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Economics of biological control of cassava mealybug in Africa

J. Zeddies[a], R.P. Schaab[a], P. Neuenschwander[b,*], H.R. Herren[b,1]

[a] *University of Hohenheim, Institute of Agricultural Economics (410 B), D-70593 Stuttgart, Germany*
[b] *International Institute of Tropical Agriculture (IITA), 08 B.P. 0932, Cotonou, Benin*

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Abstract

Pest populations of the cassava mealybug *Phenacoccus manihoti* Mat.-Ferr. (Homoptera: Pseudococcidae) were reduced successfully by the biological control agent *Apoanagyrus (Epidinocarsis) lopezi* De Santis (Hymenoptera: Encyrtidae) throughout most of sub-Saharan Africa. The economics of the project were evaluated based on data from field trials, socio-economic surveys, published results, and financial information provided by the International Institute of Tropical Agriculture (IITA) and the national programmes. Costs and benefits for the biological control of *P. manihoti* were calculated over 40 years (1974–2013) for 27 African countries, for four different scenarios, taking into account that impact by *A. lopezi* and speed of the impact differ between ecological zones. A reasonable calculation considering compounded interest resulted in a benefit cost ratio of about 200 when cassava was costed at world market prices, and of about 370–740 when inter-African prices were considered.

Keywords: Economics of biological control; *Phenacoccus manihoti*; *Apoanagyrus lopezi*; Cassava; Africa

1. Introduction

The cassava mealybug *Phenacoccus manihoti* Mat.-Ferr. (Homoptera: Pseudococcidae) was first observed in Zaire and Congo in the early 1970s and quickly became the most important pest on cassava. First efforts at biological control against this pest started in 1977. Over the years, *P. manihoti* spread throughout the entire cassava belt of Africa, with the major exception of Madagascar. The exotic parasitoid *Apoanagyrus (Epidinocarsis) lopezi* De Santis (Hymenoptera: Encyrtidae) was released from 1981 onward (Herren et al., 1987). By the end of the decade, the biological control agent had spread to all the major mealybug infestations and had brought the pest under control in 95% of all the fields (Herren and Neuenschwander, 1991).

This vast biological control project involving foreign exploration, quarantine, rearing, release, field and laboratory studies, monitoring, coordination, training, awareness building and impact studies was carried out by the International Institute of Tropical Agriculture (IITA) in collaboration with many other institutions during the last 15 years and counts among the best researched biological control projects (Neuenschwander, 1994, 1996). An early economic analysis of the impact arrived at a rather high return (Norgaard, 1988). It was based on rough estimations and the extrapolation from a few West African data, which demonstrated successful biological control, to the whole continent, where *A. lopezi* had not yet been established or not yet exerted control.

* Corresponding author. Tel.: +229-35-01-88;
fax: +229-35-05-56.
E-mail address: p.neuenschwander@cgiar.org
(P. Neuenschwander).
[1] Present address: International Centre of Insect Physiology and Ecology (ICIPE), Box 30772, Nairobi, Kenya

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The present analysis includes data on damage by *P. manihoti* also from East Africa. It incorporates the documented impact by *A. lopezi* and its speed, both of which differ between ecological zones, on the basis of data from many countries, published in the 10 years since Norgaard's analysis. Monetary benefits accruing from increased cassava yields are calculated under different assumptions, but environmental and other social benefits are not taken into account. For several realistic scenarios, benefits are compared with costs, which had been mostly covered by donor agencies. Both benefits and costs are discounted over time and the ratio gives an idea of the returns on the investment into this biological control programme.

2. Materials and methods

2.1. Sources for the data base

For the economic analysis, cassava production figures for each country were obtained from Production Yearbooks of the Food and Agricultural Organisation of the United Nations (FAO, 1975–1995). An average yield of 8 tonnes/ha was used as a basis (years 1982–1991, from CIAT, 1993). According to various country maps and the atlas of cassava for Africa (Carter et al., 1992), a percentage attribution of this production to three zones, namely savanna, rainforest and highlands, was made. Economic data were available from official sources by African governments, as provided to the Food and Agriculture Organisation of the United Nations (FAO, 1975–1995), from IITA's Collaborative Study on Cassava in Africa (COSCA) (Nweke et al., 1989), and other publications (Lynam, 1987; Dorosh, 1988; Carter et al., 1992; CIAT, 1993). In addition, reports by the German Ministry of Agriculture and Toepfer International, Hamburg; the Central Bureau of Statistics, Ministry of Planning and Development in Nairobi, Kenya; Barcley's Business Guide to Kenya; the Statistics Department, Ministry of Planning and Economic Development and the Consumer Price Index, Entebbe, Uganda; as well as others were used (for details see Schaab, 1997).

When *P. manihoti* invaded Africa it reached extremely high population levels wherever it appeared and became the most important pest insect on cassava within short time. The data concerning crop loss by the cassava mealybug and crop loss reduction through biological control were obtained by IITA and its collaborating partners. They have to be seen against the background data on the dynamics of the pest and beneficiaries through the years, in the various countries and agroecological zones.

From 1981 onward, *A. lopezi* was released in about 150 sites in 20 countries. Repeated surveys gave quantitative data about establishment and spread in the following countries, some of which received *A. lopezi* by natural dispersal from neighbouring countries without release (north west to south Africa): Senegal, Gambia, Guinea-Bissau, Sierra Leone, Côte d'Ivoire, Ghana, Togo, Benin, Nigeria, Niger, Cameroon, Central African Republic, Gabon, Congo, Zaire, Rwanda, Burundi, Uganda, Kenya, Tanzania, Malawi, Mozambique and Zambia. Spot observations were made in other countries of the cassava belt (reviews in Neuenschwander, 1994, 1996).

Impact of *A. lopezi* on the cassava mealybug was rather slow. Often lower mealybug population equilibria were reached only after several years. Impact was quantified in Ghana, Benin, Nigeria, Gabon, Congo, Zaire, Tanzania, Malawi, and Zambia. Impact of biological control on tuber yield came from station experiments in Nigeria (Schulthess et al., 1991), experiments in farmers' fields in Kenya (Schaab, 1997), and from a survey in Ghana (Neuenschwander et al., 1989).

Details on expenses at IITA were obtained from the institute's financial office. Where necessary, costs of buildings and salaries were proportioned to the space and labour devoted to biological control of cassava mealybug (Neuenschwander and Haug, 1992). Costs accruing to countries, whose collaboration was highly subsidized by the project, were estimated from the corresponding donor contracts (for Kenya see Kariuki, 1992).

Farmers had no additional cost related to the biological control project, except for the fact that an increase in the quantity harvested caused slightly higher harvest costs.

2.2. Establishing the matrix

The benefits of the biological control project were calculated for each country separately and for different scenarios. The following columns were established in a matrix with lines for each year: Estimated number of hectares of cassava harvested per year, production per year, percentage distribution of cassava production by ecological zone, spread of *P. manihoti* through the years within the different ecological zones expressed in percentage of the total area under cassava in the country, spread of *A. lopezi* within the different ecological zones expressed as proportion, damage coefficients from the pest alone (before release of *A. lopezi*) and when pest and its exotic parasitoid occurred together.

Both damage by *P. manihoti*and impact by *A. lopezi* differed from one ecological zone to the other and between years following establishment. Wherever *P. manihoti* established itself, damage was very high already the same year and losses of 80% (Nwanze, 1982) were computed. Within 5 years, this value was reduced linearly to 40% in the highlands and savanna and to 20% in the rain-forest. This drop occurred because farmers adapted to the new challenge and planted more tolerant varieties. In addition, indigenous predators, particularly coccinellids, adapted to the new food source and reduced the pest population (Neuenschwander et al., 1987).

The impact by *A. lopezi* on *P. manihoti* was relatively slow and stable biological control was achieved only after several years. According to the cited impact studies, the reduction of yield loss due to *A. lopezi* was computed for each ecological zone in each country as follows (100%=yield, unaffected by *P. manihoti*): For the savanna, first year 0%, second year 25%, third and subsequent years 37% (out of an average yield loss of 40%); for the forest zone, the corresponding reductions were 0, 10 and 15% (out of an yield loss of 20%). This left a residual damage concentrated in foci of infestation on sandy soils as described from several surveys (Neuenschwander et al., 1990, 1991). For the highlands, reductions of 0, 10, 20, 30, and 35% were computed for the first to the fourth (and subsequent) years (Schaab, 1997). Once a new stable equilibrium was achieved under biological control conditions, the value of crop loss reduction was kept constant for the rest of the 40-year-period considered in this evaluation (1974–2013).

For each zone, these figures were entered for the year the cassava mealybug and *A. lopezi* had been reported for the first time, respectively. Before this time, losses due to mealybug were computed as being zero.

2.3. Economic analysis

The economic evaluation aimed at determining a benefit cost ratio. Because of uncertainties in some biological and economic parameters, a range of possible results was computed and subjected to a sensitivity analysis. The economics of the following four scenarios were investigated.

2.3.1. Additional cassava production

It is assumed that *A. lopezi*'s action resulted in a country-specific, additional quantity of cassava that could be harvested, as compared to the situation where *P. manihoti* had caused uncontrolled damage. To estimate the benefit, crop loss reduction in tonnes was multiplied with a ‘world market price’. Because of the high grain prices in the European Union (Lynam, 1987) and its grain subsidies (Schumacher, 1990) the world market price for cassava is distorted and pertains to animal feed only. As a rough approximation, it was estimated at US$ 90 per tonne dry weight, from 1995 to 2013.

The US$ 90 per tonne price is, however, too low for cassava traded within Africa. Average price per tonne fresh weight varies a lot from one year to the next and among countries and ranges from about US$ 50 to 100). This translates into US$ 167 to US$ 333 per tonne dry weight (conversion factor fresh to dry weight=0.3), and sometimes even higher. The African prices are used to calculate alternatives to Scenario 1.

2.3.2. Additional cassava under import conditions

In the second scenario, the amount of cassava lost to unchecked damage by *P. manihoti* was to be imported. Biological control would then reduce this importation. Costs for transport to the interior of the country were added to the farm-gate price (world market level) of the first scenario. The costs for transportation were estimated at about US$ 140 per tonne per 1000 km (US$ 5000 for a 36 tonne trailer for 1000 km). For the calculation, the distance from the nearest harbour to the middle of each country was chosen. Costs were assumed to be constant through the years.

2.3.3. Additional production of an alternative crop, i.e. maize

In this scenario, it was assumed that losses due to *P. manihoti* were compensated for by locally grown maize. *A. lopezi*'s action reduced this need or allowed the additional maize to be sold. This additional maize production was valued under the assumption of an average yield at the world market price for (yellow) maize (FAO, 1975–1995) adding a quality bonus of 20% for white maize.

2.3.4. Additional maize under import conditions

In this scenario, the loss in cassava due to the ravages of the mealybug was to be compensated for by importing maize, e.g. as food aid. The reduction of this loss due to biological control was computed using the price of maize under the previous scenario and by adding costs for transport to the interior of the country as in Scenario 2.

All calculations were compounded or discounted by 6% p.a., the investment base being 1994. Costs and benefits are presented in nominal terms as well as at present value (end of 1994). Most funds for this project stem from industrialized countries, where the interest rates rarely exceeded this value during the last two decades. A period of 40 years, i.e. 1974–2013, was chosen as an adequate duration for calculating the economic impact of biological control across the continent. This is the duration usually applied for long lasting projects (including buildings).

For evaluating the total benefit of *A. lopezi*, the following formula was applied to the data of the spreadsheets:

$$\text{Benefit} = \sum_{z=1}^{27}\sum_{i=1}^{40}\left(\sum_{j=1}^{3} P_{zi}E_{zij}G_{ij}\right)0.3Y_{zi}D_i$$

with z the 27 African cassava countries (1=Angola, 2=Benin,...,27 =Zambia); I the specific year (1=1974,...,40=2013); j the ecological zones (1=savanna, 2=rain forest, 3=highland); P_{zi} the total cassava production in fresh weight for country z and year i; E_{zij} the share of cassava production with influence of *A. lopezi* in country z in year i and zone j; G_{ij} the relative gain (=saved loss) factor in zone j and year i; 0.3 the constant conversion factor from fresh to dry weight; Y_{zi} the price of cassava (or maize substitutes according to scenario) in US dollars per tonne of dried cassava in country z in year i and D_i is the discounting/compounding factor for year i.

The total costs for controlling *P. manihoti* were divided into four parts, namely (i) the costs to IITA, (ii) overhead costs to the donor countries (O) (15% in addition to the IITA expenditures for administration, planning, evaluation, etc.), (iii) costs to African governments (G) and (iv) costs to African farmers (F), and added up as follows (in US$):

$$\text{Costs} = \sum_{i=1}^{40}(\text{IITA}_i + O_i + G_i + F_i)D_i.$$

3. Results

3.1. Losses and savings

The economic analyses of biological control of *P. manihoti* included 27 countries in Africa (Table 1), which together produced about 94% of the total African cassava output in 1995. By this year, all cassava growing areas in each country (with the exception of Uganda) had been infected with *P. manihoti*.

The value of cassava was estimated from the about 9 million ha of cassava harvested in Africa, with an average yield of 8 tonnes/ha. This amounts to 72 million tonnes of fresh cassava annually. Multiplied with the conversion factor for dried material, i.e. 0.3, gave the 21.5 million tonnes marketable cassava (Table 1).

The total benefit of *A. lopezi* was directly related to the total cassava production per country. The biggest benefits were attributed to Zaire, Nigeria, Ghana, Tanzania, Mozambique and Uganda, which together produced more than 78% of all the cassava involved in the analysis.

The benefits of all 27 countries, accumulated over the 40 years of analysis (Table 2), amounted to US$ 9.4 billion in Scenario 1 (under the assumption of a world market price of US$ 90 per tonne), with an yearly gain of US$ 235 million For the cassava area of about 9 million ha, the reduced loss thus became US$ 26 per ha and year.

Instead of calculating the losses and gains under the assumption of replacement of cassava at world market price (Scenario 1), three other scenarios were calculated. Each assumes a different reaction to the loss caused by the cassava mealybug. While losses varied between the scenarios, the impact of *A. lopezi* remained an unchanged percentage. All scenarios are realistic for specific conditions in a particular country, though none would have applied over the entire con-

Table 1
Basic data from 27 African countries for the economic analysis of the impact of the biological control programme against cassava mealybug

Country	Percentage of cassava in			Cassava production in 1991		First record of	
	Savanna	Rainforest	Highlands	In 1000 tonne	In %	*P. manihoti*	*A. lopezi*
Angola	18	2	80	1850	2.83	1975	1983
Benin	95	5	0	889	1.36	1979	1983
Burundi	0	0	100	580	0.89	1987	1988
Cameroon	29	40	31	1378	2.11	1985	1985
Central African Rep.	75	25	0	520	0.80	1984	1988
Congo	60	40	0	780	1.19	1973	1982
Côte d'Ivoire	40	60	0	1250	1.91	1985	1986
Equatorial Guinea	0	100	0	55	0.08	1989	1989
Gabon	20	80	0	250	0.01	1976	1984
Ghana	67	33	0	3040	4.65	1982	1984
Guinea Bissau	100	0	0	6	0.01	1982	1984
Guinea Conakry	90	0	10	450	0.69	1986	1989
Kenya	29	1	70	650	0.99	1990	1990
Liberia	10	90	0	300	0.46	1990	1990
Malawi	89	1	10	168	0.26	1985	1985
Mozambique	95	>0.5	5	3690	5.65	1986	1988
Niger	100	0	0	216	0.33	1986	1986
Nigeria	15	85	>0.5	20000	30.6	1979	1981
Rwanda	0	0	100	560	0.86	1984	1985
Senegal	100	0	0	14	0.02	1976	1984
Sierra Leone	60	40	0	90	0.14	1982	1985
Tanzania	40	10	50	6266	9.59	1987	1988
Togo	95	5	0	500	0.77	1980	1984
Uganda	5	0	95	3350	5.13	1992	1992
Zaire	45	35	20	18227	27.9	1972	1982
Zambia	5	0	95	270	0.41	1984	1984
All 27 countries	37	42	21	65355	100		

tinent. These scenarios can therefore be seen as the vertices of a four-dimensional decision space.

Under import conditions of Scenario 2, the transport of food to the interior of the countries would strongly increase the costs of substitution. Including transport to the interior of all the 27 African countries, the benefit by saved investment would increase to approximately US$ 20.2 billion.

If lost cassava would have been replaced by maize, as assumed in Scenario 3, the benefit would have been US$ 8 billion, and with maize food aid in Scenario 4, US$ 14 billion.

3.2. Costs and benefits

The nominal costs of all biological control activities from 1979 (start of the programme) to 2013 were estimated at US$ 34.2 million (Table 2). Compounded /discounted at a rate of 6% relative to the base year of 1994, they accumulated to a total of US$ 46.9 million, which was derived as follows: the total costs for IITA related to cassava mealybug biological control amounted to US$ 37.7 million (nominal US$ 27.4 million). To this, 15% donor agencies' contributions were added, i.e. US$ 5.7 million compounded (US$ 4.1 million nominal). Finally, costs of African governments covering expenses for personnel, buildings, electricity, communication, water, and experimental plots were roughly estimated at US$ 100 000 per country over the whole period of the analysis. This hypothetical average for each of the 27 countries amounted to US$ 3.6 million compounded (US$ 2.7 million nominal) in addition to the support received from donors through IITA.

Since the donor agencies and the African governments financed the local and the overall campaigns, the African farmers had no expenses for the biological control of *P. manihoti*.

Table 2
Costs and benefits (in US$ million) of the biological control project against the cassava mealybug in Africa, with a discount factor of 6% (base year=1994)[a]

Year	Compounding/ discounting factor	Costs								Benefits in scenario			
		To IITA		To donors (overheads)		To African governments		Total					
		A[b]	B[b]	A	B	A	B	A	B	1	2	3	4
1974	3.21	0	0	0	0	0	0	0	0	0	0	0	0
1975	3.03	0.	0	0	0	0	0	0	0	0	0	0	0
1976	2.85	0	0	0	0	0	0	0	0	0	0	0	0
1977	2.69	0	0	0	0	0	0	0	0	0	0	0	0
1978	2.54	0	0	0	0	0	0	0	0	0	0	0	0
1979	2.40	0.30	0.72	0.05	0.12	0	0	0.35	0.84	0	0	0	0
1980	2.26	0.70	1.58	0.11	0.25	0	0	0.81	1.83	0	0	0	0
1981	2.13	1.00	2.13	0.15	0.32	0	0	1.15	2.45	0	0	0	0
1982	2.01	1.00	2.01	0.15	0.30	0	0	1.15	2.31	21	35	16	24
1983	1.90	1.80	3.42	0.27	0.51	0	0	2.07	3.93	98	164	80	117
1984	1.79	2.00	3.58	0.30	0.54	0.20	0.36	2.50	4.48	114	241	135	205
1985	1.69	2.50	4.23	0.38	0.64	0.20	0.34	3.08	5.21	135	314	151	250
1986	1.59	2.00	3.18	0.30	0.48	0.20	0.32	2.50	3.98	329	624	184	343
1987	1.50	1.50	2.25	0.23	0.35	0.20	0.30	1.93	2.90	400	789	196	405
1988	1.42	1.50	2.13	0.23	0.33	0.30	0.43	2.03	2.89	442	890	306	546
1989	1.34	1.32	1.77	0.20	0.27	0.30	0.40	1.82	2.44	408	886	342	600
1990	1.26	1.27	1.60	0.19	0.24	0.30	0.38	1.76	2.22	542	1063	383	666
1991	1.19	1.22	1.45	0.18	0.22	0.30	0.36	1.70	2.02	612	1144	407	699
1992	1.12	1.17	1.31	0.18	0.20	0.20	0.22	1.55	1.73	506	1038	406	699
1993	1.06	1.10	1.17	0.17	0.18	0.20	0.21	1.47	1.56	457	982	396	685
1994	1.00	1.10	0.10	0.16	0.16	0.20	0.20	1.46	1.46	452	968	383	666
1995	0.94	0.80	0.75	0.12	0.11	0.10	0.09	1.02	0.95	395	897	371	648
1996	0.89	0.70	0.62	0.11	0.10	0	0	0.81	0.72	376	854	354	617
1997	0.84	0.60	0.50	0.09	0.08	0	0	0.69	0.58	360	818	339	593
1998	0.79	0.50	0.40	0.08	0.06	0	0	0.58	0.46	343	782	324	568
1999	0.75	0.40	0.30	0.06	0.05	0	0	0.46	0.35	325	742	307	539
2000	0.70	0.30	0.21	0.05	0.04	0	0	0.35	0.25	308	703	291	512
2001	0.67	0.20	0.13	0.03	0.02	0	0	0.23	0.15	292	667	276	486
2002	0.63	0.20	0.13	0.03	0.02	0	0	0.23	0.15	276	633	261	461
2003	0.59	0.20	0.12	0.03	0.02	0	0	0.23	0.14	261	597	247	435
2004	0.56	0.20	0.11	0.03	0.02	0	0	0.23	0.13	246	563	233	411
2005	0.53	0.20	0.11	0.03	0.02	0	0	0.23	0.13	232	531	220	388
2006	0.50	0.20	0.10	0.03	0.02	0	0	0.23	0.12	219	501	207	366
2007	0.47	0.20	0.09	0.03	0.01	0	0	0.23	0.10	207	473	195	345
2008	0.44	0.20	0.09	0.03	0.01	0	0	0.23	0.10	195	446	184	325
2009	0.42	0.20	0.08	0.03	0.01	0	0	0.23	0.09	184	421	174	307
2010	0.39	0.20	0.08	0.03	0.01	0	0	0.23	0.09	173	397	164	290
2011	0.37	0.20	0.07	0.03	0.01	0	0	0.23	0.08	164	375	155	273
2012	0.35	0.20	0.07	0.03	0.01	0	0	0.23	0.08	154	354	146	258
2013	0.33	0.20	0.07	0.03	0.01	0	0	0.23	0.08	146	334	138	243
Total		27.38	37.66	4.15	5.73	2.70	3.61	34.23	47.00	9372	20226	7971	13970

[a] Benefits for four scenarios: 1 — cassava price at farm gate, 2 — cassava price plus transport, 3 — price of local maize as substitute, 4 — maize price plus transport.
[b] A — nominal, B — present value at end of 1994.

Table 3
Sensitivity analysis of different scenarios for calculating the losses and benefits of the cassava mealybug biological control project, varying the total duration of the coverage of the calculations (100 years versus 27 years), the discounting/compounding factor (12% p.a. versus 0% p.a.), and the efficiency of *Apoanagyrus lopezi* (impact half of the one documented)

Variant	Standard assumptions (US$ per tonne)[a]			Duration (years)		Discounting/compounding factor		Yield loss reduction by *A. lopezi*
	90	167	333	100	27	12%	0%	50%
Costs in million US$	47.0	47.0	47.0	48.19	45.56	70.61	33.72	47.00
Benefits in million US$								
Scenario 1	9372	17432	34676	11729	6623	8981	11873	6596
Scenario 2	20226	37620	74836	25622	13934	18959	26223	14568
Scenario 3	7971	14826	29493	10201	5371	7335	10539	5855
Scenario 4	13970	25984	51689	17905	9382	12823	18513	10285
Benefit cost ratio								
Scenario 1	199	371	738	243	145	127	352	111
Scenario 2	430	800	1592	532	306	268	778	239
Scenario 3	170	315	628	212	118	104	313	94
Scenario 4	297	553	1100	372	206	182	549	165

[a] Duration 40 years, discounting/compounding factor 6%, yield loss reduction depending on ecological zone (about 90%), for three different price levels.

The total annual costs for the biological control of *P. manihoti* peaked in 1985 at US$ 5.2 million, compounded to the base 1994 at 6% p.a. From 1985 onward, there was a continuous decline in the annual budgets.

Benefit cost ratios for the biological control of *P. manihoti* varied depending on the different assumptions. In Scenario 1, costs of US$ 47 million brought returns of US$ 9.4 billion (Table 2), i.e. a benefit cost ratio of 199 through 40 years of analysis. With the same expenses, benefit cost ratios were 430 in Scenario 2, 170 in Scenario 3 and 297 in Scenario 4 (Table 3).

3.3. Sensitivity analyses

Since many data were based on uncertain assumptions, sensitivity analyses were carried out by varying some of those parameters (Table 3).

The most important factor affecting the cost-benefit analysis is the initial assumption about the cost of the commodity. In the preceding analysis, all benefits were based on a world market price of cassava. Within Africa, where most of the cassava from this continent is traded, prices of cassava are, however, much higher. Thus, with a conservative price of US$ 167 per tonne dry weight, the benefit in Scenario 1 amounted to US$ 17.4 billion and the benefit cost ratio became 371. With the higher commodity price of US$ 333 per tonne the benefits became US$ 34.7 billion and the benefit cost ratio 738.

For various discounting rates, the total benefit changed from US$ 9.0 billion with 12% p.a. to US$ 11.9 billion with close to 0% p.a., and the benefit cost ratio from 127 to about 352.

If *A. lopezi* was assumed to cut yield loss (of 40%) in half, instead of the reduction by about 9/10th used in the base line analysis, the benefit cost ratio would still be 111.

By contrast, if the analysis was extended for 100 years, the benefit cost ratio would only rise to 243 as compared to a benefit cost ratio of 145 under a 27-year-duration (up to the end of the year 2000).

The results for other scenarios are given in Table 3. They indicate that even with pessimistic assumptions this biological control project would still remain highly profitable.

4. Discussion

Complete economic analyses of biological control projects are rare. One famous example, the complete control of the rhodesgrass mealybug by the encyrtid *Neodusmetia sangwani* (Rao), featured an evaluation of the loss in turfgrass, partially compensated for by insecticide treatments and the reduction in head of cattle feeding on susceptible grasses (Dean et al., 1979). Analysis was done on an yearly basis and not compounded. Returns within 1 year were far greater than the outlays of the research station or the costs of control with insecticides. This evaluation was done in an economic environment where all costs and benefits could be labelled quite clearly. The calculations did not, however, reflect the costs accruing because insect populations treated with insecticides are likely to develop pesticide resistance (Gutierrez et al., 1979).

While impact of biological control could also be assessed in terms of reduced use of insecticides in Asian rice systems (Fox, 1991; Kenmore, 1991), this is not possible for African small holder farms, where no insecticides are used on cassava.

In the present study, all statistical figures reported and cited are less clear than in the above examples. National cassava production and average prices are extremely difficult to estimate, because of a high regional diversity of cropping patterns and fluctuations in yield (Nweke, 1996a). Yield measurements on farmers' fields are uncommon and the price of cassava, which is traded freely, is rather volatile. Evaluating the economic benefits of a biological control project across all of Africa is therefore difficult and can yield broad estimates only.

In all scenarios, changes in prices caused by the reduction in supply and, after biological control had been established, the increase in supply were not considered directly and prices were kept constant. All the other factors affecting cassava prices, like quality, processing technology, market access, etc. (Nweke, 1996a, b; Prudencio et al., 1992) were not included either. The influence of these fluctuations was, however, gauged by comparing scenarios with different prices. Thus, in scenario 1, the benefit cost ratio is about 200 with the low world market price and about 370 and 740 with low and high price levels, respectively, as they are paid at different times in the inter-African market.

Cassava has become a prime cash crop across much of Africa (Nweke, 1996a) and better processing technologies allow further expansion of cassava (Nweke, 1996b). Scenario 1 of the present study, with local increase in cassava production attributed to *A. lopezi*, seems therefore the most realistic one for areas where land reserves are still available. Scenario 2 would apply to those countries or regions, which responded to the mealybug disaster by importing cassava from neighboring countries. Scenario 3 applies to the regions, where a collapse of cassava production necessitated a change to increased maize production. This scenario turns out to be cheaper than Scenario 1. On paper this may be so, but since dietary habits of peoples are a powerful force, it does not follow from this price differential that maize would be preferred. Also, it assumes that indeed more maize could have been produced, which depends on soil and climate. Cassava being the far hardier plant than maize, this scenario becomes unrealistic under harsh conditions. Its main attraction is the fact that maize has a well established world market price. Scenario 4, with import of maize as food aid, applied to the early years of mealybug infestation and only to a few countries (Pelletier and Msukwa, 1990). It must, therefore, be stressed that none of the scenarios is equally likely for all countries and all years, and the evaluation for some of the countries might be better served by still other scenarios. Thus, alternatives for cassava would be rice for Côte d'Ivoire, yams for Nigeria, banana for Uganda, and so on, while no alternative might exist for the Democratic Republic of Congo.

The economic impact of biological control of the cassava mealybug had been analyzed before (Norgaard, 1988), based on rough estimations, as the author conceded himself, and the extrapolation of a few West African data over the whole continent. The Norgaard study did not have access to the detailed country information and ecological background, which became available for the present analysis. The present study goes further by investigating how the loss in cassava production could be valued under different circumstances. Different scenarios are presented and sensitivity analyses made. Another difference concerns the longer time frame (40 as compared to 25 years) and a lower interest rate (6% with 1994 as base year versus 10%, with 1982 as base year) of the present study. We contend that the present choices of time frame and interest rates are based on common practice and justified by the long-term nature of the project. Thus, for instance for 1991, the average interest rate on new commitments for the private sector was 7.6% according to the World Bank Annual Report 1992, and agroforestry projects have commonly been evaluated within a 50 year time frame (Engelhardt, 1989). Both parameters, duration and interest rates, were then tested in the sensitivity analysis. With longer time frames it was shown that any additional revenue accruing beyond 40 years was negligible. Even with the unrealistically high interest rate of 12%, the project would still have given a high benefit cost ratio.

In the present study, Norgaard's assumption that the impact of biological control tapers off was rejected as a general concept. Adaptation of indigenous coccinellids to the new food source, *P. manihoti*, which led to an early reduction of pest damage, was, however, included in the calculations. While this initial reduction of *P. manihoti* by indigenous coccinellids was considerable, the impact of local predators proved to be much smaller once biological control by *A. lopezi* was established and mean population levels of *P. manihoti* were low (Gutierrez et al., 1988). We know of no case where this biological equilibrium between *P. manihoti* and its natural enemies, including *A. lopezi*, was abandoned and where long-term biological control would have failed. We, therefore, see no reason to have the effect of *A. lopezi* taper off after this initial adjustment.

Norgaard's costs of US$ 14.8 million were much smaller than assumed here, because no donor overheads had been included, and cost attribution within IITA had been done differently and more favourably for a good return. His benefits were US$ 2.2 billion and the benefit cost ratio was 149. This result is lower than the present sensitivity analysis and comes quite close to the benefit cost ratio of 145 calculated for the pessimistically short period 1974–2000.

In conclusion, the present analysis was based on much more reliable data than those available to Norgaard, (1988), who visited IITA as a consultant at the beginning of the biological control programme. After correcting some wrong assumptions, improving the time frame of impact of *A. lopezi*, putting costs on a broader and more realistic basis, developing some realistic scenarios of reaction by the farmers and governments to the mealybug disaster, the actual benefit cost ratios of the present study are higher, but not vastly different from Norgaard's. In both the studies, the internal rates of return (261, 328, 245, 289%, respectively, for the four scenarios of the present study) are extremely high.

The present evaluation must be judged as conservative. *P. manihoti* does more damage under conditions prevailing in the savanna zones than in the forest. Biological control by *A. lopezi* brings correspondingly higher return in the savanna (Neuenschwander et al., 1989). Proportioning cassava to the different ecological zones was based on maps. This underestimates the contribution to crop loss reduction from the savanna zones on two counts. First, cassava production is moving into ever drier areas (Nweke et al., 1994); second, areas with true rainforest conditions are shrinking at a fast pace, so that the area covered by rainforest is now much reduced by comparison to the maps used (Sayer et al., 1992). Finally, the chosen parameters did not take into account the observed intensification of cassava culture (Nweke and Spencer, 1995), which would mean higher yields, but also higher potential losses, and higher savings due to biological control.

The present evaluation was made at a time when an area producing about 3 million tonnes of cassava per year, including Madagascar, had not yet been infested by *P. manihoti*. Further spread to India and the rest of Asia remains a threat, which has to be delayed as long as possible by careful quarantine inspection. For these areas, biological control by *A. lopezi* constitutes a technology on the shelf, which can be called for at little cost.

In the present project analysis, secondary costs, like basic research, training, collaboration with national programmes, etc., were incorporated. The total costs divided through the 9 million ha of cassava in Africa would result in a single treatment of US$ 5.2 per ha. Divided over the 40 years of the analysis, yearly costs amount to 13 US-cents per ha.

Beside the benefit of higher yield of cassava tubers, as evaluated in the present study, there is also a higher leaf yield for African families eating cassava leaves as vegetable. Another positive side effect of the biological control, not incorporated into the evaluation, was the higher yield of stems, which are sometimes also used for fuel (Schaab, 1997).

Finally, the benefit of maintaining a healthy environment through the use of biological control can only be stated in words, but should be recognized as a benefit. Current efforts at expressing benefits to the environment in monetary terms have generally been confronted with difficulties and the need for a more strategic approach to ecological impact assessment has been identified (Treweek, 1996). While some projects might have to balance short-term monetary gains against long-term benefits of sustainability, this antagonism did not materialize in the present biological control project. There simply was no short-term answer since all potential alternatives were generally not effective and not feasible under the given conditions. The project has thus become a good example in the use of technologies that substitute for external inputs, thereby guaranteeing sustainability (Meerman et al., 1996).

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