is negligible, we build a closed-economy market model. The supply and demand curves are assumed to be linear, whereby the domestic sweet potato supply curve is horizontally disaggregated into n production regions. This is instructive because divergent technology potentials are expected for the West and the Central/East of Kenya. Yet there is substantial interregional trade so that all regions are facing the same aggregate demand curve. [1] Market clearing is ensured by:

$$\sum_{i=1}^{n} q_{s,i}(p) = q_d(p), \tag{1}$$

where $q_{s,i}$ is the sweet potato quantity supplied by region i, and q_d is the total quantity demanded at equilibrium price p. Now we introduce biotechnological progress into sweet potato production, which will cause the regional supply curves to shift downwards in a parallel fashion. [2] The technology shift factor $K_{i,t}$ is defined as the potential proportionate per unit cost reduction (C), to be realised when using the technology, multiplied by the innovation adoption rate (A) in a given year t. Differentiating Eq. (1) and solving for the price change, we derive the following formulation:

$$\frac{dp}{p} = \frac{\sum_{i=1}^{n}(ss_i\, \varepsilon_{s,i} K_i)}{\varepsilon_d - \sum_{i=1}^{n}(ss_i\, \varepsilon_{s,i})}, \tag{2}$$

where ss_i is the production share of region i, $\varepsilon_{s,i}$ the price elasticity of supply in the same region and ε_d is the price elasticity of demand. In general, this information is sufficient to calculate the technology-induced changes in producer and consumer surplus.

3.2. Subsistence consumption

For a highly commercialised commodity, the differentiation between producers and consumers is clear. Many crops in developing countries, however, are produced on a semi-subsistence basis, as was shown to be the case for sweet potatoes in Kenya. This means that the general division between producer and consumer surplus is flawed. Hayami and Herdt (1977) developed a model in which they complemented the market demand curve of a semi-subsistence crop with an additional demand curve for home consumption. This approach has been adopted by a number of other authors in more recent studies. In general, home

[1] Similar farm-gate prices across regions indicate that arbitrage takes place and that it is appropriate to consider the Kenyan sweet potato market as being fairly integrated.

[2] Whether the supply shift should be modeled in a parallel or a pivotal way has been controversially discussed in the literature. Alston et al. (1995) argue in favor of a parallel shift, whenever empirical evidence for a pivotal shift is missing.

consumption of an own-produced crop is less price responsive than market demand for the same commodity. In the absence of more detailed information it might be a simplified but not unrealistic approximation to assume that the demand curve for subsistence consumption is vertical, i.e. it is completely price inelastic. The aggregate demand curve is then defined as:

$$q_{\mathrm{d}}(p) = q_{\mathrm{d}}^{\mathrm{market}}(p) + \sum_{i=1}^{n} q_{\mathrm{d},i}^{\mathrm{home}}. \tag{3}$$

Thus, the magnitude of the overall change in economic surplus is the same as without home consumption, only that part of the consumer surplus remains with the producers, who profit from cheaper subsistence consumption. The annual change in producer surplus (ΔPS) and in consumer surplus (ΔCS) can be calculated as:

$$\Delta PS = \sum_{i=1}^{n} \left[p q_{\mathrm{s},i} \left(\frac{\mathrm{d}p}{p} + K_i \right) \times \left(1 + 0.5 \varepsilon_{\mathrm{s},i} \left(\frac{\mathrm{d}p}{p} + K_i \right) \right) + (-\mathrm{d}p\, q_{\mathrm{s},i} h_i) \right], \tag{4}$$

$$\Delta CS = -p q_{\mathrm{d}} \frac{\mathrm{d}p}{p} \left(1 + 0.5 \varepsilon_{\mathrm{d}} \frac{\mathrm{d}p}{p} \right) - \left(-\mathrm{d}p\, q_{\mathrm{d}} \sum_{i=1}^{n} (h_i\, \mathrm{ss}_i) \right), \tag{5}$$

where h_i is the home-consumed share of sweet potato production in region i.

3.3. Time dimension

The changes in producer and consumer surplus to be quantified with Eqs. (4) and (5) indicate the technology-induced welfare gains in a given year t. Technology impacts, however, cannot be appropriately modelled for a single year because innovation adoption by the farmers is usually a gradual process spanning several years. Hence, benefits are calculated for a period of 16 years, separately for the virus and weevil resistance technologies. Annual average figures will be expressed in the form of annuities. It could be argued that the biotechnology applications might produce benefits for a period longer than 16 years, especially when the list of transformed varieties is eventually extended. But technological obsolescence might occur through possible resistance breaking or because other and superior innovations will be developed. And even if the technologies would still be used after that period, the procedure of discounting prevents benefit flows that occur in the distant future from changing the model results significantly.

Another aspect to be considered is that food demand does not remain constant over time. Demographic developments will cause sweet potato consumption to rise during the period of consideration. To account for this, we follow an approach suggested by Norton et al. (1987): we let the aggregate demand curve exogenously shift rightwards by the population growth rate. Annual population growth in Kenya has been 2.6% in recent years (World Bank, 2000). An additional shift in demand could generally occur through increasing purchasing power, but significant per capita income growth in Kenya is not expected in the short to medium run.

4. Empirical basis

The information needed for the calculations can be subdivided into market-related data on the one hand, and technology-related data on the other. The market-related figures — such as sweet potato quantities and prices — are based on secondary sources (MALDM, 1998; FAO, 1999). Price elasticities of demand and supply in Kenya could not be found for sweet potatoes or other root and tuber crops. But Omosa (1997) studied price effects of sweet potato demand in different urban areas of Kenya, finding that the retail price level is inversely correlated with consumption for the majority of households. This result suggests that the price elasticity of demand is negative and significantly different from zero. For that reason we assume an aggregate price coefficient of −0.4 for sweet potato market demand in Kenya. On the supply side, Bashaasha and Mwanga (1992) estimated a price responsiveness of 0.3 for sweet potatoes in Uganda. We assume the same value for the growers in Kenya. Production systems are similar in the West and the Central/East, so there is no reason to expect that the price elasticity of supply would differ significantly between the regions. Other production variables needed for the calculations are

Table 2
Anticipated productivity effects at the farm level (%)[a]

	West		Central/East	
	Virus resistance	Weevil resistance	Virus resistance	Weevil resistance
Yield increase[b]	20	25	12	25
Per unit cost reduction	17	20	11	20
Increase in sweet potato income	31	38	19	40

[a] Expert interviews and farm survey by the author (1998).
[b] The yield increases have been derived as mean values from the expert interview.

based on the farm survey mentioned above (see Section 2).

Specifying the technology-related data, however, is not a straightforward procedure. As neither of the two resistance technologies has yet been released, the potential per unit cost reductions and the innovation adoption rates needed to determine the technology shift factors cannot easily be observed. To come up with realistic ex ante assumptions, 20 sweet potato researchers have been interviewed. These researchers included representatives of KARI, Monsanto, CIP, ISAAA, universities and other national organisations. To increase the objectivity of the information, 5 of the 20 experts were completely independent, i.e. they were not involved in the sweet potato biotechnology projects. The interviews covered questions about expected technology yield gains (or avoided yield losses), the likely time-horizon for technology development, adoption and application as well as R&D cost estimates. The farm survey and additional discussions with 10 agricultural extension officers in Kenya's main sweet potato-growing regions helped to translate the information from the research level to realistic economic data at the farm level.

4.1. Potential productivity effects

There are currently no economically feasible measures for Kenyan farmers to control the crop damage caused by sweet potato viruses and weevils. The main agronomic effect of the transgenic resistance technologies will therefore be to reduce crop losses; that is, to increase the effective yields obtained by growers. The anticipated productivity effects at the farm level are shown in Table 2.

The significance of SPVD varies according to agro-ecological zone. A moist and warm environment promotes the incidence of insect vectors. So virus pressure, and thus the potential of the virus resistance technology, is higher in the Lake Victoria basin than in the drier areas of the Central/East. Weevil problems, on the other hand, show the same severity in all sweet potato-producing provinces of Kenya. Hence, it is expected that the weevil resistance technology would offer the same potential in both the West and Central/East regions.

As mentioned before, the transgenic varieties will be distributed as a public good; i.e. farmers will not pay a technology premium. Plant propagation in sweet potato is traditionally conducted by using vine cuttings, which facilitates technology multiplication by the growers themselves. Also, the use of the technology does not require an adjustment of traditional cultivation practices. Given constant per hectare production costs and rising yields, both technologies will bring about significant per unit cost reductions and remarkable increases in sweet potato incomes.[3]

4.2. Technology adoption

Varietal replacement is always associated with a certain degree of risk. Early adopters, for instance, do not know in advance how the consumer market will react to the new variety. Furthermore, a new variety might require adjustments in traditional cropping practices. Partly due to such risk aspects, the adoption of new high-yielding varieties over time has often been modelled as a logistic function (e.g. Feder et al., 1985).

[3] Note that the income increases shown in Table 2 assume a constant sweet potato farm-gate price. This might be realistic for some early technology adopters. Given a more widespread distribution, however, productivity increases will cause the producer price to fall. This is accounted for in the economic surplus model.

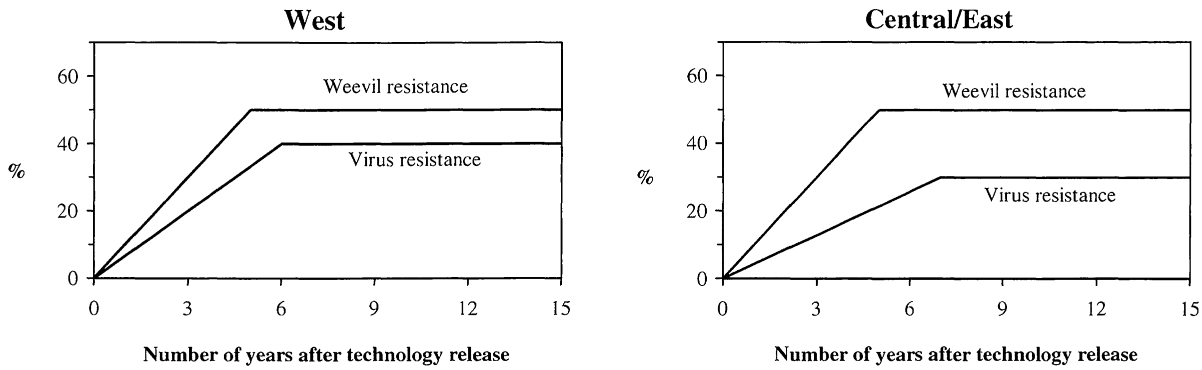

Fig. 1. Estimated technology adoption profiles, by region (%).

However, adoption risk is reduced substantially in the case of transgenic crops with resistance to biotic stress factors. Complementary inputs are not required. For the sweet potato technologies it is even likely that some of the varieties already in use will be genetically transformed so that agronomic and quality characteristics remain entirely unchanged. Given the relatively low risk of technology adoption from the farmers' point of view we assume a linear adoption profile instead of a logistic curve.

The transgenic varieties will diffuse in the same way as new conventional material is spread today. KARI conducts on-farm demonstration trials with the new varieties in collaboration with contact farmers. During a meeting towards the end of the season, other sweet potato growers can observe the yield and quality performance and may then take a handful of vine cuttings for their own propagation and further dissemination. As the introduction of new sweet potato varieties is a rather new activity in Kenya, no exact information is available about the possible speed of variety adoption. Farmers are choosy, especially in regards to taste characteristics of sweet potato cultivars. But preliminary experience suggests that acceptable germplasm can quickly spread through an informal exchange of vine cuttings from farmer-to-farmer (Carey et al., 1997).

The expected linear adoption curves for the transgenic resistance technologies were determined together with the interviewed researchers and extension specialists. They are depicted in Fig. 1. The first virus-resistant variety could be released in 2002, with additional cultivars following in subsequent years. The time path for the weevil resistance technology is less clear. The graphs build on the assumption that it will be released simultaneously with the virus-resistant varieties, but this is just for comparative purposes. As explained above, the weevil project is at an earlier stage; technology release cannot be expected before 2004.

Given farmers diverse varietal preferences, the speed of adoption and the maximum adoption rates will closely correlate to the number of available transgenic varieties. The adoption patterns assume that, in due time, five or more varieties would be transformed for virus and weevil resistance, respectively. Due to the more severe virus pressure in the moist Lake Victoria basin, adoption of the virus resistance technology will be faster and somewhat more widespread in the West than in the Central/East. For the weevil resistance technology, adoption behaviour is presumed to be identical in both regions. It is likely that weevil-resistant varieties will be taken up slightly more rapidly than virus-resistant ones, because farmers are more aware of the weevil problem and consider the pest to be the most severe production constraint.

5. Model results

5.1. Welfare gains

On the basis of the model and data explained above, the changes in economic surplus induced by the two transgenic sweet potato technologies have been calculated for a period of 16 years after the assumed technology release. The results are summarised in Table 3.

Table 3
Projected annual welfare gains (mUS$)[a]

	Virus resistance	Weevil resistance
Total gain in economic surplus	5.42	9.93
Western producers	3.67	5.53
Central/eastern producers	0.35	1.83
Consumers	1.40	2.57

[a] The figures are annuities that have been calculated using a discount rate of 10%.

The two innovations are likely to bring about substantial welfare gains in Kenya. For the virus resistance technology, the annual gain is projected at 5.4 mUS$, whereas for the weevil resistance technology it is 9.9 mUS$. The difference occurs mainly because weevils depress current sweet potato yields more than viruses. Moreover, farmers will adopt weevil-resistant varieties more quickly and more widely. Yet this comparison should not be misunderstood as a priority-setting exercise. In the future, both resistance mechanisms will become available, possibly even incorporated in the same varieties. The reason why we refrain from evaluating both technologies together is that little is known about possible synergies in the crop losses caused by viruses and weevils. Assumptions about the yield effects of stacked resistance mechanisms would be pure speculation.

For both technologies, sweet potato producers will capture the largest part of the overall welfare gains; remember that the benefits through subsistence consumption are covered on the producer side. Noteworthy is that the benefit share attributable to producers would shrink from 74 to 57% without accounting for subsistence consumption. Comparing the regional distribution of producer benefits with the regions' initial production shares (see Section 2) reveals that the virus resistance technology is slightly biased towards the West. This is due to the high virus pressure in the moist Lake Victoria basin. Farmers in the West are somewhat resource-poorer than in the Central/East on average, so that this bias does not have undesired equity implications. Weevil problems, on the other hand, are oppressive in all of Kenya's sweet potato-producing regions, so the regional benefit distribution of the weevil-resistant varieties almost exactly corresponds to the initial regional production shares.

Since sweet potato is an inferior commodity in Kenya, poor population segments will be the main beneficiaries of the transgenic varieties. In peasant production systems, the crop is predominantly managed by the female household members, so an explicit gender perspective appears instructive. In general, new crop technologies are often associated with changes in tasks and responsibilities between men and women. Increased commercialisation, for instance, can lead to male household members taking control of crop income previously controlled by female household members. However, unlike typical cash crops which render a comparatively big cash income at one point in time, sweet potatoes in Kenya are harvested in a piecemeal fashion. A continuous flow of revenues is generated which is used by the women for the immediate household needs. Hence, the additional sweet potato income created by transgenic technologies might actually increase female household members' economic independence, with concomitant positive effects on the food security and health situation at the household level.

5.2. Cost–benefit analysis

Since Kenyan sweet potato growers will receive the transgenic technologies free of charge, the cost of R&D is not captured in the economic surplus calculations. The changes in producer and consumer surplus only represent the gross benefit of the innovations. In order to estimate the social profitability of R&D investments, a cost–benefit analysis is carried out in this sub-section. Detailed R&D cost data for the sweet potato virus resistance project have been obtained from the different organisations involved, whereby expenditures yet to be made were estimated by the representatives. As the weevil resistance technology is still at a much earlier stage, comprehensive information on research expenditures for this innovation could not be assembled. It is expected that costs might be much lower for this research than for the virus-resistance project, because considerable experience with transgenic sweet potato technology is already available. Nonetheless, as a conservative assumption, we use the same cost data for both technologies. For the cost–benefit analysis, the research expenditures have been juxtaposed to the projected welfare gains on an annual basis, taking account of

Table 4
IRRs under different assumptions (%)

	Virus resistance	Weevil resistance
Full R&D cost, Kenyan sweet potato area	26.1	33.3
Full R&D cost, Kenyan sweet potato area doubled	33.7	41.7
Full R&D cost, Kenyan sweet potato area quadrupled	41.9	50.7
Only applied R&D cost, Kenyan sweet potato area	59.5	77.3

the time lags between research start and technology release. Table 4 shows the resulting internal rates of return (IRRs) under different assumptions.

The first row in Table 4 takes into account the complete R&D expenditure borne by the involved organisations (i.e. Monsanto, KARI, USAID, World Bank, ISAAA, CIP). The IRRs are significantly above 10%, the standard discount rate used for investments in low-income countries. Yet, in an international comparison of IRRs in agricultural research, the figures obtained range at the lower end of the spectrum. This should not surprise because the welfare gains imputed on the benefits side are confined to Kenya. Although spillover effects to other African countries will be part of the transgenic sweet potato projects, they are not included in the calculations due to a lack of reasonable ex ante data. For illustrative purposes, the second and third rows of Table 4 demonstrate the impact that an increase in the sweet potato area (e.g. through extending the technology to neighbouring countries) would have on the aggregate benefit–cost measures. Of course, varietal adjustments and national biosafety procedures would be necessary before farmers in other countries could use the technology. But to gain a sense of perspective, it should be kept in mind that Tanzania's sweet potato area is almost three times larger than Kenya's, and Uganda's area is larger than Kenya's by a factor of 7.

On the cost side, it is necessary to consider whether it is appropriate to include the total cost of R&D in the calculations. Apart from the anticipated technology spillovers to other countries, the basic research component and related knowledge gains of the virus resistance project will also facilitate the development of other transgenic sweet potato technologies in the future. Concentrating on the biotechnology transfer from the US to Kenya, it is informative to calculate supplementary IRRs, where only the cost of applied R&D and national capacity building is considered. For this purpose, the expenditure directly borne by Monsanto in the USA during the first project phase is disregarded, and the research lag has been shortened by 50%. The results are shown in the last row of Table 4. It can be seen that the biotechnology transfer creates high returns on project investments. This might be of interest to other countries planning to import recombinant sweet potato technologies in the future.

5.3. Sensitivity analysis

It is in the nature of ex ante studies that their data are uncertain. In order to strengthen the credibility of the numerical results and the derived statements, sensitivity analysis is carried out with respect to pivotal parameters. Key variables determining the technology shift of the sweet potato supply curves are the per unit cost reduction (C) and the technology adoption rate (A). As expected, the gains in total economic surplus change in proportion to variations of these two parameters. The benefit partitioning between producers and consumers remains unaffected. Although the influence on the IRRs is significant, the overall profitability of both technologies is not jeopardised even with an 80% reduction of either C or A — i.e. the IRRs remain above 10%.

Because no reliable estimates are available for the price elasticities of sweet potato supply and demand, the robustness of the results is also tested with respect to changes in these parameters. Changes in the values of the supply and demand price coefficients in reasonable dimensions have a comparatively small impact on the aggregate economic surplus gains and thus on the IRRs. Yet the surplus distribution between producers and consumers is influenced. Not surprisingly, the consumer share increases to some extent with a rising price elasticity of supply, whereas a stronger price responsiveness of consumers would lead to higher benefit shares attributable to producers. These effects are lessened, however, because a significant proportion of Kenya's sweet potato output is directly consumed by producing households.

Finally, it could be argued that the period of 16 years for which benefit flows have been considered is too long, because resistance mechanisms may break down earlier. Both the sweet potato virus and weevil technologies are based on single gene resistances, a strategy that usually lowers the likelihood of long durability. On the other hand, it is expected that selection pressure in pathogen populations is comparatively low in Kenya: owing to the small-scale production systems, there will always be sufficient non-transgenic refuge areas nearby. Nonetheless, the possibility of resistance breaking has been considered. Due to the discounting procedure, however, the economic impacts are more or less negligible. Even when a 5-year shortening of benefit flows is assumed, the IRRs are still 24 and 32% for the virus and weevil resistance technologies, respectively. In summary, the sensitivity analysis underlines the validity of the welfare and profitability outcomes, even under extreme parameter variations.

6. Conclusions

Biotechnology helps to bring forth innovations that could not be achieved using conventional research tools alone. The development and adoption of transgenic virus and weevil-resistant varieties is expected to bring about significant productivity growth in the Kenyan sweet potato sector, with remarkable welfare gains for producers and consumers. Thus, the technologies will contribute to poverty reduction and improved food security in rural and urban areas. The examples analysed clearly show that modern biotechnology can offer promising alternatives for developing countries, if the specific needs of these countries are not neglected in international research. Pest and disease-resistant transgenic crops are very appropriate for smallholder agriculture because they do not require profound modifications in traditional cultivation practices.

Also, the collaborative R&D projects demonstrate the viability of successful partnerships between the public and private sectors. As most of the biotechnology tools available to date are patented by private companies, more interactions of this kind are required. Working with typical semi-subsistence crops, such as sweet potato, is particularly appealing because it immediately targets the poor. Furthermore, licensing agreements between private companies and public organisations are facilitated because a clear-cut segmentation of commercial and non-commercial markets is possible. Genetic engineering allows the use of technologies across various crop species. So private companies can share their technologies with the public sector for use in orphan commodities without jeopardising their own business ventures in crops of commercial interest. The sweet potato projects show that private companies are even willing to donate proprietary technologies for the adaptation to non-commercial markets if they can watch over their safe employment.

However, within the development of sweet potato virus resistance, Monsanto is certainly more than just the donor of available technology. The main part of the research has been carried out in Monsanto laboratories, and, despite the financial support from public organisations, the company carries around 70% of the total cost of R&D. Given that the technology will eventually be distributed by KARI as a public good, Monsanto's own interest in the project is not apparent at first sight. Yet it must not be neglected that such philanthropic initiatives can help improve the public image of a company, especially in times of limited public biotechnology acceptance. Furthermore, through the project, Monsanto establishes a new institutional network and gains experience with African seed markets. These aspects could considerably contribute to the company's business success in the long run. Despite such strategic incentives, though, it is unlikely that the example of cost sharing can be taken as a general model for biotechnology research in semi-subsistence crops. The cost of the development of transgenic orphan commodities will decrease over time, once more basic biotechnology tools and transformation protocols become available. Nonetheless, it is essential to increase public sector contributions in terms of funds and expertise in order to encourage collaborative R&D initiatives in the future. Harnessing the comparative advantage of the public and private sectors is a prerequisite for the efficient provision of highly beneficial biotechnology innovations for the poor.

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