The Economic Effects of Genetically Modified Orphan Commodities: Projections for Sweetpotato in Kenya

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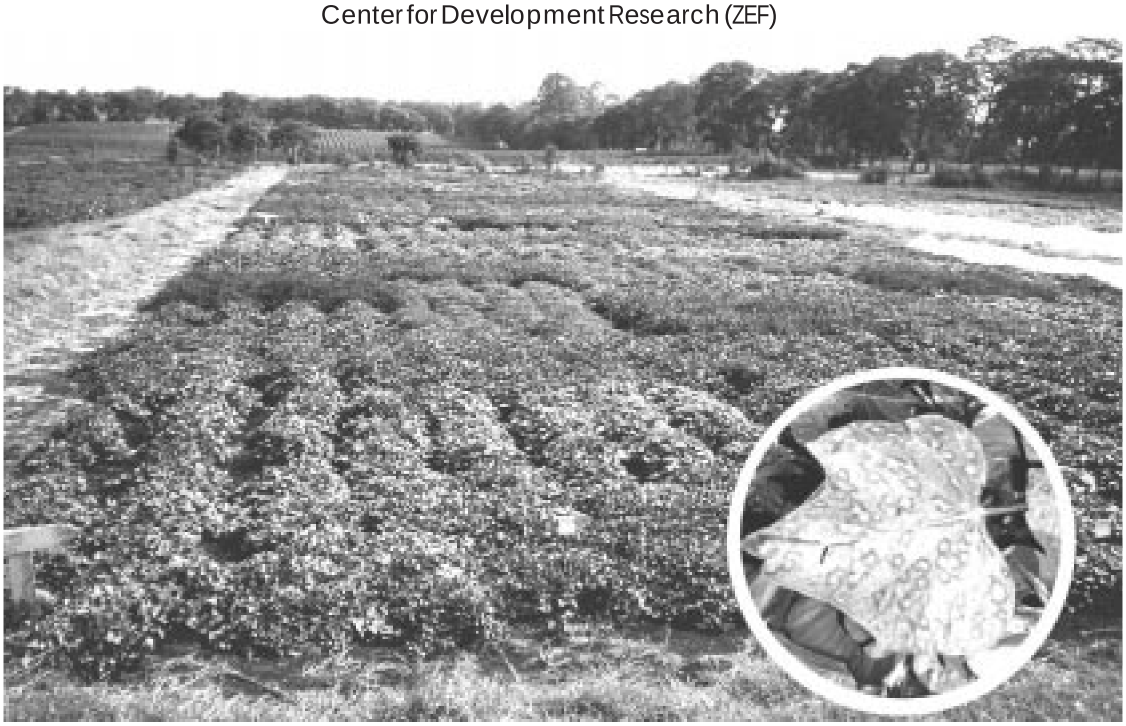
Agricultural Economist
Center for Development Research (ZEF)



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Foreword

Despite the ongoing controversial debates about genetically engineered crops, there is little doubt that biotechnology will substantially impact on global agricultural production. But how can developing countries, where the need for agricultural innovation is greatest, become the main beneficiaries? Biotechnology research is capital- and knowledge-intensive, and without targeted support there is the risk that the technology will bypass the small farm sector and poor consumers in the South. If we are to tackle the problems of the poor we must develop innovative research projects.

This report by Matin Qaim analyzes international research projects jointly launched by the Kenya Agricultural Research Institute (KARI), Monsanto, and other organizations to develop genetically engineered sweetpotatoes with resistance to major pests and diseases. The expected economic ramifications are analyzed for small-scale farming systems in Kenya, where the transgenic varieties will first be deployed in the near future. The report shows that both sweetpotato producers and consumers will profit from the technology. In addition to these direct, positive impacts on the income and food security situation of households, the initiatives advance significant biotechnology capacity-formation in the Kenyan agricultural research system. Indeed, the examples in the study clearly demonstrate the viability of public-private sector research partnerships for the benefit of developing countries. Working with typical semisubsistence crops—such as sweetpotato—is particularly attractive because it targets the poor and avoids conflicts with the private sector's business interests.

Having analyzed transgenic potato technology in Mexico and tissue culture banana technology in Kenya, the present study is the third fieldwork-based socioeconomic biotechnology assessment carried out independently by the Center for Development Research (ZEF) and published in collaboration with the International Service for the Acquisition of Agri-biotech Applications (ISAAA). The combined results of these studies underline even more firmly that modern agricultural biotechnology can provide great benefits to low- and middle-income countries, including the smallholder sector. Yet these benefits will not materialize without public support. The international community must translate the promise of biotechnology for the South into actual benefits through appropriate policies. Apart from higher financial commitments for public biotechnology research targeting smallholders and poor consumers, profound institutional changes in national and international agricultural innovation systems are necessary to respond efficiently to the rapidly changing framework conditions.

Joachim von Braun
Director, ZEF

Executive Summary

Biotechnology has the potential to boost global agricultural productivity in a sustainable way. The prospects are particularly bright for the developing world, where the need for new farm technologies is most pronounced. Biotechnology advances, however, are predominantly taking place in the industrialized world. The research capacity in many developing countries is limited, and so these countries will have to import biotechnology in order to be able to use it. But technological requirements differ across countries, and some fear that the needs of the South will be bypassed by biotechnological research programs that are dominated by the private sector in the North. For the so-called "orphan commodities," those food crops that have minor international appeal but that are of great importance to semisubsistent farmers in developing countries, this could especially prove true. In this study, however, we examine innovative undertakings that have been jointly launched by the public and private sector to develop recombinant sweetpotato technologies for use in Africa. The economic impacts of the resulting transgenic sweetpotato varieties for Kenya are scrutinized using an *ex ante* analytical framework. The study seeks to improve the empirical evidence about the repercussions of biotechnology in the small-farm sector of developing countries. It also seeks to enrich the knowledge base needed for formulating policies that include the poor in the biotechnology revolution.

In Kenya, as in other countries of sub-Saharan Africa, sweetpotato is mainly grown by resource-poor women farmers. Sweetpotato provides an important security function for the producing households because—under adverse climatic conditions and low-input regimes—it yields higher amounts of food energy and micronutrients per unit area than any other crop. The amount of land used for sweetpotato production in Kenya has grown substantially in recent decades due to population pressure. Today, Kenyan farmers cultivate the crop on about 75,000 hectares that are spread over various agroecological zones. In the farming systems of Kenya, sweetpotato is usually part of a diversified cropping pattern. A farm's average sweetpotato holding is 0.45 acres (0.18 hectares), and some 40 percent of the harvest is kept for household consumption. In spite of the crop's robustness, farmers suffer significant yield losses caused by pests and diseases, notably sweetpotato viruses and weevils. Efficient methods to control these pathogens are not available, and compared to other sweetpotato-producing regions in the world, the yield levels obtained in Kenya are low. This problem is exacerbated by the neglect of national and international agricultural research on sweetpotato.

A research project to advance nonconventional virus resistance in sweetpotato, however, was launched in 1991/92 by the private company Monsanto and the Kenya Agricultural Research Institute (KARI). Apart from funds Monsanto provided, the first phase of the initiative was cosponsored by the US Agency for International Development (USAID). The University of Missouri also assisted with coordination efforts. Basic research components of the project—such as the development of suitable biotransformation and plant regeneration protocols—have been carried out in Monsanto's US laboratories in collaboration with KARI scientists. The transfer of the recombinant sweetpotato technology from the USA to Kenya is scheduled for 1999. A royalty-free licensing agreement has been signed, 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, beginning in 1999, is sponsored by the Agricultural Research Fund (ARF), which is being 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). During this phase, virus-resistant sweetpotatoes will be field-tested in Kenya and transgenic varieties will subsequently be released. This technology is Kenya's first experience with bioengineered crops, and so capacity building for biosafety is an integral part of the project's activities. Kenya's farmers could receive the new transgenic varieties as early as 2002. In the meantime, KARI will transform additional varieties for virus resistance in its newly refurbished biotechnology laboratory. Given the heterogeneous varietal preferences among sweetpotato producers, this is important for promoting widespread technology adoption.

Other research undertakings have recently begun with the objective of developing transgenic weevil resistance in sweetpotato for use in Africa. These undertakings involve different public organizations, although the work is also partly based on proprietary technology patented by the private sector. Given the experience of the Monsanto/KARI project, Kenya will probably be one of the first countries to deploy the weevil resistance technology in sweetpotato, possibly as early as 2004.

This study investigates the potential impacts of both virus and weevil resistance in the Kenyan sweetpotato sector. Interview surveys conducted in 1998 of researchers, extension workers, and farmers, constitute the data basis for the quantitative analysis. First, the likely effects are analyzed at the level of the individual farm. It is expected that by using transgenic virus-resistant varieties farmers will be able to increase their sweetpotato yields by 18 percent. Due to spatially divergent virus pressures, productivity increases will be somewhat higher in the moist, western part of Kenya than in the drier central and eastern regions. The potential yield gains for weevil-resistant varieties are even higher: 25 percent, with no significant regional differences. Farmers will easily be able to integrate both resistance technologies into their traditional cropping systems without additional costs. The projected sweetpotato income gains at the farm level are sizable. Under the simplified assumption of constant output prices, the relative income increase would be 28 and 39 percent for virus and weevil resistance technology, respectively. Rising cash revenues as well as the greater availability of sweetpotato for subsistence consumption will contribute significantly to improved food security for rural households.

The potential effects of transgenic technologies are also analyzed for the Kenyan sweetpotato market as a whole. For this purpose, an economic surplus model with technological progress is employed. In addition to the agronomic technology potentials, innovation adoption rates are important model parameters. Given the widespread informal exchange of sweetpotato planting material among farmers, a fairly quick dissemination is anticipated if the resistance mechanisms are incorporated into varieties acceptable to farmers. The model simulations show that the virus-resistant varieties would produce an aggregate annual benefit of 324 million Kenyan Shillings (KSh) (5.4 million US$), whereas the weevil resistance technology could create welfare gains of 593 million KSh (9.9 million US$) per year. For both technologies, about 26 percent of the overall surplus will be captured by food consumers, since the growth in productivity will cause the sweetpotato market price to decline.

Juxtaposing the benefits to the costs of research and development (R&D), the virus resistance technology produces an internal rate of return (IRR) of 26 percent. The research on sweetpotato weevil resistance is at a much earlier stage, so no reliable R&D cost figures could be assembled for this technology. But assuming the same investments as for the virus research project, the weevil resistance technology creates an IRR of 33 percent. It should be noted, however, that a direct comparison of the IRR figures could be misleading because it neglects the positive dynamic effects of capacity-building, which are difficult to quantify. The implementation of the weevil resistance technology in Kenya will profit from the knowledge and experience acquired from the virus resistance project. In the longer run, it is likely that varieties with both resistance mechanisms incorporated will also become available. Furthermore, it needs to be stressed that the stated benefit-cost ratios grossly underestimate the actual social returns on research investments. Eventually, the innovations will also be used in other African countries, so it is inappropriate to impose the whole cost of basic research in an analysis confined to Kenya. Taking into account only the more applied research components and the cost of local capacity building, the IRR for the virus resistance technology is 60 percent, and for the weevil resistance technology it is 77 percent.

The examples clearly show that modern biotechnology can offer promising solutions to the problems of resource-poor farmers in developing countries if their specific needs are explicitly taken into account in biotechnology research. Moreover, the international collaborative R&D projects demonstrate the viability of successful partnerships between the public and the private sectors. As most of the basic biotechnology tools available to date are patented by private companies, which often do not have enough market incentives to develop end-technologies designed to serve resource-poor farmers in the South, more interactions of this kind are needed. Firms are particularly inclined to donate proprietary technology (e.g., certain genes) for use in public sector research on orphan commodities, such as sweetpotato. The reason for this is that these crops do not conflict with the private sector's commercial interests. Donor organizations should make more funds available for innovative public-private partnerships and biotechnology transfers so that developing countries can gain access to the benefits of biotechnology.

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List of Abbreviations and Acronyms

ABSP	Agricultural Biotechnology Support Project
ARF	Agricultural Research Fund
Bt	*Bacillus thuringiensis*
CGIAR	Consultative Group on International Agricultural Research
CIP	International Potato Center
FAO	Food and Agriculture Organization of the United Nations
FDA	Food and Drug Administration
IITA	International Institute of Tropical Agriculture
IPR	Intellectual Property Rights
IRR	Internal Rate of Return
ISAAA	International Service for the Acquisition of Agri-biotech Applications
KARI	Kenya Agricultural Research Institute
kcal	Kilocalorie
MALDM	Ministry of Agriculture, Livestock Development and Marketing
NARL	National Agricultural Research Laboratory
NARS	National Agricultural Research System
R&D	Research and Development
SPCSV	Sweetpotato Chlorotic Stunt Virus
SPFMV	Sweetpotato Feathery Mottle Virus
SPVD	Sweetpotato Virus Disease
USAID	United States Agency for International Development
ZEF	Zentrum für Entwicklungsforschung (Center for Development Research)

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1. Introduction

There is widespread agreement today that biotechnology will have significant repercussions on worldwide agricultural development (e.g., Kendall et al., 1997; ODI, 1999). In particular, plants that are genetically engineered to resist biotic and abiotic stress factors could increase food production and farm incomes in a sustainable way. Developing countries stand to benefit most, because in these countries food insecurity continues to be a serious problem and agriculture is the main source of income and employment for most of the population.

Biotechnology applications, however, remain concentrated in the industrialized world, and the private sector usually decides the direction of related research (cf. James, 1998). 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 semisubsistence crops—do not provide sufficient incentives for private sector research and development (R&D). Such crops have been termed "orphan commodities" (Persley, 1990). 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 centers—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 much more efficient than public research alone. Moreover, basic biotechnology tools often apply to a diverse range of crops and problems. Because commercial enterprises hold the lion's 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, therefore, are needed to effectively provide the poor in developing countries with promising biotechnology products (James, 1997). Although a number of public research initiatives with private sector links have been launched in recent years, not a single bioengineered orphan commodity has yet been developed into a commercial application. This means that there is very little evidence about its related economic impacts. Because such information could assist decision-making and stimulate future cooperative research programs targeted to benefit developing countries, the present study attempts to improve the information base by projecting the effects of transgenic sweetpotato technology in Kenya. Sweetpotato producers in sub-Saharan Africa are mostly small-scale and resource-poor farmers (Scott and Ewell, 1992).

A collaborative effort between the US life-sciences company Monsanto and the Kenya Agricultural Research Institute (KARI) to advance non-conventional virus resistance in sweetpotato began in 1991/92. The initial phase of the project has been cosponsored by the US Agency for International Development (USAID). A coat protein gene encoding resistance to the most important virus type had been previously available from the public sector, so the research activities of the project focused on developing effective gene constructs and plant transformation and regeneration systems for sweetpotato (cf. Wambugu, 1996). To perform these tasks and for training purposes, different KARI researchers have worked at Monsanto's St. Louis-based facilities. Reliable laboratory protocols have been obtained, and since 1997 scientists have been screening the transgenic sweetpotatoes for virus resistance. In 1998, Monsanto and KARI signed a licensing agreement for a royalty-free transfer of the technology to Africa. Kenyan field trials for the first transgenic sweetpotato are scheduled to start in 1999. The next phase of the project is sponsored through the Agricultural Research Fund (ARF), with institutional support from Monsanto, the International Service for the Acquisition of Agri-biotech Applications (ISAAA), and the International Potato Center (CIP). The ARF foresees field-testing and the subsequent release of Kenya's first virus-resistant sweetpotato variety. Since no transgenic crops have yet been commercialized in Kenya, this will also involve the development and consolidation of efficient biosafety procedures. Kenyan farmers are expected to have access to the new varieties beginning in the year 2002. Furthermore, KARI has established a plant biotransformation laboratory in Nairobi, and there are plans to transform a number of additional sweetpotato clones for virus resistance. Monsanto will provide technical assistance and will continue to work on the development of new gene constructs.

Apart from the virus resistance technology, there are different public research institutes in the USA that are developing transgenic weevil resistance in sweetpotato for use in sub-Saharan Africa. This is also a very desirable crop trait for Kenya, and based on the Monsanto/KARI project experience, the weevil resistance technology could be adapted and delivered to the national producers as soon as it becomes available. The present study analyzes the potential economic impacts of both transgenic sweetpotato virus and weevil resistance.

1.1 Conceptual Framework

Although the Monsanto/KARI biotechnology research project began in 1991/92, the virus resistance technology has not yet been released for commercial application in Kenya. The same holds true for the weevil resistance technology, which is at an even earlier stage. This means that the economic impacts of the innovations can only be anticipated by employing an *ex ante* analytical framework. For a detailed description of conceptual issues in *ex ante* biotechnology evaluation, reference is made to Qaim and von Braun (1998) and Qaim (1998). The technologies' ability to increase the yields (or avoid current yield losses) at the farm level is assessed based on interviews with 20 different sweetpotato experts. These experts included representatives from KARI, CIP, ISAAA, Monsanto, the Kenyan Ministry of Agriculture, and national universities. To increase the objectivity of the information obtained, five out of the 20 experts were not part of the virus resistance biotechnology project. The expert interviews also covered questions about the likely time-horizon for technology development and application as well as R&D cost estimates. Primary data about the current sweetpotato farming systems and input-output relations were collected from a survey of 47 farms in the five most important producing provinces of Kenya (Nyanza, Western, Central, Eastern and Coast, see Figure 3). The farm interviews were supplemented by discussions with agricultural field extension officers. The author undertook all of these surveys in late 1998. The potential effects of transgenic virus and weevil resistance on sweetpotato incomes and productivities are scrutinized by comparing crop enterprise budgets without, and hypothetically with, the use of the technologies. As geographical differences are expected, the sweetpotato farms are disaggregated into two groups—those located in the western part of Kenya and those in the Central and East. Biotechnology research impacts at the national level are projected using an economic surplus model of the Kenyan sweetpotato market with technological progress.

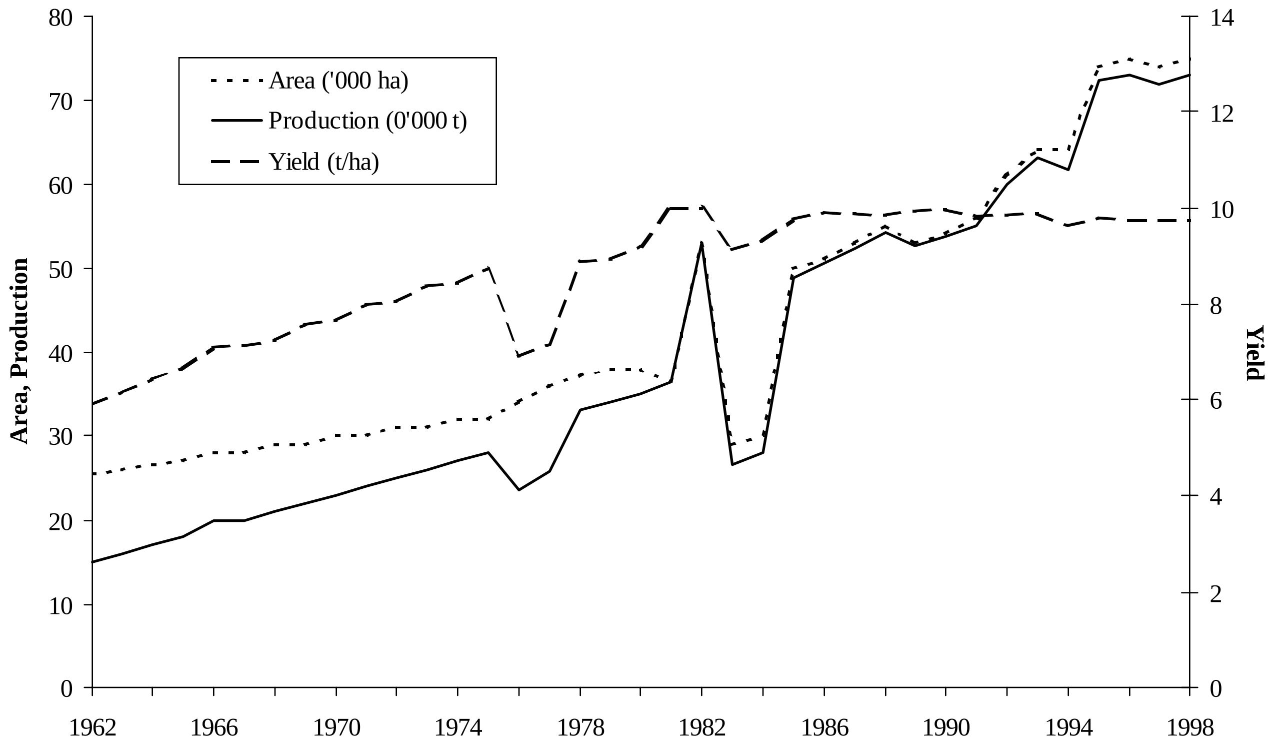
1.2 Study Overview

Chapter 2 describes the current situation of sweetpotato production and consumption in Kenya. The description partly builds on the CIP and KARI body of literature. Yet there is scarcely any published material available, especially with respect to the cost of sweetpotato production, so the enterprise budgets presented are based on the primary data collection outlined above. Chapter 3 gives a more detailed overview of the biotechnology R&D projects and the technologies' potential yield effects. The economic impact analysis is conducted in chapter 4, first at the level of the individual farm and then at the national market level. Measures for research investment returns under different project cost and benefit assumptions are also calculated. Chapter 5 concludes with some generalized policy implications.

2. The Kenyan Sweetpotato Sector

Developing countries produced almost 99 percent of the worldwide sweetpotato production of 130 million tons in 1998. The crop is predominantly a primary or secondary staple food for the world's poor, especially in rural areas. The international trade in sweetpotato is almost nil. Asia is by far the largest producing continent, and China alone accounts for more than 80 percent of the global output. Africa makes up 5 percent of the total production. Notwithstanding this comparatively small share, some sub-Saharan Africa countries—notably Burundi, Rwanda, and Uganda—are among those with the highest sweetpotato per capita consumption figures (CIP, 1996).

Figure 1: Development of sweetpotato production in Kenya (1962-1998)



Source: Based on data from FAO (1999).

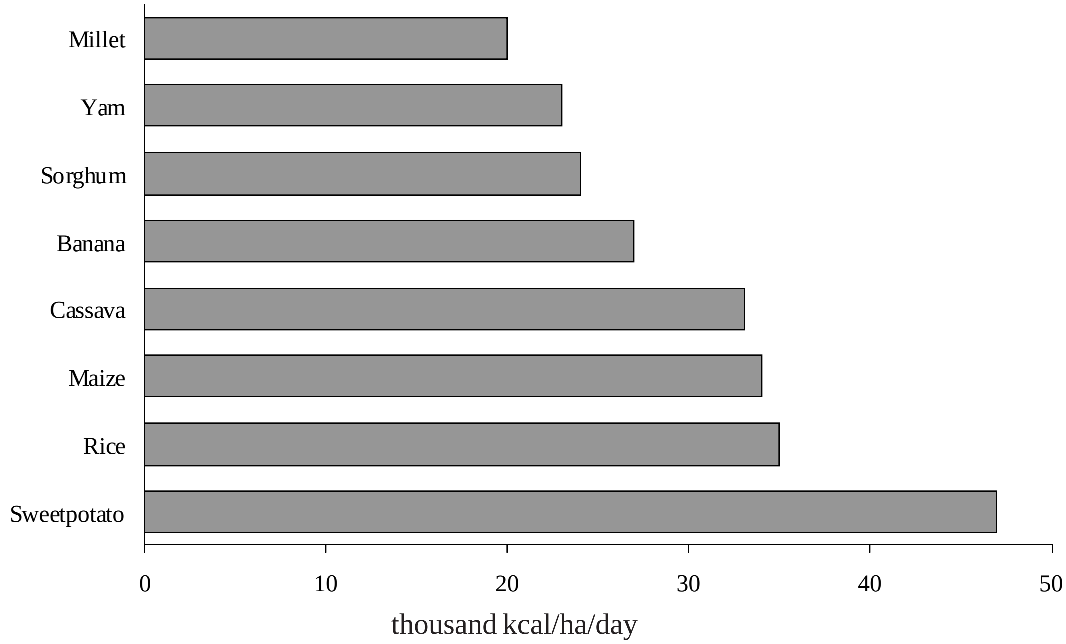
Kenya is the fourth largest sweetpotato producer in Africa. In 1998, the crop covered 75,000 hectares, or about 1.9 percent of Kenya's total arable land. As in other African countries, sweetpotato production in Kenya rose significantly during the last decades. Figure 1 shows that the production almost multiplied by a factor of 5 from 1962 to 1998.

Per unit productivity increases were relevant during the 1960s and 1970s, but since the early 1980s, the yield levels obtained in Kenya have stagnated. Compared to other food crops, national and international agricultural research institutes have given little attention to sweetpotato (Horton and Ewell, 1991). Most of the production growth is due to increases in the area under sweetpotato cultivation.[1] The main reason for the crop's rising importance is the growing population pressure on land suitable for cultivation and concomitantly declining farm sizes. In some areas the crop is now grown on more arid lands with low soil fertility. Sweetpotato is highly adaptable to marginal climatic and soil conditions.[2] On the other hand, it has also been substituted for other food crops because it yields considerably higher amounts of food energy per unit area under prevailing low-input production conditions (see Figure 2). The same holds true for a number of vitamins and micronutrients, especially the orange- and yellow-fleshed varieties (Woolfe, 1992; Low et al., 1997). Sweetpotato is well suited as a food security crop, and it would be even more so if appropriate technologies could contribute to higher yields in farmers' fields.

[1] In contrast, the area planted with sweetpotato in Asia and Latin America declined during the last decades.

[2] Given the high population growth rates and the fact that 80 percent of Kenya's land is classified as arid and semiarid (Republic of Kenya, 1997), it can be expected that the importance of sweetpotato will further rise in the future.

Figure 2: Average food energy yields of different food crops in Africa



Note: The daily kcal figures are based on average yield levels and lengths of crop cycles under African conditions.
Source: Adapted from Woolfe (1992).

2.1 Regional Production Aspects

In Kenya, sweetpotato is grown under various agroecological conditions, from the coastal lowlands to altitudes of about 2000 meters in the Central Highlands and Lake Victoria Basin. Noteworthy amounts are produced in six provinces (Nyanza, Western, Rift Valley, Eastern, Central and Coast, see Figure 3). Strikingly, according to Ministry of Agriculture statistics (MALDM, various issues), the national sweetpotato area is only half the size of the sweetpotato area stated for Kenya by the FAO (1999). Because official statistics tend to underestimate the true area under semisubsistence crops, the higher figures appear to be the more realistic ones. But since the FAO only provides statistics for the country as a whole, we multiplied the aggregate area figures by MALDM's area ratios for the individual provinces in order to derive the regional information shown in Table 1. This procedure implicitly assumes that the national statistics underestimate the sweetpotato area in all growing-provinces more or less to the same relative degree.

Sweetpotato production conditions differ by location due to distinct agroclimatic and socioeconomic factors. For the purpose of this study, Kenya is subdivided into two major sweetpotato-producing regions: the West (Nyanza and Western Provinces) and the Central/East (Rift Valley, Central, Eastern and Coast Provinces).[3] Almost 75 percent of the total sweetpotato production is concentrated in the densely populated Lake Victoria Basin in the West. This region is mostly humid or semihumid (Rees et al., 1997). Although some of the producing areas in the Central and Coast Provinces show humid conditions as well, the majority of them are classified as semiarid (Ngunjiri et al., 1993).

Because the official yield levels for the individual provinces are partly inconsistent, we decided to use the average yield figures elicited in the farm interview survey. Weighting these figures with the regions' production shares, we derive a national average of 9.8 tons per hectare. This is similar to

[3] As will be shown later, this regional approach is instructive because virus problems – and thus the potentials of the virus resistance technology – differ according to agroecological conditions.

Figure 3: Map of Kenyan provinces

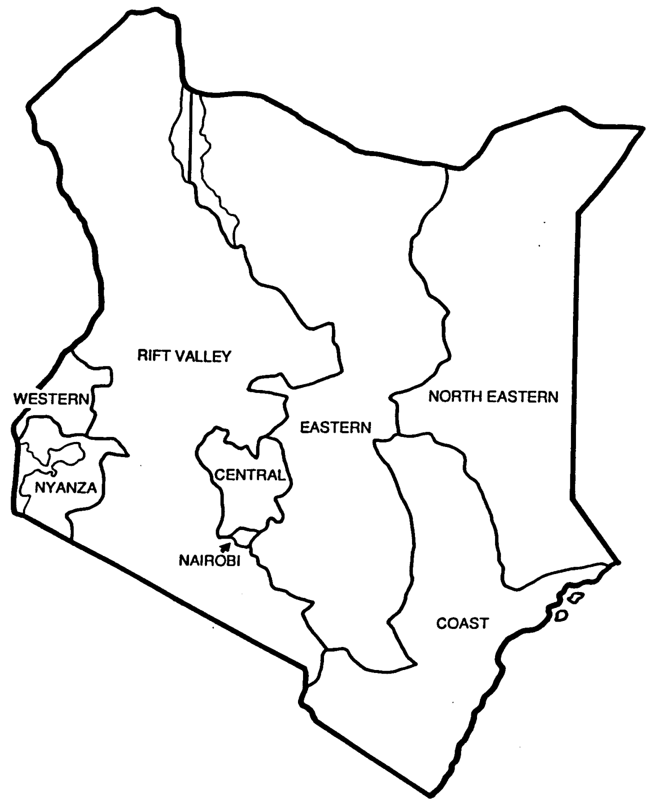


Table 1: Sweetpotato production statistics for the Kenyan provinces (1996-1998 averages)

Province	Area (ha)	Production (t)	Production share (percent)
Nyanza	35,950	362,373	49.9
Western	17,953	180,971	24.9
Total West	**53,903**	**543,344**	**74.8**
Rift Valley	3,675	32,485	4.5
Central	3,558	31,449	4.3
Eastern	12,414	109,744	15.1
Coast	1,117	9,871	1.3
Total Central and East	**20,764**	**183,549**	**25.2**
Total Kenya	**74,667**	**726,893**	**100.0**

Notes: The total area corresponds to FAO statistics, whereby the area shares of the individual provinces are taken from MALDM. The regional average per hectare yields (West: 10.08 t/ha, Central and East: 8.84 t/ha) have been obtained from the author's farm survey.
Sources: FAO (1999), MALDM (1996, 1997), and the author's interview survey (1998).

the aggregate 1996-1998 figures stated by MALDM (10.4 t/ha) and FAO (9.7 t/ha). Although Kenya's sweetpotato yields exceed the African average, they are significantly below the yield levels obtained in Asia (15 t/ha).

2.2 Sweetpotato Farming Systems

In Kenya, sweetpotato is predominantly grown on small and resource-poor farms, usually without purchased inputs. The cropping patterns of sweetpotato-producing farms typically embrace a large number of activities, including the cultivation of other staple food crops (e.g., maize, cassava, banana, etc.), fruits, vegetables, and export commodities such as tea and coffee. In addition, the majority of the farms is engaged in some form of livestock keeping. The average size of a sweetpotato-producing farm in the sample of 47 respondents is 5.7 acres.[4] The mean sweetpotato holding has a size of about 0.4 acres, with a range between 0.1 and 2.5 acres. We chose not to differentiate further between farm sizes because the production conditions on smaller and larger sweetpotato farms were found to be very similar (also see Ngunjiri and Ewell, 1992). Most of the farmers grow two sweetpotato cycles per year, the first one in the long rainy season and the second one during the short rains. Sweetpotato is commonly cultivated as a pure crop. Sometimes intercropping or relay cropping with maize and other plants is practiced.

Sweetpotato often takes the role of an insurance crop in these farming systems. As mentioned above, if offers comparatively better yields under adverse climatic conditions and low-input regimes. A significant share of the harvest is consumed directly on a subsistence basis; sweetpotato is not primarily considered a main cash earner. Still, the interviews revealed that on average around 60 percent of the farm production is sold to raise small amounts of money. The sweetpotato income is usually spent on basic items that the farm family urgently needs. Unfortunately, no previous comparable data on sweetpotato sales at the farm level are available for Kenya. Based on a review of studies that have been carried out in various sub-Saharan countries during the 1980s, Scott and Ewell (1992) estimate that the home-consumption share was probably more than 90 percent. Although it should be kept in mind that our sample size is quite small, it appears that sweetpotato commercialization increased substantially during the last decade. The main reason for a trend towards closer market integration is probably Kenya's increasing urbanization. Rising sweetpotato demand in the cities is leading to better marketing potentials for farmers. A swelling population in the cities also restricts the space available for urban agriculture in kitchen gardens, which could increase sweetpotato purchases.[5] Home-consumed shares are slightly higher in the western parts of the country as compared to the Central and East. Such regional differences are shown in Table 2.

The average size of sweetpotato-producing farms in the West is much smaller than in the Central and East. This reflects the higher population density in the Lake Victoria Basin. Although no comprehensive information on overall household incomes was collected in the farm survey, own observations and experts' statements suggest that farms in the western region are somewhat resource-poorer on average than those in the rest of the country. The superiority of sweetpotato over other crops in terms of food energy production per unit area has already been discussed. Population pressure might also partly explain the relatively higher importance of sweetpotato for farms in the West. Factors of culture and tradition, however, are probably more relevant.

Table 2: Characteristics of sweetpotato farms, by region

	Average farm size (acres)	Average sweetpotato area (acres)	Sweetpotato cycles per year	Input use [a] (percent)	Female managed [b] (percent)	Home consumption (percent)
West	5.02	0.42	2.10	5	86	41
Central and East	7.81	0.47	1.85	8	73	37

[a] This is the percentage of farmers in the sample using irrigation, farmyard manure, chemical fertilizers, or any kind of pesticide for sweetpotato production.
[b] This is the percentage of farmers who stated that sweetpotato is predominantly managed by women.
Source: Author's interview survey (1998).

[4] Although official area statistics are usually given in hectares, we use acres for the description of farming systems. This is the more common reference among farmers themselves (1 acre = 0.405 ha).

[5] This linkage has been shown, for instance, by Tardif-Douglin (1991) in Rwanda.

Table 3: Average sweetpotato production cost, by region (per acre and season)

Cost items	West		Central and East	
	Labor-days	Cost (KSh)	Labor-days	Cost (KSh)
Cost for land [a]	-	810	-	590
Plowing	5.21	438	5.86	551
Mounding/ridging	16.05	1,348	11.13	1,047
Vine preparation	4.90	412	4.88	459
Planting	4.64	390	5.50	517
Weeding	35.22	2,960	24.88	2,339
Harvesting	22.42	1,884	19.67	1,849
Other [b]	-	176	-	429
Total	**88.44**	**8,418**	**71.92**	**7,781**

Note: The average daily labor rate is 84 KSh in the West and 94 KSh in the Central and East (1 US$ = 59.7 KSh).
[a] This is the prevailing average per acre rent for a period of 6 months.
[b] Other cost items include expenditures for inputs, such as fertilizers and irrigation.
Source: Author's interview survey (1998).

Table 2 also reveals that sweetpotato is considered a women's crop by the majority of farm families. The female household members are responsible for most of the operations. Men usually assist only with land preparation. Even the monetary income from sweetpotato is often controlled by women, because smaller units of sweetpotatoes are sold continuously, whenever cash is needed to meet the basic household requirements—unlike typical cash crops, which are usually marketed in comparatively large amounts during the harvesting season. Some highly commercialized sweetpotato growers in Nyanza and Central Province, where higher levels of inputs are used and where men control the production and marketing of the crop, are exceptions to this pattern. But for Kenya as a whole, these commercial sweetpotato growers play a subordinate role.

2.3 Cost and Income Calculations

Kenyan farmers usually grow sweetpotato without any purchased inputs. But the crop is comparatively labor intensive, and under labor-scarce conditions it would be misleading to neglect this important cost component. Allocating family labor to sweetpotato reduces this household resource for other activities and imposes an opportunity cost. Hiring external labor is also not uncommon for certain operations, especially for land preparation and harvesting in some cases. Sixty-six percent of the interviewed farmers stated that they hire laborers for sweetpotato on an occasional basis. For the cost calculations, we value each labor-day at the prevailing regional rate for casual workers, regardless of whether it is family or outside labor. This procedure has also been used by Ngunjiri and Ewell (1992), which is the only previous source on the cost of sweetpotato production in Kenya. The average cost accounts are shown in Table 3 for the western and central/eastern regions. The calculations refer to one crop cycle (about 6 months) on a per acre basis. Although sweetpotatoes are cultivated on plots that are usually smaller than one acre, we chose this benchmark for comparative purposes. Farmers' statements have been linearly extrapolated, which is justified given the absence of operations with significant scale effects. The individual operations are explained in greater detail in the following paragraphs.

Land for sweetpotato cultivation is rarely hired. Nevertheless, the average regional rent is imposed in the cost budgets to approximate the foregone benefit from cultivating other crops. Given the higher population pressure in the West, it is not surprising that the price for land is higher there than it is in the Central and East. On the other hand, relative labor scarcity is more salient in the Central and East, which the higher wage rate in this region reflects. Plowing is done either by hand or by animal traction. In some cases the soil is plowed more than once before planting. Rarely, no plowing at all is carried out, especially on light and sandy soils. Eighty-three percent of the interviewees reported that they cultivate sweetpotatoes on mounds or ridges. The preparation and maintenance of mounds and ridges is labor-intensive, but it provides better growing conditions for the roots, and farmers know that the additional labor cost is usually rewarded by higher average yields. Those respondents who grow the crop on flat ground stated that the main reason they do so was labor shortage. The prevalence of farmers cultivating sweetpotato on flat land is somewhat higher in the Central and East.

Farmers predominantly plant sweetpotato at the beginning of the rainy season, usually cultivating more than one sweetpotato variety. Sometimes they use a number of different varieties even on a single plot. Important variety characteristics are yield performance, high dry matter content (closely related to the taste of the roots), the time period needed for the crop to mature, and the amount of foliage production. Farmers' preferences and the local suitability of certain cultivars are fairly diverse. Even for a single farmer the preferences are often not easily defined. Various respondents, for instance, said that they like early maturing varieties because they can earn some cash before other crops are harvested, while they choose late-maturing varieties for subsistence consumption. Kenyan farmers are growing a wide range of sweetpotato varieties, many of which have not yet been unambiguously characterized by researchers (CIP, 1991).

Vine cuttings are used as planting material. They are usually obtained from farmers' own stocks and preserved over the dry spell in moist and shaded areas. Before planting, cuttings that show visible signs of pest or disease infection are often sorted out. When farmers want to test new varieties, or when their own supplies are scarce, neighbors supply planting material free of charge. In drought years, when many growers run out of their own material, cuttings sometimes have to be bought on local markets, where supplies from other regions are marketed. Whenever outside sources of sweetpotato vines are used, the exchanged amounts are small (e.g., a handful). They need to be multiplied first to obtain enough material for establishing a whole plot. This crop delay affects the magnitude and timing of income flows. Additionally, pest and disease problems can become more severe in these instances, because proper vine selection is disregarded due to the lack of time to obtain enough healthy material. The scarcity of planting material in dry years is considered a serious constraint in Kenya and in other countries of sub-Saharan Africa (e.g., Bashaasha et al., 1995; Kapinga et al., 1995). Once enough cuttings have been obtained, planting is carried out manually. The average labor requirements for vine preparation and for planting are shown in Table 3.

Weeding is predominantly done once per crop season with a hand hoe. This is a time-consuming task because special care has to be taken not to hurt the emerging sweetpotato storage roots. To control pest problems, it is also important that the roots remain covered with soil. If labor availability permits, a second weeding procedure is carried out later during the season, when weeds are uprooted manually. This operation often includes the maintenance of mounds or ridges for optimal plant development. Significantly more labor is allocated to weeding in the West than in the Central and East.

Except for very few farmers who apply fertilizers or irrigation to sweetpotatoes, no other production costs arise before the roots are harvested. Almost 90 percent of the sampled farms perform harvesting in a piecemeal fashion. Only the amounts needed immediately for their own consumption or for sales are harvested. Thus, harvesting can continue for a period of several months, starting when the first roots are mature (about three months after planting) up until the plot is needed for the next crop. The main reason for this practice is the in-ground storage function. Sweetpotato is a perishable commodity, and in the absence of appropriate alternative storage techniques postharvest losses can be high (Smit, 1997). Because sweetpotato is rarely processed in Kenya, piecemeal harvesting is the only way to conserve the commodity until it is consumed. Casual laborers are often hired when larger amounts of sweetpotatoes are harvested for outside transactions.

The total average amount of labor allocated to growing sweetpotato is 23 percent higher in the West than in the Central and East. It is hypothesized that the more intensive production practices in the Lake Victoria Basin are mainly due to the higher population pressure in this region. Because of the lower wage rate, however, the per acre production cost in the West is only slightly above the cost in other parts of the country. Given the higher yield levels, the western producers are economically somewhat more efficient than their counterparts in the Central and East, as is demonstrated by the per unit cost of production (see Table 4). Interestingly, the situation would be vice versa under the assumption of an equal wage rate for both

Table 4: Average sweetpotato enterprise budgets, by region (per acre and season)

	West	Central and East
Production cost (KSh)	8,418	7,781
Yield (t)	4.08	3.58
Farm-gate price (KSh/t)	5,885	5,885
Gross revenue (KSh)	24,016	21,073
Net income (KSh)	15,599	13,292
Per unit cost (KSh/t)	2,063	2,173

Note: 1 US$ = 59.7 KSh.
Source: Author's interview survey (1998).

regions. The gross revenues from sweetpotato production have been obtained by multiplying the root yields by the average farm-gate price.[6] Most farmers use sweetpotato vines and foliage as animal feed, but the amounts are difficult to estimate since this occurs over an extended period of time during piecemeal harvesting. The value of this crop by-product is disregarded in the calculations. The per acre net incomes are also shown in Table 4. Compared with the Central and East, average sweetpotato incomes are 17 percent higher for farms in the West.

2.4 Sweetpotato Marketing and Consumption

Although Kenyan farmers market substantial amounts of sweetpotatoes, for most of them commercialization is not the main reason for growing the crop. Selling sweetpotatoes is often a spontaneous decision made by households whenever cash is needed, and the marketing channels are rather informal. Sixty-four percent of the farmers stated that they sell sweetpotatoes directly at the farm-gate, when traders come to pick up the produce. But these traders come in irregular intervals, and when they are not available farmers have to transport their sweetpotatoes to the local market. In remote locations, where farmers commercialize only small amounts of sweetpotatoes, transporting the crop as a head-load to the nearest village is usually the only marketing option. This is either done by female household members or by laborers hired for this purpose.[7] In the villages, farmers themselves often retail the sweetpotatoes, but roadside dealings with middlemen, who transport the commodity to urban markets, are also common. The bulky, perishable nature of sweetpotato and the irregularity of sales increase the transportation and transaction costs for middlemen. This often makes the urban retail price for fresh roots a multiple of the price observed in rural areas. Unfortunately, no data were found on domestic sweetpotato trade between deficient and surplus areas in Kenya. It is striking that the mean adjusted farm-gate prices derived from the survey were almost identical for the western and the central and eastern regions. This indicates that there are efficient arbitrage transactions, and that it is appropriate to consider the Kenyan sweetpotato market as a fairly integrated one. International trade with sweetpotatoes is not reported for Kenya (FAO, 1999).

In terms of annual per capita consumption of sweetpotatoes, Kenya—with 21 kilograms—ranks fifth among the African countries after Burundi, Rwanda, Uganda, and Madagascar (CIP, 1996). It is considered a secondary food crop in Kenya, where the primary staple foods are grains, particularly maize and wheat. Due to the semisubsistent production patterns of sweetpotato, consumption figures are expected to be significantly higher in rural than in urban areas. Still, Omosa (1997) found that over 90 percent of households in major cities also consume fresh sweetpotatoes at least once per week. Moreover, a stratification of consumers according to income levels did not reveal a clear trend. Whereas in Nairobi richer households consume sweetpotatoes more often than poorer ones, in Kisumu it is the other way around. Bashaasha and Mwanga (1992) reported that in Uganda sweetpotato has a low but positive income elasticity. In Kenya, demand elasticity estimates are not available. Aggregating over rural and urban demand, it is presumed that sweetpotato in Kenya is slightly inferior or has an income elasticity close to zero. The parameter could increase if new ways of processing the storage roots (e.g., to flour) were introduced. With respect to sweetpotato prices, Omosa's study (1997) revealed that the retail price level is inversely correlated with consumption for

[6] The farm survey rendered an average farm-gate price of 5898 KSh/t in the West, and 5848 KSh/t in the Central and East. This is not a statistically significant variance so that a weighted national mean of 5885 KSh/t has been used in the calculations.

[7] For the analysis, all prices stated by the interview respondents for the point of first sale were adjusted to the farm-gate.

the majority of households. This suggests that the aggregate price elasticity of demand is negative and significantly different from zero. Taking these considerations into account, we assume a price coefficient of –0.4 for sweetpotato demand in Kenya.

2.5 Phytosanitary Problems

Although sweetpotato can withstand adverse growing conditions much better than most other plant species cultivated for human consumption, there are certain pests and diseases that seriously affect the crop and its yield performance. World-wide, the most important phytosanitary problems are sweetpotato weevils (*Cylas* spp.) and, particularly in sub-Saharan Africa, different types of viruses (Ames et al., 1997; CIP, 1995).

In Kenya, the weevil is the single most important biotic production constraint (Smit, 1997; Ngunjiri et al., 1993). Weevil-induced crop losses on individual fields can reach over 80 percent. Interviewed experts estimate that the national average yield reduction caused by the pest in Kenya is 20 percent. The ant-like adults feed on the sweetpotato foliage and on the storage roots. The insect is particularly active under drier conditions. Because Kenyan farmers practice piecemeal harvesting, the storage roots remain in the ground for some time during the dry spell, and so they are especially vulnerable to weevil damage. On the other hand, harvesting the whole plot at maturity would lead to higher postharvest storage losses. More detailed studies have not been carried out so far. Although one might expect higher crop losses in the drier central and eastern region, the researchers and extensionists consistently stated that the weevil problem is at least as important in the West. It could be that the initial weevil population is higher in the Lake Victoria Basin because of more widespread sweetpotato cultivation. Furthermore, farmers in the drier zones might use better adapted management practices (e.g., harvesting dates) because they are aware of the greater potential severity of the pest (E. Carey, personal communication). For our analysis, it is assumed that the current weevil-caused yield loss is on average 20 percent in both regions. There is no effective method to combat this pest. However, in addition to appropriately timing dates for planting and harvesting, crop rotation and the use of varieties with deep storage roots can reduce the problem. The level of natural resistance found in the sweetpotato germplasm is fairly low, limiting the success of conventional resistance breeding (Zhang et al., 1998; Collins and Mendoza, 1991).

The most widespread sweetpotato virus in Kenya is the sweetpotato feathery mottle virus (SPFMV) (Wambugu, 1991). A member of the *Potyviridae* family, it is transmitted by a range of different aphid species. The virus often only manifests itself in mild leaf symptoms. Although economic losses have been noted in certain varieties, SPFMV alone is not considered a severe production constraint. In interaction, however, with the whitefly-transmitted sweetpotato chlorotic stunt virus (SPCSV, family *Closteroviridae*), it forms the sweetpotato virus disease (SPVD) complex, the most important sweetpotato disease in Kenya and other countries of sub-Saharan Africa (Geddes, 1990).[8] Many farmers do not explicitly recognize viruses as a problem. Although SPVD shows obvious symptoms, these symptoms are often misinterpreted as direct insect damage. The significance of SPVD varies according to agroecological zone. A moist and warm environment promotes the incidence of insect vectors, so the virus pressure is more severe in the Lake Victoria Basin than it is in the drier areas of the Central and East. Apart from insect transmission, the virus is also dispersed through infected sweetpotato vines. Transmission through insects is called primary infection; dispersal through unhealthy planting material is called secondary infection. Both types occur in the small-scale and semisubsistent growing conditions of sweetpotato in Kenya.

Virus control is impossible once the plant has been infected, and the use of chemical measures against the insect vectors is not economically feasible. Yield reductions caused by SPVD can be devastating. The disease can lead to complete crop destruction on severely infected plots grown with susceptible varieties (Karyeija et al., 1998). The actual average yield losses in farmers' fields are much lower, which is probably attributable to two factors (cf. Gibson et al., 1997): First, farmers commonly

[8] SPCSV in the absence of SPFMV is also not considered a severe constraint.

select healthy looking vines for planting, and so likely sort out SPVD infected material due to the clearly visible symptoms. Second, a fairly high degree of natural resistance to virus diseases occurs in some sweetpotato landraces. Although farmers' knowledge about viruses is generally low, it is expected that virus resistance is implicitly one of the main variety selection criteria in affected areas. Virus degeneration presumably also contributes to the comparatively rapid replacement of certain sweetpotato varieties in Africa. For Kenya, exact information about actual virus-induced yield losses is not available. The interviewed experts estimate regional average yield reductions of 12-15 percent in the West and of 7-10 percent in the Central and East. In addition to the direct yield reductions, there is another point that needs to be considered when assessing the economic importance of sweetpotato viruses. The agronomic trait of natural virus resistance is often negatively correlated with the genetic yield potential of a sweetpotato clone (Aritua et al., 1998b), and so in high virus pressure areas an indirect loss occurs when farmers obtain reduced output growing lower-yielding resistant varieties instead of higher-yielding susceptible varieties.

Except for sweetpotato weevils and viruses, other biotic stress factors are of minor aggregate importance in Kenya. Locally, however, vertebrate pests – such as monkeys, moles, rats, and porcupines – can also be serious obstacles to sweetpotato production.

3. The Transgenic Resistance Technologies

This study seeks to analyze the potential impacts of two different sweetpotato biotechnologies: transgenic virus resistance and transgenic weevil resistance. Although the Kenyan government has identified biotechnology as a priority for combating national food deficit problems, the country is still in the first stages of development in terms of biotechnological research (Wafula and Falconi, 1998). Hardly any work related to crop genetic engineering has been carried out so far. The initial sweetpotato virus resistance project, therefore, has a strong capacity-building component, in addition to the merits of the resulting technology product itself. We first describe the collaborative research projects on virus and weevil resistance (see section 3.1) and then discuss the technologies' potentials and risks.

3.1 The Biotechnology Research Projects

3.1.1 Virus Resistance

Monsanto and KARI launched the sweetpotato virus resistance project in 1991/92. In the initial phase, some financial support was provided by USAID, which also contributed to the project through its extensive experience in Africa. The initiative also benefited from the coordinating efforts of the University of Missouri. The project's main objectives are twofold. First, it aims to develop effective sweetpotato virus resistance technology. Second, it seeks to transfer this technology to Kenya—and eventually to other African countries—to benefit sweetpotato producers and consumers, as well as biotechnology capacity-building in the National Agricultural Research System (NARS).

The viral coat protein gene conferring resistance to SPFMV was available from the public sector. It had been previously isolated by scientists at North Carolina State University and cloned in collaboration with CIP and the Scripps Institute in the USA (Wambugu, 1996). It is expected that the SPVD complex can be controlled by expressing SPFMV resistance in sweetpotato, (see also discussion in sections 2.5 and 3.2). The project still needed a transferable gene construct containing the coat protein gene, and effective sweetpotato transformation and regeneration systems. As part of the collaborative strategy, a postdoctoral scientist from KARI worked with the project from 1992 to 1994 in Monsanto's St. Louis-based laboratories. The gene construct was developed incorporating marker and promoter genes patented by Monsanto. After 1994, several other KARI scientists—partly funded by the ISAAA Biotechnology Fellowship Program—were also sent to Monsanto for training and to consolidate the sweetpotato technology. One USAID-sponsored Kenyan scholar doing project-related research is also absolving a Ph.D. program at the University of Missouri. An American postdoctoral fellow was sent through USAID's Agricultural

Biotechnology Support Project (ABSP) to work with the project team at Monsanto. Crop transformation was conducted using *Agrobacterium tumefaciens*, and successful expression of the viral coat protein has so far been achieved in two different sweetpotato lines (CPT-560 and Jewel).Virus tests with American SPFM strains showed a statistically significant resistance in both lines (Hinchee, 1998). In 1998/99 protection studies have also been carried out with African virus strains, revealing similar resistance levels.

To date, all research has been carried out in the USA, but preparatory activities for the technology transfer have also been started in Kenya.Tissue culture capability for sweetpotato, which is important for the regeneration and rapid multiplication of transgenic plants, is already available at KARI. The facilities at KARI's National Agricultural Research Laboratory (NARL) have been completely refurbished with support from the World Bank, and they are now fitted for plant transformation and other biotechnology activities.Scheduled for 1999, CPT-560 will be the first transgenic virus-resistant sweetpotato clone transferred to Kenya.[9] Genetically engineered livestock vaccines are already being tested in Kenya, but the sweetpotatoes will be the first transgenic crops to be field released in the country.Developing efficient biosafety regulations, therefore, is an integral part of the project. ISAAA assisted with this effort by making its experience available through extensive consultations and the organization of a workshop on risk assessment (Wambugu et al.,1995).

In 1998, mock trials were carried out with conventional CPT-560 and a number of locally used sweetpotato varieties at five different on-station sites in Kenya. The main objectives of these trials were to familiarize KARI staff members with general trial procedures and to evaluate the performance and economic importance of CPT-560. Preliminary results indicate that the nontransformed clone is susceptible to viruses but has an outstanding yield performance in low virus-pressure areas. Its consumer acceptance is moderate (KARI, 1999). Transgenic trials will begin in 1999 at the same five sites. At least three cycles of on-station trials will be carried out, so that—if successful—the first on-farm tests could take place in the year 2001. Assuming simultaneous bulking of planting material, KARI could officially release transgenic CPT-560 for commercial application in 2002, followed by more widespread technology dissemination to farmers in subsequent years.

A new project phase was launched in 1999, sponsored through the Agricultural Research Fund (ARF), which is administered by the World Bank. It is a direct continuation of the Monsanto/KARI initiative, and apart from these organizations it explicitly involves CIP for institutional and research collaboration and ISAAA for project facilitation. The main objective of this new phase is to establish and strengthen Kenya's sweetpotato biotechnology capacity, which includes research, biosafety institution-building, and effective dissemination to resource-poor farmers. Crop transformation of popular Kenyan varieties for virus resistance will be performed at NARL in close interaction with Monsanto researchers. It is important to extend the list of transformed clones in order to satisfy the diverse varietal preferences of sweetpotato producers and consumers. Monsanto will continue its in-house sweetpotato research by developing new transferable gene constructs for virus resistance to steadily improve the quality of the technology product.To commercialize the additional bioengineered varieties, the same biosafety procedure as mentioned above for transgenic CPT-560 will be applied.

Concerning intellectual property rights (IPRs), Monsanto and KARI signed a nonexclusive, royalty-free licensing agreement in 1998. The agreement allows KARI to use and further develop the transgenic virus resistance technology in sweetpotato. KARI is also permitted to protect the resulting transgenic varieties under the plant breeders' rights convention or similar regulations effective in Kenya.Additionally, the technology may be transferred to any other country in Africa. Given these contractual arrangements, Monsanto's own interests in the project are not apparent at first sight, but it is expected that the company's incentives include the following:

- Recognizing biotechnology's promising potentials for the developing world, Monsanto

[9] Jewel is an American clone that is not well adapted to African conditions.

wanted to share its research progress with Africa as humanitarian aid. The public is still strongly skeptical about biotechnology, so the project could improve the image of biotechnology in general and of the company in particular.

- Taking sweetpotato as a model species offered the advantage of directly targeting R&D efforts to the poor, who dominate the crop's production and consumption. Because Monsanto is not commercially interested in sweetpotato, the collaborative project does not contradict its own business activities.
- The demand for seed technology in Africa is expected to increase tremendously in the future. The project's partnership with KARI and other organizations active in the region offers Monsanto a unique opportunity to gain valuable experiences for prospective business ventures and contribute to establishing an institutional network.

3.1.2 Weevil Resistance

The research on sweetpotato weevil resistance is not a single project, and there are different efforts underway. The University of Missouri, for instance, recently started a research project in collaboration with KARI, CIP, and Monsanto. Tuskegee University has launched another initiative. A number of different *Bacillus thuringiensis* (*Bt*) genes are available, mostly patented by the private sector, and *Bt*-based insect resistance is already used commercially in a number of crops and countries (cf. Krattiger, 1997). The available *Bt* strains of different companies are screened to identify those that produce toxins against the African weevil species. Once the appropriate genes for weevil resistance have been found, they are introduced to superior African sweetpotato varieties. In this study, we consider the two technologies—virus resistance and weevil resistance—independently of each other because the virus resistance project has advanced much further than the research on weevil resistance. Forecasts of when the first transgenic weevil-resistant variety will be released in Kenya or another African country cannot yet be reliably made. It is expected that the development time could be comparatively short (possibly only 5 years), thanks to the sweetpotato biotechnology capacity gained within the virus resistance project and the already extensive experience with *Bt*-technology.

3.2 Agronomic Technology Potentials

Increasing the yield levels currently obtained by Kenya's sweetpotato growers will be the main agronomic effect of the virus and weevil resistance technologies. It is expected that the damage caused by the SPVD complex can be controlled through transgenic resistance to SPFMV alone (also see section 2.5), but this can only be determined through field tests. The probability of success is fairly high because SPVD has never been identified in the absence of SPFMV, and the typical, potyvirus disease symptoms even suggest that SPFMV dominates within the complex (Karyeija et al., 1998). On the other hand, coat protein technology does not confer absolute virus immunity, so some small level of infection will persist. The remaining SPFMV titer is too low to cause direct damage, but it is unclear whether it could interact with SPCSV to form the virus complex. Aritua et al. (1998a) even presume that infection with SPCSV might cause a loss of resistance to SPFMV. But this hypothesis is based on the surveillance of clones that are naturally resistant to SPFMV. Because the natural resistance mechanism is different from the coat protein-mediated one, this observation cannot simply be transferred to the transgenic technology. In *ex ante* analyses used as guidelines for deciding whether or not to start with a certain research project, such uncertainty about the research success is usually accounted for with the help of probability functions (e.g. Mills, 1997). In our case, however, the research project is already underway. Should the resistance performance prove unsatisfactory in the first run, investigations would continue to amend the technology's effectiveness. Besides new gene constructs based on the SPFMV coat protein, this could also include work on the identification of genes responsible for resistance to SPCSV. Rather than being a question of success or failure, the uncertainty is a matter of possible extended research costs and time lags. This should be kept in mind in regards to the sensitivity analysis of the results.

It was argued in section 2.5 that viruses cause an indirect loss because some higher yielding sweetpotato clones cannot be used in high virus pressure locations due to their susceptibility to disease. In fact, nearly all introduced exotic varieties that outyielded local varieties under low virus pressure conditions succumbed to the disease in locations where virus pressure was more severe

(Carey et al., 1997). In addition to the currently observed direct yield reductions, therefore, the option of endowing some promising exotic clones with transgenic virus resistance in the future has to be accounted for in assessing agronomic technology potentials. The estimated yield gains attributable to the virus resistance technology at the farm level are shown in Table 5. The percentage figures reflect that virus pressure is higher in the western parts of the country and low to moderate in the Central and East of Kenya.[10]

In the recent past, conventional breeding programs in sub-Saharan Africa have also created high-yielding sweetpotato varieties with a satisfactory degree of genetic virus resistance. Although it might be easier with recombinant techniques to endow acceptable clones with the additional trait of virus resistance, a transgenic breeding approach should not be seen as a substitute for the conventional one. Eventually, measures of cost-effectiveness will determine the appropriate toolbox for achieving certain breeding objectives. An alternative to genetic virus resistance would be establishing a more sophisticated system to distribute certified and pathogen-free sweetpotato planting material. Although primary virus infection via insect transmission could still occur, a more widespread use of healthy vine cuttings would certainly reduce secondary virus infection. Yet building up and maintaining a system in which all small-scale farmers regularly purchase clean sweetpotato planting material would be much more demanding than introducing durable genetic resistance that farmers could reproduce themselves.

Table 5: Potential yield gains of sweetpotato virus and weevil resistance technologies, by region (percent)

Region	West	Central and East
Virus resistance	20	12
Weevil resistance	25	25

Note: The figures are farm level estimates for plots where technology application is assumed. They take into account the average regional pathogen pressure, and the percentage gains refer to the current yields obtained without the use of the technology.
Source: Author's calculations based on interviews with 20 sweetpotato experts (cf. section 1.1) supplemented by literature sources indicated in the text.

The potential yield gains of the weevil resistance technology are also shown in Table 5. The percentage figures are translations from the aforementioned economic losses induced by weevils. Weevil problems are severe in all sweetpotato-producing regions of Kenya, so it is expected that the weevil resistance technology would offer the same agronomic potential in both the West and Central/East regions. As argued before, using recombinant techniques for the weevil resistance trait is particularly appealing because there are no known resistance genes in sweetpotato or its wild relatives for conventional breeding programs.

3.3 Technology-Inherent Risks

Arguments about the risks associated with bioengineered organisms are dominating the international biotechnology debate. Although this study focuses on the benefits of transgenic sweetpotatoes, a comprehensive economic evaluation must also take into account possible negative externalities for the environment and for human health.

Crop transformation in sweetpotato is conducted directly with desired varieties so that further crop improvement through conventional breeding is unnecessary. Any unexpected plant characteristics or phenotypic aberrations resulting from genetic interactions within the plant genome would be recognized at the primary transformant stage, and no such abnormalities have been reported in the transformation process for virus resistance. But the possible interactions with the environment of bioengineered plants or introduced transgenes can often only be assessed through direct observations in field tests. To date, no field trials of genetically engineered virus or weevil-resistant sweetpotatoes have been carried out. The given statements are based on expert interviews and on previous experience with other transgenic plants. Risk elements of the sweetpotato virus and weevil resistance technologies include the following:

- The first obvious risk of transgenic plants is the possible outcrossing of the transgenes into the environment (vertical gene transfer). Such outcrossing can occur through the transmission of pollen from a bioengineered domestic plant

[10] More distinct yield gains could be expected in parts of Uganda, Rwanda, and Burundi, where virus pressure is still higher than in western Kenya.

to a related wild species. Sweetpotato is thought to have originated from Central and South America (CIP, 1996), so East Africa is not a center of genetic diversity for the crop. Nonetheless, there are some wild flowers (e.g., morning glory) in Kenya that are naturally crossable with sweetpotato. The interviewed researchers stated that such crossings could occur but would not result in fertile progeny. A further spread of the transgenes into the environment would thus be prevented.

- Possible human health risks also need to be examined. Although little specific information on transgenic sweetpotato is yet available, the likelihood that the considered technologies might cause adverse health implications is very low. The SPFMV coat protein genes used for transformation are part of the viral genome itself. Humans consume them whenever they eat virus-infected sweetpotatoes. Regarding the other genes used in the gene constructs (e.g., promoter and marker genes) considerable foodsafety information has been obtained through other technology products that have already been released for commercial use in North America. The Food and Drug Administration (FDA), which is the responsible authority for foodsafety issues in the USA, has deregulated all constituent parts of the gene constructs used for virus resistance. The gene constructs for the *Bt* technology have not yet been developed, but they will build upon proven and tested gene sequences as well.
- Another risk applicable to all biotic resistance technologies is that pathogen populations could overcome transgenic resistance mechanisms. Although this would not have detrimental effects for the environment or for human health, it would diminish the effectiveness of the innovations. Both technologies are based on single gene resistances, a strategy that usually lowers the likelihood of long durability. Little related evidence is available regarding coat protein-mediated virus resistance, but the possibility of *Bt* technology breaking down has been extensively discussed in the literature (e.g., Krattiger, 1997). It is hypothesized that the African sweetpotato production systems would enable comparatively long effectiveness. Small-scale farmers usually grow different varieties on adjacent fields, or sometimes even on a single plot. Consequently, there will always be sufficient nontransgenic refuge areas nearby to reduce the selection pressure for resistance development in pathogen populations. In respect to the weevil resistance technology, other insecticidal proteins, such as protease inhibitors (cf. Zhang et al., 1998), have already been identified and could be used in combination with *Bt* to broaden the spectrum of protection for the long run.
- *Bt* toxins are generally considered innocuous for predator insects and other nontarget organisms but they are very specific to their target pests. Still, little experience has yet been gained with transgenic *Bt* technology in the tropics, where insect-toxin linkages might be different than in other agroclimatic regions. Furthermore, the long-term effects of insect-resistant plants on natural food chains are not yet well understood (e.g., Losey et al., 1999; Sianesi and Ulph, 1998). Although negative environmental consequences due to weevil-resistant sweetpotatoes are not expected, appropriate risk studies of the transgenic varieties need to be carried out within pre- and post-approval trials. Sweetpotato weevils cannot effectively be controlled by chemical insecticides, but, in general, the environmental impacts of transgenic insect resistance should be compared with conventional methods for pest control that are often associated with much more severe negative externalities (cf. Schuler et al., 1999).
- A particular risk of the virus resistance technology is that novel viruses could be created through transgenic recombination. Theoretically, when using viral coat proteins for resistance, there is the possibility that the transgenes could interact with other virus types contaminating the plant. Known as heteroencapsidation, this can lead to the emergence of new virus strains that are more aggressive than the existing ones (cf. Tepfer, 1993). But heteroencapsidation is not confined to transgenic crops. The recombination of different viruses infecting a conventional plant could occur in just the same way, and there is no evidence that transgenic recombination would occur with increased frequency. Moreover, while heteroencapsidation has been demonstrated in highly unnatural in vitro conditions, it has rarely been observed in nature (Kendall et al., 1997).

In summarizing, it can be presumed that the risks associated with the two sweetpotato biotechnologies are rather low. Conclusive statements, however, cannot be made prior to the transgenic field trials. In any case, the safe use of biotechnology requires a sound biosafety regulatory framework. In Kenya, this still needs to be consolidated. Efforts to establish and adjust efficient guidelines at the institutional and national levels are already underway (Thitai et al., 1998), and the sweetpotato biotechnology developments—particularly the initial KARI/Monsanto virus resistance project—will further contribute to relevant capacity building.

4. Potential Technology Benefits and Costs

4.1 Methodology

This chapter attempts to analyze the benefits and costs of the sweetpotato biotechnologies in quantitative terms. Potential benefits of the technologies are assessed by means of a partial equilibrium model of the Kenyan sweetpotato market. This is the standard procedure for modeling technological progress associated with specific commodities (Alston et al., 1995). Nevertheless, it should be mentioned that economic surplus measures in a partial equilibrium setting only capture the direct and immediate benefits of a technology for producers and consumers. Indirect effects and spillovers to other markets are disregarded. For the biotechnology projects analyzed such indirect effects could include:

- Long-term benefits associated with project-related capacity- and institution-building. The transgenic virus-resistant sweetpotatoes 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 sizable. 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 sweetpotato and other crops.
- Technology-related productivity gains lead to increasing purchasing power and thus to rising consumer demand for food and nonfood 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 linkages to growth from 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 technological effects in the Kenyan sweetpotato sector. It should be kept in mind, however, that the welfare gains identified through the modeling approach will undervalue the true long-term benefits of the biotechnology projects.

4.1.1 The Model

Qaim (1999) applied an economic surplus model to investigate the impact of banana biotechnology in Kenya. This model is based on linear functions of supply and demand in an economy without international trade. It is assumed that innovation causes the supply curve to shift downwards in a parallel fashion. In order to analyze the technology's likely distribution effects, the national supply curve has been disaggregated into the supply curves of producer groups with different farm sizes. Furthermore, the downward sloping market demand curve has been supplemented by a vertical demand curve for home consumption. Neglecting home-consumed shares would underestimate benefits to producers and overestimate benefits to market consumers for technologies related to a semisubsistence crop (cf. Hayami and Herdt, 1977; Norton et al., 1987). We apply the same model to the Kenyan sweetpotato market. But instead of analyzing distribution effects between different farm sizes, the supply disaggregation is used in a geographical sense: it is differentiated between the sweetpotato producers in the West and those in the Central and East of Kenya. All producers are facing the same market demand curve, so there is only a single equilibrium price. As seen in section 2.4, spatial market integration is fairly close.

The changes in consumer surplus (*CS*) and producer surplus (*PS*) for farmers in region *i* are defined as follows (Qaim, 1999):

$$\Delta CS = -p \cdot q_d \cdot \frac{dp}{p} \cdot \left(1 + 0.5 \cdot \varepsilon_d \cdot \frac{dp}{p}\right) - \left(-dp \cdot q_d \cdot \sum_{i=1}^{n} \left(h_i \cdot ss_i\right)\right) \tag{1}$$

$$\Delta PS_i = p \cdot q_{s,i} \cdot \left(\frac{dp}{p} + K_i\right) \cdot \left(1 + 0.5 \cdot \varepsilon_{s.i} \cdot \left(\frac{dp}{p} + K_i\right)\right) + \left(-dp \cdot q_{s,i} \cdot h_i\right) \tag{2}$$

where p is the equilibrium price, q_d is the total quantity demanded (market plus home-consumed) and $q_{s,i}$ is the total quantity produced by farmers in region i. ss_i is region i's production share and h_i is the average proportion of home consumption. ε_d and ε_s are the price elasticities of demand and supply, respectively. The technology downward shift factor K for producers in region i in a given year t is defined as:

$$K_{i,t} = C_{i,pot} \cdot A_{i,t} \tag{3}$$

with C_{pot} the region-specific potential per unit cost reduction through the transgenic sweetpotato varieties, and A the region- and time-specific technology adoption rate.

This model is applied independently for the two different technologies considered. It is run for a 16-year period, beginning with the release of the respective technology. 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 gradually extended. But technological obsolescence might occur through possible resistance breaking (see section 3.3) 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 far in the future from changing the model results significantly. The possibility that pathogens could overcome the resistance mechanisms before the end of the 16-year period is taken into account in the sensitivity analysis.

4.1.2 The Data

The data needed to run the described economic surplus model with biotechnological progress can be subdivided into two categories. First, the technology-related data, i.e., the per unit cost reduction, and the technology adoption rate. These two parameters are discussed in sections 4.2 and 4.3, respectively. Second, the sweetpotato market-related data, particularly the equilibrium quantities, prices, and price elasticity coefficients. The quantity and price figures have already been discussed above. They refer to 1998. Yet, due to population growth, it is expected that the overall sweetpotato demand curve (market purchases plus home-consumed shares) will shift rightward over time (cf. Norton et al., 1987). The annual exogenous shift in demand is assumed to be 2.6 percent, which corresponds to the contemporary population growth rates in Kenya (World Bank, 1999). Significant per capita income growth is not expected for the period under consideration. Given that the income elasticity of sweetpotato consumption is assumed to be near zero, rising purchasing power would hardly influence the demand side anyway. Price elasticities of demand and supply in Kenya could not be found for sweetpotatoes or other root and tuber crops. It was argued in section 2.4 that a price demand parameter of –0.4 would be a reasonable appraisal. On the supply side, Bashaasha and Mwanga (1992) estimated a price responsiveness of 0.3 for sweetpotatoes in Uganda. We assume the same value for the growers in Kenya. Production systems are similar in the West and the Central and East, so there is no reason to expect that the price elasticity of supply would differ significantly between the regions. The region-specific production shares and home-consumed sweetpotato proportions were presented earlier.

4.2 Cost and Income Effects at the Farm Level

In this section, the potential benefits of the transgenic sweetpotato technologies are analyzed at the individual farm level. For this purpose, the enterprise budgets currently observed in the West and the Central and East of Kenya are compared with hypothetical ones, for which the use of the virus and the weevil resistance technology is assumed, respectively. Among other significant indicators, we are particularly interested in the technologies' impacts on the per unit cost of sweetpotato production. The per unit cost reduction is the standard measure for describing technological progress at the farm level, and the algebraic formulations above showed that the figure is needed to determine the shift of the sweetpotato supply curve in the economic surplus model. The comparison of the regional enterprise budgets is shown in Table 6.

The without-technology reference reflects the sweetpotato cost and income figures already discussed in chapter 2. For both with-technology scenarios, no change in the per acre cost of production is projected.[11] This is realistic because no additional inputs are needed to realize the technologies' yield gain potentials. For the transgenic planting material itself, it can be assumed that farmers will obtain it through the same informal channels that they obtain conventional sweetpotato vines: exchange between neighbors. Although Monsanto also invested a sizable sum to develop the virus resistance technology, this contribution has to be seen as humanitarian aid to Africa. No technology premium will be charged to the Kenyan sweetpotato farmers.

Given constant per acre production costs and rising yields, both technologies will bring about significant per unit cost reductions, and remarkable increases in sweetpotato incomes can be expected.[12] Due to the higher virus pressure in the West, the potential positive impact of the virus resistance technology is higher in this region than in the Central and East. The weevil resistance technology, however, shows almost the same effects in both regions, as expected. Potential per unit cost reductions and income gains for weevil resistance are more pronounced than for virus resistance in both regions, though with only a comparatively small difference in the West.

Technology-induced agricultural productivity gains in developing countries are often associated with changes in tasks and responsibilities between men and women (e.g. Quisumbing et al., 1995). Increased commercialization, for instance, can lead to male household members taking control of crop income previously controlled by female household members. Although this could happen with the

Table 6: Potential cost and income effects of sweetpotato virus and weevil resistance technologies at the farm level, by region (per acre)

	West			Central and East		
	Without technology	Virus resistance	Weevil resistance	Without technology	Virus resistance	Weevil resistance
Production cost (KSh)	8,418	8,418	8,418	7,781	7,781	7,781
Yield (t)	4.08	4.90	5.10	3.58	4.01	4.48
Gross revenue (KSh)	24,016	28,837	30,014	21,073	23,599	26,365
Net income (KSh)	15,599	20,419	21,596	13,292	15,818	18,584
Per unit cost (KSh/t)	2,063	1,718	1,651	2,173	1,940	1,737
Income increase (percent)	-	30.9	38.4	-	19.0	39.8
Unit cost reduction (percent)	-	16.7	20.0	-	10.7	20.1

Notes: The sweetpotato farm-gate price is assumed to be 5885 KSh per ton in all scenarios (1 US$ = 59.7 KSh).
Source: Author's calculations based on potential yield gains derived in section 3.2.

[11] The labor requirements will slightly increase because of the higher per acre yields to be handled. However, on account of piecemeal harvesting the additional amount of labor is difficult to estimate. Hence, we refrained from including this minor cost increase.

[12] Note that the income comparisons assume a constant sweetpotato 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 later in the economic surplus model.

technologies considered, it is likely that the tendency for women to lose their decision-making power will be less pronounced in sweetpotato than in other crops. This is because the widespread custom of piecemeal harvesting provides a continuous flow of income that is used for immediate household needs. Hence, the increased sweetpotato income created by transgenic technologies might actually increase female household members' economic independence. There is widespread evidence that women's income has a greater positive impact on household food security than men's income (e.g. von Braun and Kennedy, 1994).

4.3 Technology Adoption

We define technology adoption as the proportion of Kenyan sweetpotato production under the new transgenic varieties. Generally, adopting new varieties is a successive process over time. First, some progressive farmers start to use a new seed technology, and then the number of users increases in subsequent growing periods. But varietal replacement is also a gradual process at the level of the individual farm. Farmers test a new variety on part of their land, and then extend this area when satisfied with the results. 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 adjusting traditional cropping practices. Partly due to such risk aspects, the adoption over time of new high-yielding varieties has been observed to follow a logistic function in many ex post empirical studies [see Feder et al. (1985) for a review]. In the case of bioengineered crops with resistance to biotic stress factors, the risk of adoption for farmers is reduced substantially. Adjustments to the traditional input mix are not necessary. And, especially for the weevil resistance technology, it is likely that some of the varieties already in use will be genetically transformed, which further reduces the risk of technology adoption (also see Qaim (1998) for transgenic technology adoption aspects).[13] We therefore assume a linear adoption profile instead of a logistic curve.

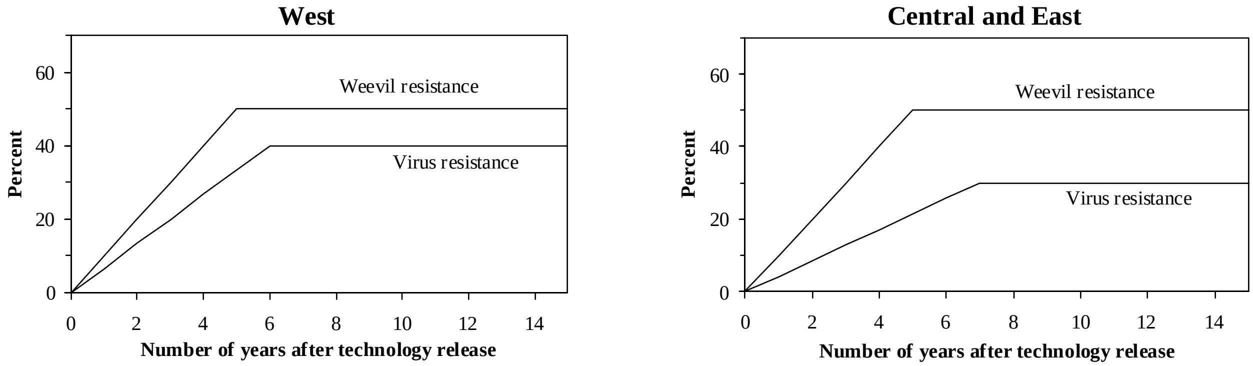
New conventional sweetpotato germplasm is disseminated in the following manner. Whenever KARI identifies a promising clone in on-station tests, on-farm demonstration trials are carried out with contact farmers. At the end of the season, a meeting is organized for sweetpotato growers to observe the yield and quality performance of the new variety. Farmers may then take a handful of vine cuttings for their own propagation and for further dissemination. In western Kenya, KARI sometimes also cooperates with women's groups that multiply sweetpotato planting material and then sell it to interested farmers at a comparatively low rate. The targeted introduction of new sweetpotato varieties from abroad or from regional breeding programs is a rather new activity in Kenya, and no exact information is available about the possible speed of variety adoption. Farmers are choosy, especially in regards to taste characteristics of sweetpotato cultivars. But preliminary experiences from Kenya and other countries with similar conditions suggest that acceptable and superior germplasm can quickly spread through informal exchanges of vine cuttings from farmer to farmer (cf. Carey et al., 1997; Minde et al., 1997). It is expected that transgenic varieties will diffuse in exactly the same way as conventional material.

The estimated linear adoption profiles for the transgenic resistance technologies are graphically depicted in Figure 4. If successful, the first transformed virus-resistant clone (CPT-560) could be released in 2002, with additional varieties 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 or 2005.

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

[13] For virus resistance it is less feasible that the technology be incorporated in already popular varieties, especially in high-virus pressure areas. Since farmers in these areas are generally using landraces with natural resistance, it is rather desirable to endow higher-yielding but naturally susceptible varieties with the trait of transgenic virus resistance (also see section 2.5).

Figure 4: Estimated adoption profiles of sweetpotato virus and weevil resistance technologies, by region



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 will be somewhat more widespread in the West than in the Central and East. For the weevil resistance technology, adoption behavior is presumed to be identical in both regions. It is expected that farmers will adopt weevil-resistant varieties more rapidly because most of them are aware of the weevil problems. By contrast, farmers are much less aware of virus problems. Finally, if more varieties are transformed in the future, then maximum adoption rates could be higher for both resistance mechanisms. The technologies' shift factors (*K*) of the regional supply curves—resulting from multiplying the per unit cost reductions by the technology adoption rates—are given in the Appendix, Table A1.

National and international biotechnology opponents have recently initiated a media campaign in Kenya against the introduction of transgenic crops (e.g., Muli, 1998; Redfern, 1998). Because the average educational standard in Kenya is comparatively low, the population can easily be influenced by this biased information. As a result, some food consumers and producers may not want to accept transgenic crops, which would depress technology adoption rates. It is important to support the flow of objective information about biotechnology so that the public can make an educated, informed choice about these new technologies. Risks and fears must not be played down, but they should always be balanced with potential benefits. This holds true for developing and developed countries alike.

4.4 Projected Welfare Effects

After all the variables have been specified, the expected welfare effects of the biotechnology projects can be simulated with the described sweetpotato market model. Changes in producer and consumer surplus are calculated annually for the considered 16-year period of technology application. Because it is assumed that both technologies will be released in 2002, the analysis covers the period 2002-2017. The technology release date is realistic for the first transgenic virus-resistant variety, and as elaborated before, the same assumption for the weevil resistance technology used only for comparative purposes. The complete model results are shown in the Appendix, Table A2. They are summarized in Table 7.

Both technologies will create substantial welfare gains for Kenyan sweetpotato producers and consumers.[14] For the virus resistance technology, the annual gain is projected at 324 million KSh. For the weevil resistance technology it is 593 million KSh. The difference in the values occurs mainly because weevils depress current sweetpotato yields more than viruses. Moreover, farmers will adopt

[14] Once their success has been proven in Kenya, the sweetpotato biotechnologies are planned to be transferred to other sub-Saharan African countries in the future. The benefit projections given in this report constitute only a small fraction of the total potential technology gains. Kenya's production share in African sweetpotato production is about 9 percent.

Table 7: Projected welfare effects of virus and weevil resistance technologies

	Producers		
	West	Central and East	Consumers
		Virus resistance technology	
Annuity of surplus change[a]	219.3	21.0	83.5
Share of total producer surplus (percent)	91.2	8.8	25.8 [b]
Regional production share (percent)	74.8	25.2	-
		Weevil resistance technology	
Annuity of surplus change[a]	330.1	109.4	153.3
Share of producer surplus (percent)	75.1	24.9	25.9 [b]
Regional production share (percent)	74.8	25.2	-

[a] The annuity figures are given in million 1998 KSh (1 US$ = 59.7 KSh). They have been calculated using a discount rate of 10 percent.
[b] The share given for consumers refers to the proportion of the overall economic surplus attributable to sweetpotato consumers.
Source: Author's calculations.

weevil-resistant varieties more quickly and more widely. For both technologies, the relative benefit distribution between sweetpotato producers and consumers is identical. Consumers capture around 26 percent of the overall welfare gains due to price decreases. Remember that the technology benefits associated with home consumption in the farm households are included on the producer side. For a fully commercialized commodity, the benefit share of market consumers would rise to 43 percent. Among producers, welfare distribution of the virus resistance technology is biased towards western sweetpotato farm households. Given lower virus pressure in the Central and East, this is not a surprise. Sweetpotato farms in the West are comparatively resource-poorer on average, so that this bias does not have undesired equity implications. Weevil problems, on the other hand, were oppressive in all of Kenya's sweetpotato-producing regions, so the regional distribution of the producer surplus created by weevil resistance almost exactly corresponds to the initial regional production shares.

This comparison of the welfare effects of virus and weevil resistance should not be misunderstood as a competition between two mutually exclusive technologies. On the contrary, both resistance mechanisms will be available for Kenyan sweetpotato growers in the future, possibly in the same varieties. We refrain from evaluating both technologies together because little is known about possible synergies in the crop losses caused by viruses and weevils. Assumptions about the yield effects of combined resistance mechanisms would be pure speculation.

4.5 Benefit-Cost Analysis

R&D cost data for the sweetpotato virus resistance technology have been assembled in the interviews with representatives of the different involved organizations. The data up until 1999 refer to actual expenditures related to the project. For years after 1999, the interviewees were asked to give realistic estimates on the expected future project costs. The costs carried by the individual organizations involved in the virus resistance project are discussed in the following paragraphs. An overview is given in the Appendix, Table A3.

- **USAID:** USAID provided financial assistance for the first project phase, from the end of 1991 until 1998. The funds cover scholarship programs and research support for Kenyan and other external scientists who worked with the project at Monsanto. Some of these contributions were administered through ABSP and the University of Missouri. Moreover, USAID sponsored capacity-building activities in Kenya, such as updating KARI's laboratories and training local staff in biosafety and similar issues.
- **Monsanto:** The company carried the bulk of the St. Louis-based research activities and overhead costs. This includes the salaries and travel costs of its own researchers and support staff associated with the project, short-term stipends for external researchers, the provision of laboratory facilities, such as transformation equipment and growth chambers for the transgenic material, as well as operational expenditures. Major research costs are estimated to continue until 2001 and gradually diminish in subsequent years.

- **KARI:** Before 1997, KARI administered grants from USAID, so significant costs related to the project did not accrue to the institute. In 1997/98 KARI refurbished its research facilities at NARL, partly supported by the World Bank. In 1998 the institute financed mock trials with CPT-560 and other national sweetpotato clones. KARI will also carry the salary of its own researchers working under the project once the technology enters Kenya. After the donor support fades out in 2002, it is expected that KARI's cost will increase somewhat before shrinking again. After 2008, it is assumed that there is only a minor annual cost for maintaining the transgenic germplasm.
- **World Bank:** The World Bank partially supported the laboratory refurbishment at NARL in 1997/98. Moreover, the Agricultural Research Fund (ARF), out of which the three-year project period starting from 1999 is sponsored, is administered by the World Bank. The ARF provides for operational expenditures and research equipment needed for KARI to carry out sweetpotato transformation. Training activities, the support of biosafety developments, and project overhead are also covered. A small part of the fund is also designated for the facilitation work of CIP and ISAAA.
- **ISAAA:** ISAAA granted several short-term scholarships for KARI researchers to travel to the USA. ISAAA has also assisted the project with biosafety issues, IPR regulations, and writing funding proposals on a rather informal basis. More formal involvement of ISAAA begins in 1999 onwards, when the sweetpotato technology is transferred to Kenya. ISAAA will then take responsibility for institutional facilitation and for monitoring the different project activities (technology transfer, field trials, technology dissemination, maintaining the network with the different involved organizations, etc.).
- **CIP:** CIP has the international mandate for research in root and tuber crops and has extensive experience in many parts of the world. CIP's regional office in Nairobi is an important partner for KARI's sweetpotato program, and in regards to developing the virus resistance technology, CIP will collaborate with KARI in field trial evaluations as well as in the bulking and distribution of transgenic material to farmers that will occur later. Although these activities are actually financed by the ARF, it is expected that some additional costs might accrue and that these will be covered by CIP.

For the weevil resistance technology, no R&D cost data have been collected. Related research has only just begun, so cost estimates must remain speculative at this point. The projects carried out at different universities will profit greatly from the basic knowledge (e.g., transformation and regeneration protocols) already generated through research on sweetpotato virus resistance, so it is likely that the cost of developing sweetpotato weevil resistance will be much lower than the one shown in Table A3. Nevertheless, for comparative purposes it is instructive to assume equal costs for both projects when calculating benefit-cost measures. Table 8 shows the internal rates of return (IRRs) under different assumptions for the virus and the weevil resistance technology, respectively.

The first row in the Table takes into account the complete R&D expenditure borne by the different organizations. The IRRs are significantly above 10 percent, the standard discount rate used for investments in low and middle-income economies. Yet in an international comparison of annual rates of return on agricultural research investments, the

Table 8: IRRs of virus and weevil resistance projects under different assumptions for R&D costs and benefits (percent)

	Virus resistance	Weevil resistance
Full R&D cost, Kenyan sweetpotato area	26.1	33.3
Full R&D cost, Kenyan sweetpotato area doubled	33.7	41.7
Full R&D cost, Kenyan sweetpotato area quadrupled	41.9	50.7
Only applied R&D cost[a], Kenyan sweetpotato area	59.5	77.3

[a] The cost borne by Monsanto has been subtracted and the research lag has been shortened from 11 to 5 years.
Source: Author's calculations.

figures obtained range at the lower end of the spectrum (cf. Ruttan, 1982). Because the analysis of technology benefits is confined to Kenya this is not surprising. Although spillover effects to other countries of Africa will be part of the transgenic sweetpotato projects, they are not included in the calculations due to the lack of reasonable *ex ante* data. For illustrative purposes, the second and third row of Table 8 demonstrate the impact that an increase in the sweetpotato area (e.g., through extending the technology to neighboring 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 sweetpotato 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 sweetpotato technologies in the future. Concentrating on the biotechnology transfer from the USA to Kenya, it is informative to calculate supplementary IRRs, where only the cost of applied R&D is considered. Even though a clear-cut separation between basic and applied research is difficult, assessing the applied research components can be attained by subtracting the project expenditure directly borne by Monsanto. The remaining cost items include the establishment of the bioengineering laboratory in Kenya, in-country transformation, regeneration, testing of different sweetpotato varieties, and national capacity-formation in biosafety and related regulatory procedures. Moreover, the research lag would be shortened substantially when excluding basic research. Given the availability of elementary techniques, it is expected that a transgenic sweetpotato variety could be developed and released within a time frame of about 5 years. On the basis of these assumptions, additional IRRs have been calculated, which are also shown in Table 8. It becomes apparent that the transfer of both sweetpotato technologies is a highly profitable undertaking. The efficiency effects from a Kenyan point of view are even more positive, because foreign organizations carry the lion's share of the project costs. The figures could also represent important economic information for other countries planning to import recombinant sweetpotato technologies. Needless to say, benefit-cost ratios would still be higher in countries with larger sweetpotato areas or with more biotechnology experience already at hand.

4.6 Sensitivity Analysis

It is the nature of *ex ante* studies for their data to be associated with uncertainty. In order to strengthen the credibility of the numerical results and the derived statements, a sensitivity analysis is carried out with respect to pivotal parameters. Key variables that determine the technology shift of the sweetpotato supply curves are the per unit cost reduction (*C*) and the technology adoption rate (*A*). As expected, the gains in total economic surplus change proportional to variations of these two parameters. The benefit partition between producers and consumers remains unaffected. Although the influence on the IRRs is significant, the overall profitability of both technologies (virus and weevil resistance) is not jeopardized even with an 80 percent reduction of either *C* or *A*. The IRRs would still be higher than the opportunity cost of financial resources, assumed at 10 percent.

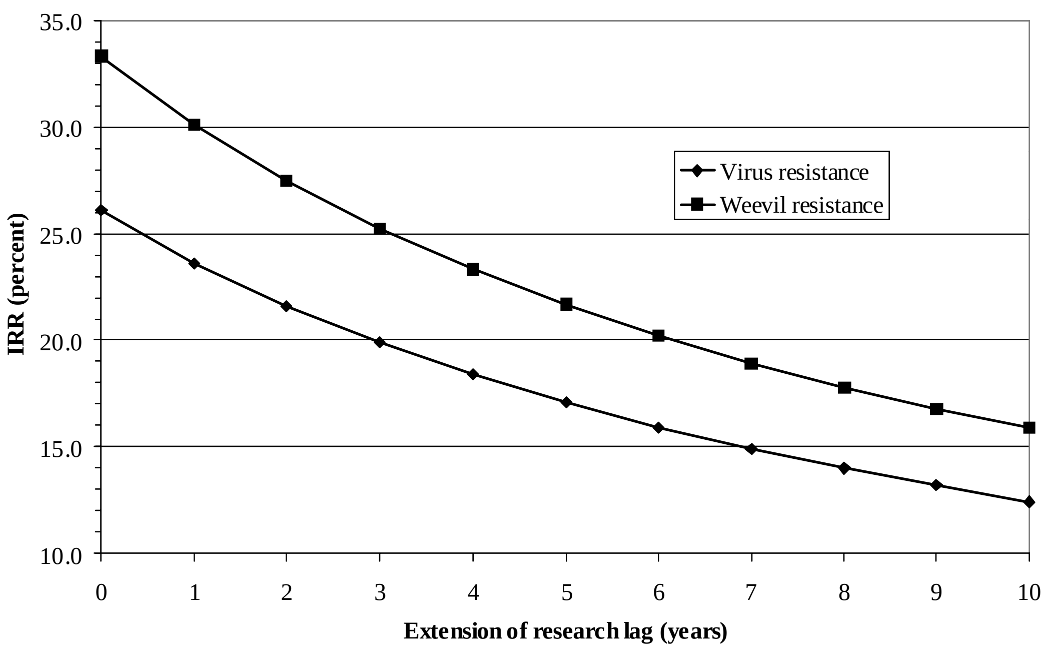
Because no reliable estimates are available for the sweetpotato price elasticities of supply and demand, the robustness of the results is also tested with respect to changes in these parameters. Changes in the values of the supply and demand price coefficients in reasonable dimensions have a comparatively 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 changes in the partition between producer and consumer surplus are lessened, however, because a significant proportion of Kenya's sweetpotato output is directly consumed by producing households.

Another important factor subject to uncertainty is the time lag between the start of the project and the first technology release. In the previous section, it became apparent that shortening the research lag leads to a substantial rise in projects' profitability. However, given that basic research components are also contemplated, the possibility of prolonged research lags needs to be taken into account as well. In section 3.2, it was noted that little is known yet about how effectively the SPFMV coat protein gene confers resistance to the whole SPVD complex. Although the probability of success is high, we cannot rule out with absolute certainty that further refinements of the gene construct will be necessary. This would expand the research lag (originally assumed to be 11 years) and the cost of R&D. For the sweetpotato weevil resistance technology, however, extending the research lag is not expected. As previously elaborated, it is likely that technology release can be accomplished much faster than in the case of virus resistance. Nevertheless, the sensitivity of the IRRs with respect to extended research lags is examined for both technologies. The results are graphically depicted in Figure 5. It can be seen that the overall profitability of the technology projects shrinks. Yet even for an extension of the research lag by 10 years, the IRRs would stay above 10 percent.

Finally, it could be argued that the period of 16 years, for which benefit flows have been considered, is too long because the resistance mechanisms may break down earlier. Although it is expected that selection pressure in pathogen populations is reduced because of the small-scale sweetpotato cultivation practices (see section 3.3), the option of shortened benefit flows was also taken into account. The impacts on the projects' economic returns are rather low: assuming a five-year shortening of benefit flows, the IRR is still 24 percent for the virus resistance and 32 percent for the weevil resistance technology.

Again, it should be clearly stated that the given IRRs underestimate the potential economic impact of the research projects, because technology spillovers from Kenya to other countries are disregarded in the analysis. In summary, the sensitivity analysis underlines the validity of the statements about welfare and profitability outcomes for the transgenic virus and weevil resistance technologies, even under extreme parameter variations.

Figure 5: Development of IRRs under the assumption of extended research lags



Note: The original research lag is 11 years. The IRRs take into account the full R&D cost, including basic research components, and they are based on the Kenyan sweetpotato area (cf. section 4.5). For each extended year, the average annual R&D expenditure that accrues during the first 11 years of the project has been added on the cost side.

5. Conclusions and Policy Implications

Viruses and weevils are the most pressing biotic production constraints for the predominantly small-scale and semisubsistent sweetpotato farms in Kenya. There are no economically viable methods to combat these pathogens once they have infected the plant. Recently, conventional efforts at virus resistance breeding produced first successes in sub-Saharan Africa. But the genetic trait of sweetpotato weevil resistance has not yet proven amenable to a conventional plant breeding approach. Biotechnology, on the other hand, extends the portfolio of tools available for disease and pest control. The bioengineered resistance mechanisms analyzed in this study will substantially reduce the sweetpotato losses caused by viruses and weevils, and they will enhance farmers' yields and incomes considerably. The project examples demonstrate that modern biotechnology can offer promising solutions to the problems of resource-poor farmers, provided that the specific needs of these farmers are explicitly taken into account in international biotechnology research.

Transgenic varieties with enhanced attributes of stress resistance fit well into the traditional sweetpotato production systems of Africa for supplementary inputs are not required. Because transgenic planting material is easy to handle and reproduce, and given the comparatively low risk of adoption for farmers, it can be expected that both the virus and weevil resistance technologies will be rapidly disseminated to Kenya's sweetpotato growers. Yet there are two factors to consider regarding technology acceptance. First, scientists and policymakers need to foster the flow of objective information about biotechnology in Kenya. Otherwise the technology could be met with disapproval due to the ongoing biased media campaign against genetically engineered crops. Second, given the distinct varietal preferences among consumers and producers, the number of different sweetpotato clones transformed will be a chief determinant of the speed and degree of technology adoption. In this respect, transgenic techniques offer another advantage over the tools of conventional crossbreeding. Once the basic recombinant sweetpotato technology becomes available, it is comparatively easy to incorporate the desired resistance mechanisms into additional varieties. KARI has established the capacity for its own in-country crop transformation. This bridges the distance between researchers and farmers and is a good starting point for participatory variety selection among the various stakeholders. Of course, biotechnology and conventional approaches to crop improvement should not be considered as substitutes. The most efficient combination of tools must be determined for each breeding objective. Furthermore, biotechnology can only be successful if appropriately integrated into the existing breeding and variety dissemination networks of a country.

Growing sweetpotato virus-and weevil-resistant varieties will improve the food situation of farm families. On the one hand, the higher yield levels obtained add to the sweetpotato availability for direct subsistence consumption. On the other hand, rising cash incomes increase households' ability to purchase other food items. Because women often control the revenues from sweetpotato sales, there is a high probability that a significant proportion of the additional income would be spent on food, especially in food-insecure households. Due to technology-induced market price decreases, urban sweetpotato consumers will also profit. About 26 percent of the overall welfare gains are captured by sweetpotato consuming, nonproducing households. Against the backdrop of the perpetual trend towards urbanization, such food price decreases through agricultural technological progress are becoming more and more important for the nutritional well-being of poor population segments.

Virus pressure varies in different parts of Kenya. The highest virus-induced crop losses are found in the densely populated Lake Victoria Basin, so it is in this western part of the country that the virus resistance technology will bring about the greatest benefits. But farms in the West are on average resource-poorer than those in the Central and East, so the distribution of benefits tends to equalize the existing regional income disparities. By contrast, weevil infestation shows more or less the same severity across all sweetpotato producing provinces of Kenya. Significantly, the expected aggregate productivity gains of transgenic weevil resistance are even higher than those of virus-resistant varieties. This comparison, however, should not be misunderstood as a priority setting exercise in which one technology is preferred over another.

Such a narrow viewpoint neglects the dynamic benefit potentials. The development of sweetpotato virus resistance is in a much more advanced stage than the weevil resistance technology, and the virus-resistant varieties will be the first transgenic crops to be released in Kenya. It has to be kept in mind, therefore, that this initial project has a strong component of knowledge-creation and capacity building—in addition to the direct welfare gains it produces in the Kenyan sweetpotato sector. The acquired research experience will support the emergence of other recombinant sweetpotato innovations, and the establishment of facilities and regulatory procedures in Kenya will facilitate future biotechnological progress in the country. It is anticipated, for instance, that the research lag for the sweetpotato weevil resistance project will be reduced by more than 50 percent compared to the virus resistance technology. In the longer run, it is likely that both virus and weevil resistance mechanisms will be incorporated into the same sweetpotato varieties.

Given the scarcity of financial resources available for international agricultural research, the benefit of a technology always needs to be contrasted to the cost of R&D. In the case of the technologies considered, especially the sweetpotato virus resistance, the cost of R&D is fairly high because it also includes components of basic research. But even if the resistance technologies were only used in Kenya, the research investments would generate significantly positive benefit-cost ratios. In reality, technology spillovers from Kenya to other countries in sub-Saharan Africa are intended, although such spillovers have not explicitly been analyzed. Clearly, however, they would multiply the social returns on basic research investments. The international collaborative R&D projects on sweetpotato virus and weevil resistance also demonstrate the viability of successful partnerships between the public and the private sector. Most of the basic biotechnology tools available to date are patented by private companies, and these companies often do not have enough market incentives to develop end-technologies explicitly designed to serve resource-poor farmers in the South. So from a development policy perspective more interactions of this kind are needed.

There are numerous examples showing that private companies are usually willing to donate proprietary technology components for use in developing countries, so long as the firms' own commercial interests are not conflicted. Technology donation therefore requires careful contractual arrangements for each specific case, stating where, under what conditions, and for what purpose the technology might or might not be used by the license-taker. If such contractual arrangements cannot be ensured, private companies are understandably hesitant to license patented innovations. Bilateral agreements between a company and a single developing country are much easier to negotiate than multilateral ones. Because of its global mandate and prevailing public good policy, for instance, the centers of the Consultative Group on International Agricultural Research (CGIAR) find it difficult to get access to proprietary research tools and technologies for further adjustment and final release. Given the international exchange of germplasm, it could not be ruled out that the resulting public sector technologies with proprietary components would also be used in countries where the conditions for commercial technology releases by the donating firms are favorable. It remains a challenging task to identify and formulate IPR regulations acceptable to all involved parties in order to foster more related research cooperation.

Working with orphan commodities, such as sweetpotato, makes things somewhat easier. Private companies have no immediate commercial interest in these poor people's crops. Biotechnology can provide the means for the transfer of genetic material across species, so that certain genes used by private firms in commercial crops could also be valuable for public R&D on orphan commodities. Apart from promoter or marker genes with a broad spectrum of possible applications, this holds true even for specific resistance genes when the relevant crop species are attacked by similar pests or diseases. The *Bt* genes that will be used for sweetpotato weevil resistance are a case in point. If private companies can watch over their safe employment, there is no reason why they should not agree to donate proprietary technologies for use in orphan commodities. Of course, in the development of sweetpotato virus resistance Monsanto is much more than just the donator of available technology. The main part of the research for the project has been carried out in Monsanto laboratories. In spite of the grants from other organizations, the company carries around 70 percent of the total cost of R&D. It is unlikely that this example of cost sharing can be taken as a model for further public-private research partnerships. The cost for the development of bioengineered orphan commodities with desired traits will decrease over time, once more basic biotechnology tools and transformation protocols become available. Nonetheless, it is essential to increase the public sector contributions in terms of funds and expertise in order to encourage collaborative R&D initiatives in the future. Harnessing the comparative advantages of the public and the private sector is a prerequisite for the efficient provision of highly beneficial biotechnology innovations for the poor.

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Table A1: Technology shift factor *K* for virus and weevil resistance technologies

Virus resistance			Weevil resistance		
Year [a]	West	Central and East	Year [a]	West	Central and East
0	0.000	0.000	0	0.000	0.000
1	0.011	0.005	1	0.020	0.020
2	0.022	0.009	2	0.040	0.040
3	0.033	0.014	3	0.060	0.060
4	0.045	0.018	4	0.080	0.080
5	0.056	0.023	5	0.100	0.101
6	0.067	0.028	6	0.100	0.101
7	0.067	0.032	7	0.100	0.101
8	0.067	0.032	8	0.100	0.101
9	0.067	0.032	9	0.100	0.101
10	0.067	0.032	10	0.100	0.101
11	0.067	0.032	11	0.100	0.101
12	0.067	0.032	12	0.100	0.101
13	0.067	0.032	13	0.100	0.101
14	0.067	0.032	14	0.100	0.101
15	0.067	0.032	15	0.100	0.101

[a] This is the number of years after the first technology release.
Source: Author's calculations.

Table A2: Technology-induced changes in producer and consumer surplus (in thousand 1998 KSh)

Virus resistance				Weevil resistance			
	Producers				Producers		
Year [a]	West	Central/East	Consumers	Year [a]	West	Central/East	Consumers
0	0	0	0	0	0	0	0
1	35,484	2,769	13,251	1	60,700	20,118	28,023
2	74,487	5,808	27,831	2	127,479	42,252	58,944
3	117,273	9,137	43,838	3	200,793	66,554	92,986
4	164,119	12,776	61,380	4	281,128	93,186	130,387
5	215,323	16,748	80,570	5	369,003	122,319	171,405
6	271,203	21,077	101,529	6	386,974	128,276	179,752
7	282,799	29,887	108,653	7	405,819	134,523	188,506
8	296,571	31,343	113,944	8	425,583	141,074	197,686
9	311,014	32,869	119,493	9	446,308	147,945	207,314
10	326,160	34,470	125,313	10	468,043	155,149	217,410
11	342,044	36,149	131,415	11	490,837	162,705	227,997
12	358,702	37,909	137,815	12	514,740	170,629	239,101
13	376,170	39,755	144,527	13	539,808	178,938	250,745
14	394,490	41,691	151,565	14	566,096	187,653	262,956
15	413,701	43,722	158,946	15	593,665	196,791	275,762

[a] This is the number of years after the first technology release.
Source: Author's calculations.

Table A3: Financial cost of the virus resistance research project by involved organizations (in thousand 1998 KSh)

Year	USAID [a]	Monsanto	KARI	Univ. of Missouri	World Bank [b]	ISAAA	CIP	Total
1992	4,541	2,418	0	0	0	0	0	**6,959**
1993	4,541	2,418	0	0	0	0	0	**6,959**
1994	5,634	11,970	0	0	0	0	0	**17,604**
1995	3,555	16,447	0	0	0	896	0	**20,898**
1996	3,555	19,462	0	0	0	0	0	**23,018**
1997	1,013	29,895	1,293	516	1,425	1,506	0	**35,647**
1998	1,013	29,417	1,621	516	1,425	2,402	0	**36,394**
1999	0	28,835	1,800	0	9,552	2,388	597	**43,172**
2000	0	28,835	1,800	0	9,552	1,194	597	**41,978**
2001	0	28,835	1,800	0	9,552	1,194	597	**41,978**
2002	0	11,940	2,985	0	0	597	0	**15,522**
2003	0	8,955	2,985	0	0	0	0	**11,940**
2004	0	5,970	2,985	0	0	0	0	**8,955**
2005	0	4478	1,493	0	0	0	0	**5,970**
2006	0	2,985	1,493	0	0	0	0	**4,478**
2007	0	1,493	1,493	0	0	0	0	**2,985**
2008	0	0	1,493	0	0	0	0	**1,493**
2009	0	0	299	0	0	0	0	**299**
2010	0	0	299	0	0	0	0	**299**
2011	0	0	299	0	0	0	0	**299**
2012	0	0	299	0	0	0	0	**299**
2013	0	0	299	0	0	0	0	**299**
2014	0	0	299	0	0	0	0	**299**
2015	0	0	299	0	0	0	0	**299**
2016	0	0	299	0	0	0	0	**299**
2017	0	0	299	0	0	0	0	**299**
Total	23,854	234,352	25,925	1032	31,505	10,177	1,791	32,8636

[a] The USAID funds include the ABSP scholarship.

[b] Although the World Bank only administers the ARF, the funds are included in this column.

Source: Author's interview survey.