The impacts of some classical biological control successes

Matthew J.W. Cock[1a*], Roger K. Day[2a], Hariet L. Hinz[3], Kathryn M. Pollard[1b], Sarah E. Thomas[1c], Frances E. Williams[2b], Arne B.R. Witt[2c] and Richard H. Shaw[1d]

Address: [1] CABI, Bakeham Lane, Egham TW20 9TY, UK. [2] CABI, Canary Bird, 673 Limuru Road, Muthaiga, PO Box 633-00621, Nairobi, Kenya. [3] CABI, Rue des Grillons 1, CH-2800 Delémont, Switzerland.
ORCID.org: [1a]0000-0003-2484-3021; [1b]0000-0002-0913-6743; [1c]0000-0002-8499-9493; [1d]0000-0003-0805-1841; [2a]0000-0002-4854-7609; [2b]0000-0002-6772-0753; [2c]0000-0003-2257-4411; [3]0000-0003-2930-6807.

***Correspondence**: Matthew J.W. Cock. Email: m.cock@cabi.org

Received: 23 July 2015
Accepted: 19 November 2015

doi: 10.1079/PAVSNNR201510042

The electronic version of this article is the definitive one. It is located here: http://www.cabi.org/cabreviews

Abstract

We differentiate between the success of a classical biological control programme and its impact; the former addressing the completed implementation of the steps of a biological control programme, and the anticipated reduction of the target pest, and the latter addressing the societal and environmental benefits of control of the target pest. We provide ten case studies in which CABI has played a role to illustrate aspects of success and impact for biological control programmes against insects pests and weeds: cassava mealybug (*Phenacoccus manihoti*), mango mealybug (*Rastrococcus invadens*), pink hibiscus mealybug (*Maconellicoccus hirsutus*), orthezia bug (*Insignorthezia insignis*), brown peach aphid (*Pterochloroides persicae*), banana skipper (*Erionota torus*), black sage (*Varronia curassavica*), rubber vine (*Cryptostegia grandiflora*), leafy spurge (*Euphorbia esula*) and water hyacinth (*Eichhornia crassipes*). In light of these we discuss the assessment of success and impact of biological control programmes, why these aspects are often not adequately addressed, how they might be retroactively addressed and the implications for donor-funding of biological control programmes for developing countries.

Keywords: Biological control agents, Insects, Weeds, *Phenacoccus manihoti*, *Rastrococcus invadens*, *Maconellicoccus hirsutus*, *Insignorthezia insignis*, *Pterochloroides persicae*, *Erionota torus*, *Varronia curassavica*, *Cryptostegia grandiflora*, *Euphorbia esula*, *Eichhornia crassipes*

Review Methodology: Case studies were selected by the authors based on their personal knowledge to provide a variety of scenarios; all involved CABI inputs at some stage and all were considered to have been 'successful'. The case studies were compiled from key references supplemented with additional information obtained by checking the references cited therein, searching CAB Abstracts, searching on the internet, and personal contacts when appropriate. The discussion of issues was based on the authors' knowledge and the case studies prepared.

Introduction

Biological control is the action of natural enemies (predators, parasitoids and pathogens, often referred to as biological control agents [BCAs]) against target pests. Classical biological control (CBC) is the introduction of a BCA, usually from a pest's area of origin, to permanently control a target pest in an area where it has become invasive. Once introduced, the intention is that the BCA should become established, reproduce and spread, and have a self-sustaining effect on the target pest. In the context of agriculture and forestry, the main beneficiaries of CBC are the farmers and foresters who have their pest problems reduced without necessarily actively promoting or introducing BCAs, which by spreading and reproducing naturally contribute to the public good [1]. The reduced crop losses from pests lead to improved food security and improved livelihoods. Farmers in most parts of the world have benefited from this approach. Farmers also benefit from reduced exposure to pesticides as a result of

Table 1 The use of biological control agents up until 2006 broken down by country income economy groups [4] (after [3])

	Biological control agents released			
	Number of countries	Total number of releases	% of total releases	Average number/ country
High-income economies	33	4078	63.7	124
Upper middle-income economies	31	1355	21.2	44
Lower middle-income economies	37	666	10.4	18
Low-income economies	37	148	2.3	4
Unclassified	7	152	2.4	22
Total	145	6399		

Each combination of source country–target country–pest–time period is counted as one release.

reduced need, and consumers benefit from reduced pesticide residues in food. Thus, CBC is a public good, as the benefits reach all who grow and use the crop, without requiring them to make any additional interventions. The use of CBC also enables producers to reduce pesticide use and residues to meet the high standards of profitable foreign export markets, resulting in job creation in the grower's country and a significant influx of foreign exchange to developing countries. For all these reasons, CBC in developing countries is often considered an appropriate form of development assistance, and suitable for development agency funding.

Cock *et al.* [2, 3] compiled a database of over 7000 classical biological introductions that had been made against all groups of invertebrate and weed pests up to 2006. They found that 2677 different BCAs had been released against at least 763 pest targets in a total of 146 different (political) countries. The 12 biggest users of biological control with more than 100 BCAs released are: USA, Australia, Canada, New Zealand, South Africa, UK (almost entirely overseas territories), Fiji, Mauritius, India, France (mostly overseas territories), Israel and Guam (in order). They showed that there is a strong correlation between the affluence of countries and the number of BCAs they have released (Table 1). Not only is CBC in developing countries appropriate for donor support, but it will also enable developing countries to obtain a share of the benefits that developed countries have already obtained from this approach.

CABI has been supporting countries to implement CBC since the 1920s, both for developed and developing countries [5]. It has particular expertise and experience in the search for, evaluation, risk assessment, supply and release of potential BCAs. It has also assisted countries with capacity building, risk evaluation and sometimes the release and monitoring of establishment and impact of BCAs. In general, both the monitoring of agents and the evaluation of CBC programmes have been neglected [6–8]. Only rarely has CABI been involved in studies on the impact of the pest prior to control or the impact of the successful implementation of CBC, which would normally be a national responsibility. For this reason, documentation of the impact of CABI's CBC activities usually depends on the work of others and the priority which the beneficiary countries placed on this.

In this review, we shall use the terms 'success' and 'successful' to refer to the extent to which the CBC programme has been carried out as planned and the target pest brought under control, and the term 'impact' to assess how this success has affected socio-economic and societal concerns (normally positively, but the possibility of adverse effects should not be ignored). This is slightly different to the useful analysis for arthropod CBC by Van Driesche and Hoddle [9], who recognized several steps in the biological control process (choosing the targets, acquiring natural enemies, choosing safe agents for release, establishing them in suitable habitats, managing the adoption process and measuring final outcomes) and suggested measures of success and failures for each. Their last step 'measuring final outcomes' includes both the successful control of the target and what we are referring to as impact. Here, we take a more truncated approach, condensing the middle four steps identified by Van Driesche and Hoddle [9] as one and dividing 'measuring final outcomes' into several steps to focus on the aspects which demonstrate success and assess impact. Thus, when evaluating the success and impact of a CBC programme, there are several steps to consider, after the initial selection of the target:

- Firstly the logistics of implementation: was a suitable BCA found? Was it successfully released in the target area? Did it become established and persist in the target area? When starting a new CBC programme, there is no guarantee that any of these steps can be completed, and their achievement needs to be documented.
- Next, is there any evidence to show what impact the BCA has had on the target pest? Can it be demonstrated that the BCA successfully reduced the population of the target pest?
- Then it needs to be tested whether reducing the population of the target pest has led to the desired benefits in terms of reduced pesticide use, reduced crop losses, increased carrying capacity, increased yields and/or environmental benefits. Such assessments

should take into consideration the possibility that reducing the incidence of the target pest merely allows some other pest to occupy this niche, so that benefits are less than anticipated.

- Finally, what economic, ecological and social changes have these benefits produced, and do these align with the goal of the intervention? In recent years, donors increasingly want to see a proper gender-sensitive impact evaluation, to help show how their funding has contributed towards achieving their objectives such as the Millennium Development Goals.

It may be helpful to consider these steps in terms of the logical framework approach, often used for monitoring the implementation and impact of development projects [10]. The steps in a CBC programme are the activities, which if successfully implemented lead to outputs and an outcome, the biological control of the target pest, i.e. a success. Beyond this relatively straightforward success, the project purpose will be achieved if the successful biological control leads to increased yields or reduced losses in the crop system (this will be different for environmental pests), and if so whether this contributes to the overall goal, which may be characterized as improved or protected livelihoods, moving people out of poverty etc. This last aspect has not necessarily been precisely formulated in older projects, although it is in most donor-funded projects now. In the past, sustainable reduced crop losses may have been seen as a self-evident public good, but now it is desirable to capture what this means in terms of the livelihoods of the farmers and consumers that were affected by that pest. There are a growing number of historical and current studies that attempt to assess what the economic impact of successful biological control has been, usually in terms of increased yield and reduced control costs (see e.g. Hill and Greathead's [11] extensive review). Relatively few studies have attempted to take the next step and assess the impact in societal terms, but it seems that more of those that have been attempted relate to successes in developing countries that were funded by donor agencies, than successes in developed countries funded by their governments.

There are many reviews and commentaries on the benefits of CBC, e.g. [11–20]. We do not attempt to review or discuss these, except to support our case studies and specific points relating to the assessment of impact rather than success, in the senses used here.

In this review we present several case studies of CBC where CABI has had some role in their implementation and there is some information available that can be associated with, or extrapolated to, their impact. We consider the components of assessing success and impact in CBC, and the implications for donor-funding to assist developing countries to use this important pest management tool.

Case Studies of some CBC Successes

In order to support our review, we have prepared ten case studies selected from amongst those where CABI has played a role in at least one part of the CBC process, but in all cases involving partners. These case studies spread over the past 65 years cover insect and weed CBC, and include examples that are from both developed and developing countries, agriculture and environment, islands and continents, well documented and poorly documented, and well evaluated and poorly evaluated, as shown in Tables 2–4.

Review of Selected Issues

Pest impact

Introduced agricultural and environmental insect pests and weeds are the typical targets of CBC, and most successes have been against these groups of pests. The impact of agricultural pests is simpler to assess, as crop yields, losses, sales and profits are all easily expressed in monetary terms, although interpreting these in light of the gender of those affected will need additional data. The impact of environmental pests is more likely to be expressed in terms of loss of ecosystem services and biodiversity; as Denslow and D'Antonio [21] conclude, there are 'few quantitative assessments of the impacts of pest plant reduction on community composition or ecosystem processes'. Many pests, especially weeds, overlap both these groups, which means that their negative impacts are diverse, affecting different parts of society and economy in different ways and to different degrees (case studies 8 rubber vine and 10 water hyacinth). Some can even have minor uses so as to make an offsetting positive contribution (case study 10 water hyacinth). The importance of these uses is likely to be different for men and women; for example women benefit far more than men from being able to collect and use the invasive woody shrub *Prosopis juliflora* (Sw.) DC. (Fabaceae) as firewood in the Lake Baringo area of Kenya [22].

Thus, measuring the impact of a pest can be multi-sectoral and differ in relation to the roles of men and women [23]; it is often much more complicated than simply crop losses. The impact of CBC will also be likely to vary with regard to the different sectors and players, and conversely the degree of control required to achieve useful impact is also likely to vary. Hence, demonstrating that CBC has reduced the population or rate of spread of a pest is the first step of what can be a complicated process to assess the impact of that successful reduction of the pest.

Nevertheless, some alien agricultural pests act purely as crop pests of a single crop that is itself introduced. As an introduced pest, the banana skipper (case study 6) acts only as a defoliating pest on bananas, which are grown for

Table 2 Overview of ten case studies on the success and impact of classical biological control prepared for this review

Case study	Insect/ weed	Common name (scientific name)	Target area	Sectors	Quality of documentation
1	Insect	Cassava mealybug *Phenacoccus manihoti* Matile-Ferrero	Tropical Africa	Agriculture	Good
2	Insect	Mango mealybug *Rastrococcus invadens* Williams	West Africa	Agriculture	Good
3	Insect	Pink hibiscus mealybug *Maconellicoccus hirsutus* Green	Caribbean	Agriculture and environment	Patchy
4	Insect	Orthezia bug *Insignorthezia insignis* (Browne)	St Helena	Environment	Good
5	Insect	Brown peach aphid *Pterochloroides persicae* (Cholodkovsky)	Yemen	Agriculture	Poor
6	Insect	Banana skipper *Erionota torus* Evans	Mauritius	Agriculture	Poor
7	Weed	Black sage *Varronia curassavica* Jacq.	Mauritius, Malaysia, Sri Lanka	Agriculture and environment	Poor
8	Weed	Rubber vine *Cryptostegia grandiflora* Roxb. ex R. Br.	Australia	Agriculture and environment	Good
9	Weed	Leafy spurge (*Euphorbia esula*)	North America	Agriculture and environment	Patchy
10	Water weed	Water hyacinth *Eichhornia crassipes (Mart.) Solms*	Various including Sudan, Bénin Malawi	Agriculture, fisheries, environment, transport, water, power	Patchy

domestic consumption and local sale or on a plantation scale for local consumption or export. However, the value of pest-free banana plants to a subsistence farmer on the poverty line in Papua New Guinea who grows banana as a staple is not the same as for an urban householder in Mauritius with a couple of banana plants in the backyard, which differs again from a plantation operator growing for export markets.

Similarly, in case study 1, cassava mealybug attacks only cassava, and both were introduced in the Old World from South America. In Africa, cassava is mainly grown as a staple crop by small-holder farmers throughout the tropics, and has an important role as a food reserve for times of shortage (the tubers can remain on the plant below ground for an extended period without spoiling). However, it is also grown on an industrial scale as a source of carbohydrates and as a biofuel, particularly in Southeast Asia.

Nevertheless, these are simple sets of impact compared with many introduced terrestrial and aquatic weeds. One striking example is water hyacinth, native to South America, but now an environmental and social menace throughout the Old World tropics. It affects the environment and humans in diverse ways; most of these are detrimental, although some are beneficial or potentially useful (case study 10). Many of these effects are due to its potential to grow rapidly and produce enormous amounts of biomass, thereby covering extensive areas of naturally open water. To measure the net impact of a successful biological control programme against water hyacinth in a comprehensive way would be a very substantial undertaking even in just one water body.

More generally, examples of the types of negative impacts caused by pests that have been targeted or controlled by CBC are open ended, but a range of the more common and important ones are summarized in Table 5, while others include:

- crop losses due to diseases vectored or otherwise facilitated by invertebrate pests;
- greater family involvement in pest management on small-holdings, such as women and children taken out of school to weed and manually collect pests; and
- human health costs associated with allergenic and sensitisation reactions to weeds or their pollen.

Amongst other aspects, the knock-on effects of these negative impacts can be considered in terms of those listed in Table 6 (as illustrated in case studies), as well as others such as:

- lost schooling and reduced opportunities for women and children who have to spend more time on weeding and other pest management measures; and
- rural stability and local security (e.g. driving conflict between displaced tribes), which may be adversely affected if livelihoods are adversely affected.

Table 3 Overview of the implementation of classical biological control (CBC) in the ten case studies on the success and impact of CBC prepared for this review

Case study	Common name	Target area	Date (and country/state) of first pest occurrence in target area	BCAs introduced (years)	Result
1	Cassava mealybug	Tropical Africa	1970s (DR Congo)	An encyrtid wasp parasitoid, *Anagyrus lopezi* (De Santis) (1981) and several other parasitoids and predators	*A. lopezi* was primarily responsible for the complete biological control of cassava mealybug throughout most of its range in tropical Africa
2	Mango mealybug	West Africa	1981 (Togo, Ghana)	Two encyrtid wasp parasitoids, *Gyranusoidea tebygi* Noyes (1987) and *Anagyrus mangicola* Noyes (1991)	Together, the two parasitoids are considered to have given complete control throughout affected areas of West Africa
3	Pink hibiscus mealybug	Caribbean	1994 (Grenada)	Two encyrtid wasp parasitoids, *Anagyrus kamali* Moursi (1996) and *Gyranusoidea indica* Shafee, Alam and Agarwal (1997), and two coccinellid beetle predators, *Crytolaemus montrouzieri* Mulsant (1996) and *Scymnus coccivora* Ramakrishna Ayyar (1996)	Successful control is mainly attributed to *A. kamali* and *C. montrouzieri*, the latter eliminating dense patches, and the former maintaining low populations
4	Orthezia bug	St Helena	1970s or 1980s	A coccinellid beetle predator, *Hyperaspis pantherina* Fürsch (1993)	Complete control and no subsequent outbreaks reported
5	Brown peach aphid	Yemen	1993	A braconid parasitoid, *Pauesia antennata* (Mukerji) (1997)	Complete control except where disrupted by use of chemical insecticides
6	Banana skipper	Mauritius	1970	An encyrtid egg parasitoid, *Ooencyrtus pallidipes* (Ashmead) (1971), a braconid larval parasitoid, *Cotesia erionotae* (Wilkinson) (1971), and two other parasitoids	*O. pallidipes* and *C. erionotae* became established. Populations of the pest rapidly fell attributed to the introduced BCAs, but there was a temporary flare up soon afterwards following a cyclone. It is assumed that the current rarity of the pest reflects renewed action by the BCAs
7	Black sage	Mauritius	About 1860	Two chrysomelid beetles, *Physonota alutacea* Boheman (1947) and *Metrogalleruca obscura* Degeer (1948), and a seed-feeding eurytomid *Eurytoma attiva* Burks (1949)	Complete control throughout the island, so that black sage is no longer known as a weed
8	Rubber vine	Australia	1860s	Several insects and a rust fungus, *Maravalia cryptostegiae* (Cummins) Ono	Most of the weed was controlled by the fungus within 7 years. Seedling establishment has been reduced to close to zero
9	Leafy spurge	North America	1827 (Massachusetts)	Several insects including five species of *Aphthona* (Chrysomelidae)	*A. czwalinai*, *A. lacertosa* and *A. nigriscutis* produced substantial but slightly variable reduction in leafy spurge cover across all affected areas. In general, infestations were reduced by 90% or more to less than 10% cover
10	Water hyacinth	Various	1955 (Sudan)	Two defoliating weevils, *Neochetina eichornniae* Warner (1978) and *N. bruchi* Hustache (1979), and a stem boring crambid moth, *Niphograpta albiguttalis* (Warren) (1980)	All three BCAs established, but their relative contribution to control is unknown. Since the establishment of CBC, there has been no accumulation of water hyacinth behind the Jebel Aulia Dam, whereas before then thousands of ha accumulated annually
			Late 1960s (Malawi)	*Neochetina eichornniae*, *N. bruchi* and *Niphograpta albiguttalis*, *Eccritotarsus catarinensis* (Carvalho) (all 1996–2001)	*Neochetina eichornniae*, *N. bruchi* and *Eccritotarsus catarinensis* became established and damaged water hyacinth, but no accurate assessment of impact has been made to date. Anecdotal evidence suggests a reduced weed status
			1977 (Bénin)	*Neochetina eichornniae* (1991), *N. bruchi* (1993) and *Niphograpta albiguttalis* (1993)	After a delay of about 10 years, the weevils are credited with having substantial impact. Villagers perceived water hyacinth as having been reduced from a serious pest to one of minor or moderate importance

Table 4 Overview of the evaluation of ten case studies on the success and impact of classical biological control prepared for this review

Case study	Common name	Target area	Key pest impacts	Type of published impact assessment	Cost: benefit (area)	Scope for further evaluation
1	Cassava mealybug	Tropical Africa	Cassava crop losses threatening livelihoods and food security	Detailed scientific assessment and cost-benefit analysis	170–1592 (Africa)	The programme in Africa has been documented, but the success and benefits of the on-going programmes in SE Asia should be fully evaluated
2	Mango mealybug	West Africa	Mango and other fruit crop losses threatening livelihoods and quality of nutrition	Detailed scientific assessment and cost-benefit analysis	145 (Bénin)	The programme in Africa has been documented, particularly in Bénin, but there is scope for extrapolating impact across the region
3	Pink hibiscus mealybug	Caribbean	Multiple crop losses affecting livelihoods and trade	Some scientific assessment and partial retrospective cost-benefit analysis	8 (Trinidad and Tobago)	It should be possible to make a more detailed Caribbean-wide cost-benefit assessment
4	Orthezia bug	St Helena	Extinction of endemics and threatened habitat change	Scientific assessment and anecdotal conservation benefits	–	Further monitoring of gumwoods, orthezia bug and BCA needed to evaluate lasting impact
5	Brown peach aphid	Yemen	Peach and stone fruit crop losses threatening livelihoods	Limited scientific assessment and anecdotal comments on socio-economic impact	–	Not practical at present, but further monitoring of aphid and BCA would evaluate lasting impact; data on on-going value and importance of stone fruits for livelihoods is needed
6	Banana skipper	Mauritius	Banana losses affecting industry and quality of nutrition	Anecdotal comments on control of target and benefits	53 (Mauritius)	Monitoring of skipper and BCAs is needed to clarify if CBC is working effectively. Building on the extrapolation presented here, a more rigorous cost-benefit analysis should be made
7	Black sage	Mauritius, Malaysia, Sri Lanka	Invasion of low-maintenance agricultural land affecting industry and livelihoods	Anecdotal comments on control of target and benefits	–	Building on the extrapolation presented here, a more rigorous cost-benefit analysis could be attempted, but is likely to be rather speculative. Surveys should be made to confirm the present distribution of the weed and effectiveness of CBC in Malaysia and Sri Lanka, as should predictions of spread and impact of the weed without CBC
8	Rubber vine	Australia	Increased costs for cattle industry and loss of biodiversity	Detailed scientific assessment and cost-benefit analysis	109	Continued monitoring and assessment of changes in biodiversity should be undertaken to confirm benefits of CBC for the environment
9	Leafy spurge	North America	Reduced cattle production and loss of biodiversity	Some scientific assessment and partial retrospective cost-benefit analysis	8.6–56 (northern Great Plains, USA)	Continued monitoring and assessment of changes in biodiversity should be undertaken to confirm benefits of CBC for the environment. It should also be possible to extend the geographically restricted cost-benefit analysis to the whole of North America, based on modelling the potential spread and impact of the weed without CBC
10	Water hyacinth	Various including Sudan, Malawi, Bénin	Adversely affected livelihoods of riparian communities; increased costs and disruption for power generation; ecosystem changes and loss of biodiversity	Sudan: anecdotal comments on control of target and benefits Malawi: anecdotal comments on apparent changes in weed status Bénin: scientific assessment and socio-economic survey	– – 124	Further work in southern Sudan is currently not practical, but eventually surveys of water hyacinth and its natural enemies should be made. Socio-economic surveys of current perceptions may be useful, but there will be few who remember the problem in detail before CBC. In Malawi, new studies should compare water hyacinth impact on local communities and biodiversity to results reported in earlier studies, although it will be difficult to separate the impact of water hyacinth from that of other water weeds

Table 5 Some of the negative impacts caused by pests that have been targeted or controlled by classical biological control, and the case studies which illustrate these

Impacts	1 cassava mealybug	2 mango mealybug	3 pink hibiscus mealybug	4 orthezia bug	5 brown peach aphid	6 banana skipper	7 black sage	8 rubber vine	9 leafy spurge	10 water hyacinth
Crop losses due to direct damage by the pest	x	x	x		x	x				
Increased pest management costs and time inputs, e.g. pest monitoring, extra pesticide applications, additional cultural control measures, weeding	x	x	x	x	x	x	x	x	x	x
Increased pesticide use and associated human and environmental harm	x	x	x		x	x				
Production of certain crops may cease to be viable if all or most of the crop is lost	x	x			x	x				
Increased costs and losses for livestock production due to displacement of desirable forage plants, stock poisoning, operational costs, etc							x	x	x	
Reduced, poor quality, pest contaminated or pesticide contaminated export crops leading to consignments being turned away, affecting national economics			x							
Market prices for the pest-affected food product rise due to crop shortages, adversely affecting quality of rural/urban nutrition		x				x				
Loss of biodiversity, habitat and ecosystem services such as watershed protection, pollination, etc.			x	x			x	x	x	x
Adverse effects on water use, including fishing, water transport and hydroelectric power										x
Agricultural land taken out of production due to weed infestation							x			

Table 6 Some of the knock-on effects of negative impacts caused by pests that have been targeted or controlled by classical biological control, and the case studies which illustrate these

Knock-on effects	1 cassava mealybug	2 mango mealybug	3 pink hibiscus mealybug	4 orthezia bug	5 brown peach aphid	6 banana skipper	7 black sage	8 rubber vine	9 leafy spurge	10 water hyacinth
Livelihoods of rural subsistence farmers, through reduced food available for on-farm consumption, reduced family income from selling produce, increased crop production costs	×	×	×		×	×				
Increased food prices generally if the production of key pest-affected crops goes down	×		×			×				
Negative impact on food security due to reduced staple food production	×	×			×					
Negative effects on the national economy due to changes in local food markets and export crop earnings	×	×	×		×	×				
Decreases in land values when alien weed infestations make them less profitable or unprofitable							×	×	×	
Plant succession initiated by the invasive species							×			×

Assessing CBC success

There are two contrasting aspects to the assessment of CBC success in terms of a reduced target pest population. Firstly, what change has there been in pest population density (and/or mortality due to BCAs), pest pattern of distribution in time and space, rates of dispersal and spread, etc.; this has been documented in all case studies. The second part is the challenge of demonstrating cause and effect. A BCA was introduced and the pest population went down, but was this because of mortality caused by the BCA or just a coincidence? This is not in itself a straightforward question, and much biological control assessment is based on correlation (i.e. the BCA population increases, then the pest population decreases), which is relatively easy to demonstrate, and shown in all the case studies presented here. See also the extensive discussion of this topic in e.g. Gurr and Wratten [17].

Assessing CBC impact

Once there is evidence to indicate that a CBC programme has successfully reduced a pest population, the resultant impact can be considered. Firstly, what is the immediate, direct value of this reduction in target pest population? Usually this is expressed in monetary terms, especially for crop pests (case studies 1 cassava mealybug, 2 mango mealybug, 3 pink hibiscus mealybug, 6 banana skipper, 8 rubber vine, 9 leafy spurge), but it is more difficult for environmental pest (case studies 4 orthezia bug, 7 black sage, 8 rubber vine, 9 leafy spurge and 10 water hyacinth). Then, what impact does this amount of pest reduction and monetarized benefits have on societal issues? Can it be shown to have made a positive change in farmer livelihoods, rural stability, food security, increased trade, national well-being, etc.? Very few CBC programmes have attempted to assess all the impact that is achieved, particularly for the bigger picture benefits to society. Some methods used include:

- economic cost: benefit analyses;
- socio-economic comparisons before and after, e.g. number of people living in poverty;
- opinions, stories and anecdotes;
- surveys of the perspectives of affected populations; and
- monitoring media coverage.

Although in most examples, CBC programmes implemented to protect the environment are challenging to assess, case study 4 on orthezia bug on St. Helena is relatively straightforward. Accepting that the gumwoods were heading for extinction, the fact that this has been reversed and other vegetation restoration projects are now able to proceed, does indicate that in this case the highest priority specific objective of the programme was achieved, even if some of the other side-benefits have not been effectively assessed. In other cases where the environmental, economic and societal damage is both severe and multi-sectoral, the impact of the pest may be so diverse and difficult to measure, particularly in a context of other land-use changes, that it is extremely difficult, time-consuming and inclusive to get beyond the successful control of the target pest to what this really means in impact terms (case study 10 water hyacinth). Rubber vine (case study 8) and leafy spurge (case study 9) had diverse effects, but evaluation for both focussed on the economic benefits to the cattle industry, while the benefits to biodiversity were less clearly demonstrated.

Cost of biological control implementation

In order to assess the value of benefits generated by CBC, it is appropriate to relate this to the cost of the research, which can be expressed in monetary terms or more simply in scientist years, for which a standard cost can be estimated. The principal cost components of a CBC programme which might be considered include:

Assessment of the problem
What is the impact of the target pest, and hence is it worth investing in biological control and what benefits are anticipated from successful control? This impact is likely to affect people differently depending on their gender and age, so this will need to be assessed. Sometimes, the decision to proceed can be an executive decision based on personal views and information from producers, which allow the relevant decision maker to immediately recognize an urgent and substantial problem that needs a radical solution. In the past, acute new invasive pests tended to be treated in this way, whereas chronic, ongoing problems might be more or less rigorously evaluated. Where there are actual or perceived conflicts of interest or potential clashes with other national legislation, then a more careful analysis and consultation may be needed, costing time and money. However, inadequate stakeholder consultation at the beginning of a project can lead to very substantial delays and costs later on.

Discovery and assessment of BCAs
Where there are no known effective BCAs, it is necessary to plan and carry out surveys to assess the role of natural enemies in the pest's area of origin. The most promising BCAs are selected, their likely efficacy and safety assessed, and rearing methods developed. Some of this work is done in quarantine, which is expensive to run. Often a pipeline of BCAs is needed, since it cannot be assumed that the first BCA introduced will provide an immediate and complete solution (the so-called 'silver bullet'). This cycle can be repeated several times for some of the more intractable pests, and the entire programme may exceptionally take decades to complete. CABI has often carried out this work on behalf of developed and developing countries.

Authorization
There will be a national process of consultation to evaluate the risks and expected benefits for each introduction. Sometimes this can be straightforward, but other times a wide ranging stakeholder consultation will be needed.

Rearing and release
In-country rearing and release programmes can be a substantial component depending on the ease of rearing and scale of release needed. In other cases, material suitable for immediate field release may be provided.

Monitoring
Following release, a monitoring programme should be implemented to recognize when BCAs become established and assess their frequency and impact on the target and any at-risk non-targets but this is often not carried out, particularly the latter (for possible reasons see below).

Evaluation
Assuming that the CBC programme appears to be successful, the BCA population will increase and then the pest population will decrease. This correlation is often assumed to imply cause and effect, and usually this is the case. However, the decline of the pest may be due to other external reasons, and experimental confirmation of the impact of the BCA is always desirable, although this can be a major exercise in its own right since long-term studies are needed. In some of the most successful programmes, it is considered so self-evident that objective quantitative data is not gathered. Sometimes it is possible to compare sites with and without BCA releases if pre-release data has not been collected. Measuring the impact of a successful CBC project in terms of societal values (including aspects which may differ in relation to gender and age) can also be a major undertaking, and particularly where there is little pre-release data on impact, the task becomes significantly more difficult or impossible.

Benefit sharing with source country
The Nagoya Protocol has been established under the Convention on Biological Diversity to establish the fair and equitable sharing of the benefits arising from the utilization of genetic resources [24]. The exact details of how this will work will be defined by the legislation adopted in each country or regional group such as the European Union. BCAs contain genetic resources and are likely to come under this legislation. It has been argued that the century old tradition of the free multilateral exchange of BCAs should be continued [2], but that will depend on each country's legislation. *A priori* it seems unlikely that countries that benefit from biological

control, particularly developing countries, would be in a position to readily share such benefits as they are a common good contributing to production, livelihoods, environmental conservation, etc., rather than a direct benefit to government finances that could be shared. In our analysis we assume that the traditional practice of free multilateral exchange will continue, but recognize that access and benefit sharing legislation could in future lead to increased costs or significant delays, which in a worst case scenario will mean that CBC ceases to be a practical option for developing countries.

The inputs necessary to achieve these different aspects of a CBC programme are highly variable. Inputs are perhaps most consistently measured in terms of scientist years needed, and this has been used where just one fairly homogenous group of projects is considered, e.g. weed biological control in North America [25, 26].

The use of scientist years facilitates rationalizing inflation of costs over time. In an analysis of water weed biological control costs in the USA, predominantly using insect BCAs, Andres [25] has suggested that assessment of the problem takes 0.5–1.0 scientist years over 1–2 seasons, 3.5 scientist years per insect biological control agent screened and 1.0–1.5 scientist years for each release programme, but did not attempt to assess the inputs required for follow up and evaluation. Today, these steps are most likely to require a much greater investment of scientist time, particularly considering the increased need to evaluate and document non-target risks [27, 28], which leads to more experimental work and more agents being discarded during the screening process [29]. The risk assessment for the early case studies using insects treated here (case studies 6 banana skipper and 7 black sage) were significantly less rigorous and costly than those from recent years, particularly when pathogen BCAs are studied for weed CBC (case study 8 rubber vine).

In general, weed biological control involves greater effort for longer (case studies 7–10) than is normally the case for insect biological control projects (case studies 1–6). A recent study on the costs of weed CBC by Paynter *et al.* [30] assessed how a variety of factors affected the cost of implementing weed biological control programmes in New Zealand (up to the point of release, i.e. excluding redistribution, monitoring and assessment costs). They showed that two factors explained almost all variation in programme cost: the number of agents released and whether this was a repeat programme based on another country's research or a novel research programme. The former costs about NZ$240 K per agent, and the latter about NZ$560 per agent (currently NZ$ is about £0.5). Novel programmes released slightly more than 3 BCAs per target, whereas repeat programmes released an average of 2.4 BCAs and so a novel programme cost 3.8 times as much as a repeat programme (NZ$1.9M versus NZ$0.5M).

Nevertheless, these are only generalizations, and there is a great deal of variation in the number of agents assessed and released, which has a knock on effect on the time taken to complete the CBC programme. Towards one extreme, the leafy spurge project (case study 9) involved 18 BCAs and took nearly 30 years [31], whereas at the other extreme the banana skipper project (case study 6) took only 2–3 years, and when repeated in other countries only a few months.

Based on experience from numerous projects, and information available in publications, reports and CABI institute annual reports, we can make at least a rough estimate of inputs in terms of scientist years, from which a cost can be extrapolated for at least the key components of the CBC process. Hill and Greathead [11] did this for some programmes, and we have attempted it in some of the case studies presented here (e.g. case studies 6 banana skipper and 9 leafy spurge).

Why is CBC impact not better assessed and documented?

There have been many reasons for not objectively assessing the impact of CBC programmes. Not many countries have designated funding for monitoring BCAs and their impact: for example this is not the case in USA and Canada [29], and in many countries, there is a disconnection in terms of units and professional competences between those who implement biological control programmes and those whose mandate is to assess the impact and benefits of a CBC programme (where these exist). This separation may be deliberate or fortuitous, but it could be argued that the group making the CBC introduction has a perceived conflict of interest when measuring the CBC impact. If there is competition for funding and resources between these groups, the disconnection is likely to be worse. Rigorous impact evaluation is not cheap or easy, especially if it is necessary to address cause and effect (was the reduction of the pest actually achieved by the introduced BCAs?) and the pest impacts are complex. Where funding is not earmarked for impact evaluation or the amount available to implement a CBC programme is inadequate, the priority is likely to be the introduction of BCAs rather than monitoring and evaluation, particularly when this is in response to what the government perceives as an emergency situation.

Many CBC programmes are carried out in response to a newly arrived alien pest creating an emergency situation, to which the government feels obliged to urgently respond. Delays to design and carry out a study to collect base-line data on socio-economic impact in a changing and worsening pest invasion are often not acceptable – neither to the people affected nor their government. The spread of pink hibiscus mealybug in the Caribbean (case study 3) is a typical example, where the demand and need was for immediate action. Grenada was the first country affected, and the first to implement a biological control programme that was subsequently effective. However, an election intervened before success was achieved and it has been suggested the apparent lack of progress until then was one factor in the incumbent government losing the election [32]. Understandably in this situation, normally the government priority will be to implement control measures rather than assess the damage; delays to measure the problem will not be accepted, and funding to measure the problem is unlikely to be allocated.

Linked to this, is the observation that the public and the government of a country with a new alien pest problem may not realise what is happening and what impact this pest is going to have, as the pest population increases and spreads. Lack of obvious impact can lead to lack of timely prioritization, increasing the need for urgent action once the true impact of the pest starts to become apparent.

When successful CBC is implemented it can be dramatic and rapid such that the pest rapidly becomes of reduced importance with little direct impact. At this point there is a temptation to see that success and impact as self-evident, to the extent that the allocation of resources to document and measure this is not a priority. At the time, those involved, but often not the general public, know that CBC saved them from a desperate situation, but in a generation or two most people will no longer know they ever had a problem (case study 7 black sage in Mauritius). Evaluation is even less likely to be prioritized if CBC is implemented on a newly arrived pest using known effective BCAs (case study 7 black sage in Sri Lanka).

Scope for retroactive evaluation of CBC impact

Here, we briefly consider what scope there is for post hoc evaluation of the impact of CBC programmes. We suggest that it is very difficult to collect objective social data on the impact of a particular pest on livelihoods retroactively. Most evidence would be anecdotal, based on the memories of the beneficiaries, and normally there would be no baseline for comparison. The older the programme, the less data can be collected, and it is clear that the most successful programmes are no longer known to many of the beneficiaries, e.g. 60 years after black sage was successfully controlled (case study 7), it is no longer even known as a formerly highly invasive weed in Mauritius.

In a few cases the impact of a pest in a country could never be properly known. This is because where a devastating pest is spreading in a region, CBC may be implemented as soon as the pest appears, and the potential impact of that pest can only be extrapolated based on the impact that it has had elsewhere. Thus, only in Grenada was the full impact of the pink hibiscus mealybug (case study 3) felt; elsewhere in the Caribbean and in the USA, CBC was implemented long before the full impact of the pest was demonstrated. The same happened in parts of Africa in the case of the spreading cassava mealybug (case study 1), as it is today in South-East Asia where the mealybug has spread and CBC is being implemented [33].

However, even in these examples, there is scope to estimate potential economic losses, based on crop losses extrapolated from data collected in other countries, sometimes for other pests. Thus, banana skipper impact on yield was assessed from general defoliation-crop loss studies (case study 6), and hence the benefits in terms of losing less to this pest could be estimated. Often crop losses are (or appear to be) self-evident when expressed in terms of observed total crop loss (most case studies), and so can be estimated from known national agricultural production figures for that crop.

Thus, we suggest that any further retroactive evaluation might best be focussed on cost: benefit analyses. To evaluate impact in terms of livelihoods, poverty, etc., it would be more effective to focus on doing this properly in the future. An example where such an approach is being implemented is a recently started, CABI-led research project on the livelihood impacts of woody invasive species in East-Africa. This multi-disciplinary project addresses livelihood impacts of *Lantana camara* L. and *Prosopis* spp. by collecting ecological and socio-economic data about the impacts of the invader, including people's perceptions, along a gradient of invader abundance. In this retroactive study of invader impacts, the invader abundance gradient is a substitution for the invasion's progression. Combining the individual beneficial and detrimental impacts will yield an assessment of the net livelihood impact of these invaders. Also planned is an evaluation of the livelihood impact of invader management (including CBC). Although this study will not be retroactive, it will provide insight into the livelihood costs and benefits of management.

Discussion and Conclusions

The final impact envisaged in the planning and preparation stage of a CBC project will have implications. What impact is desired and why is it thought that the successful biological control of one particular pest will produce this impact? In some cases, the argument for tackling a new alien pest is very clear-cut, but this is not always the case, especially when ecosystem interactions are more complex than most agricultural ecosystems, e.g. many weeds and environmental pests. Most such ex ante studies have focussed on the anticipated costs of pests based on yield losses and control costs, but Hill and Greathead [11] extend this to include the area at risk of infestation, damage level, indirect damage (e.g. side effects of pesticides or loss of habitat) and amenity costs (quality of life, human health, environment, social and cultural practices). A clear theory of change may be needed to pinpoint what impact is intended, and what impact is desirable but not the primary objective.

As our case studies and many other publications have shown, there have been many substantial successes using CBC. However, impact is often poorly assessed, if at all, and is seldom documented, especially in developing countries. There is some limited scope for retroactive studies, structured around a cost-benefit analysis, but in most cases rigorous evaluation of the socio-economic impact is no longer practical. Commonly used socio-economic methods can be and have been adapted to assessments of BCA impacts and tested to see if the tools are appropriate. It is likely that the tools would need to vary slightly to assess impact of an agricultural pest as opposed to an environmental pest. Protocols could most easily be developed and tested in programmes that reuse BCAs of known effectiveness, where basic parameters are reasonably well understood. Fine tuning some protocols specifically for these impact areas could be useful as it would provide some examples of standard good practice to work from in future programmes, especially for those who do not have a socio-economic background.

The sharing of successful BCAs is one particularly cost-effective way to support developing countries. Once a BCA has been used successfully in one country, the opportunity has often been taken to repeat that success in other countries by introducing the same BCA. The transfer of known effective BCAs is cost-effective, relatively cheap and quick to implement, and should be encouraged, subject to a fresh risk assessment for each country using data generated from earlier research if possible. In the case of weed biological control in New Zealand, Paynter *et al.* [30] showed that novel programmes cost nearly four times as much as repeat programmes, and required more BCA species to be released. Developing countries have benefited from access to such tested BCAs because research and implementation was often carried out by developed countries. For example, the work of developed countries with subtropical and tropical regions, e.g. Australia and the USA, and well as some of the more well-resourced developing countries such as South Africa, has directly benefited developing countries in the tropics and sub-tropics. At least ten such BCAs have been released in more than 30 different countries each [3]. There are examples from CABI's work in the case studies above, and many more are known [2, 31].

The data presented by Cock *et al.* [2] and discussed above showed that many different countries have been involved in CBC, but the most active national programmes are nearly all associated with developed countries. Developed countries are in a position to invest in biological control, whereas developing countries are often not and usually rely on donor support to implement one-off CBC programmes. It is a fact that the majority of biological control programmes successfully implemented in developing countries have taken advantage of earlier research carried out by developed countries in order to control pests in the tropical or subtropical parts of those developed countries. The number of programmes developed completely on behalf of developing countries only is limited, but we include several examples amongst our case studies, including cassava mealybug (case study 1), mango mealybug (case study 2), banana skipper (case study 6) and black sage (case study 7). While on the one hand, CBC has been attractive to donors because of the public good nature of its successful implementation, the traditional short term funding cycle and (perceived) desire for predictable results, has reinforced the emphasis on using known effective BCAs. There are examples where an insect CBC programme has started from scratch, and achieved excellent results within 3 years (e.g. case study 6 banana skipper), but these are not typical and most insect and all weed CBC programmes have needed longer term support [34]. There are good examples and good opportunities, but sponsorship needs to be realistic, long-term and patient (a decade or more, rather than a 3-year time frame). This should be reflected by the inclusion of realistic data collection at the beginning and end of the project to assess the impact of control of the target, and societal benefits of the CBC programme.

As noted, CABI has been involved in the successful implementation of CBC for developed and developing countries for 80 years and this approach is still central to CABI's mission. We look forward to continuing to work with our partners and sponsors to deliver cost-effective CBC of agricultural and environmental pests, but we will be asking them to provide more support for the objective assessment of success and impact in the future. We hope we will be knocking on open doors.

Acknowledgements

This review was prepared by a team of CABI scientists: Cock, Witt and Shaw designed the review, Cock led on the writing of the text and case studies 4–7, Thomas on case study 1, Pollard and Thomas on case studies 2–3 and 8, Hinz on case study 9, Day and Cock on case study 10, Williams gave advice on economics for the case studies, and all authors contributed to the completion of the main text. We thank Dr. Loke Wai Hong (CABI Malaysia), Naitram (Bob) Ramnanam (CABI Trinidad and Tobago) and Dr. Seelavarn Ganeshan (Mauritius Sugar Industry Research Institute) for advice on local staff costs for implementation at today's prices, René Eschen (CABI) for useful comments, and Lars Baker (former Weed Supervisor Fremont County, Wyoming), Dr. Dean A. Bangsund and Dr. Rodney G. Lym (North Dakota State University) for valuable input in the leafy spurge case study. Some images used to illustrate the case studies are used under Creative Commons licenses as indicated in the legends and we thank the following for making their images available in this way: Eran Finkle (via Flickr), Georg Goergen, IITA (via the CABI Crop Protection Compendium and Ecoport), Krzysztof Ziarnek of Kenraiz (via Wikipedia), Jeffrey W. Lotz, Florida Division of Plant Industry, Florida Department of Agriculture and Consumer Services (via Bugwood and Wikipedia), Peter Neuenschwander, IITA (via the CABI Crop Protection Compendium), Rishma Maini (DFID), Manie van der Schijff Botanical Garden (Pretoria), Scott Bauer, Neil Palmer and Marcia Stefani (via Wikimedia), Colin Wilson (via the CABI Crop Protection Compendium). Other images were shared directly with us, and we thank Charles Dewhurst (Papua New Guinea Oil Palm Research Association, Inc. – retired), Mark Schwarzländer (University of Idaho), Monika Chandler (Minnesota Department of Agriculture) for letting us use their pictures. The remaining images were shared by current or former CABI colleagues and we thank Fred Bennett, Tony Cross, Harry Evans, Simon Fowler, David Girling, David Greathead, Peter Ooi, Doug Williams and Alan Wood for this. This review was prepared as part of a major new investment by CABI to raise awareness of the importance of alien invasive species and the scope to improve their prevention and management in developing countries. It was supported by the CABI Development Fund, which is supported by contributions from the Australian Centre for International Agricultural Research, the UK's Department for International Development, the Swiss Agency for Development and Cooperation and others.

References

1. Tisdell CA, Auld BA. Evaluation of biological control projects. In: Delfosse ES, editor. Proceedings of the VII International Symposium on Biological Control of Weeds. Istituto Sperimentale per la Patologia Vegetale, Rome, Italy; 1990. p. 93–100.
2. Cock MJW, van Lenteren JC, Brodeur J, Barratt, BIP, Bigler F, Bolckmans K, Cônsoli FL, Haas F, Mason P.G, Parra JRP. The Use and Exchange of Biological Control Agents for Food and Agriculture. Background Study Paper No. 47. Commission on Genetic Resources for Food and Agriculture, FAO, Rome; 2009. 88 pp.
3. Cock MJW, van Lenteren JC, Brodeur J, Barratt B.I.P, Bigler F, Bolckmans K, Cônsoli FL, Haas F, Mason PG, Parra JRP. Do new access and benefit sharing procedures under the convention on biological diversity threaten the future of biological control? Biological Control 2010;55:199–218.
4. World Bank. Data and Statistics. Country groups; 2009. Available from: URL: http://go.worldbank.org/D7SN0B8YU0 (accessed 7 May 2009).
5. Blight D, Ibbotson R. CABI: a Century of Scientific Endeavour. CABI, Wallingford, UK; 2011. 171 pp.
6. Culliney TW. Benefits of classical biological control for managing invasive plants. Critical Reviews in Plant Sciences 2005;24:131–50.
7. Mason PG, Gillespie DR, Vincent C (editors). Proceedings of the 4th International Symposium on Biological Control of Arthropods, Pucón, Chile, 4–8 March 2013. Instituto de Investigaciones Agropecuarias (INIA) and Universidad de Chile; 2013. xviii + 380 pp.
8. Impson FAC, Kleinjan CA, Hoffmann JH (editors). Proceedings of the XIV International Symposium on Biological Control of Weeds. University of Cape Town, South Africa; 2014. xii + 232 pp.
9. Van Driesche RG, Hoddle MS. Classical arthropod biological control: measuring success, step by step. In: Gurr G, Wratten S, editors. Biological Control: Measures of Success. Kluwer Academic Publishers, Dordrecht, The Netherlands; 2002. p. 39–75.
10. NORAD (Norwegian Agency for Development Co-operation). The Logical Framework Approach (LFA): Handbook for Objectives-Oriented Project Planning. NORAD, Osla, Norway; 1999. 107 pp.
11. Hill G, Greathead D. Economic evaluation in classical biological control. In: Perrings C, Williamson M, Dalmazzone S, editors. The Economics of Biological Invasions. Edward Elgar Publishing Ltd, Cheltenham, UK; 2000. p. 208–23.
12. DeBach P (editor). Biological Control of Insect Pests and Weeds. Chapman & Hall, London, UK; 1964. xxiv + 844 pp.
13. Simmonds FJ. The economics of biological control. Journal of the Royal Society of Arts 1967;115(5135):880–98.
14. Greathead DJ. Benefits and risks of biological control. In: Hokkanen HK, Lynch JM, editors. Biological Control Benefits and Risks. Cambridge University Press, Cambridge, UK; 1995. p. 53–63.
15. Lubulwa G, McMeniman S. (1997) An economic evaluation of realised and potential impacts of 15 of ACIAR's biological control projects (1983–1996). Economic Evaluation Unit, Working Paper Series 26, 41 pp.
16. McFadyen REC. Successes in biological control of weeds. In: Spencer NR, editor. Proceedings of the X International Symposium on Biological Control of Weeds, 4–14 July 1999. Montana State University, Bozeman, Montana, USA; 2000. p. 3–14.
17. Gurr G, Wratten S (editors). Biological Control: Measures of Success. Kluwer Academic Publishers, Dordrecht, The Netherlands; 2000. 437 pp.
18. van Wilgen BW, de Wit MP, Anderson HJ, Le Maitre DC, Kotze IM, Ndala S, Brown B, Rapholo MB. Costs and benefits of biological control of invasive alien plants: case studies from South Africa. South African Journal of Science 2004;100:113–22.
19. Van Driesche RG, Carruthers RI, Center T, Hoddle MS, Hough-Goldstein J, Morin L, Smith L, Wagner DL, Blossey B, Brancatini V, Casagrande R, Causton CE, Coetzee JA, Cuda J, Ding J, Fowler SV, Frank JH, Fuester R, Goolsby J, Grodowitz M, Heard TA, Hill MP, Hoffmann JH, Huber J, Julien M, Kairo MTK, Kenis M, Mason P, Medalm J, Messing R, Miller R, Moore A, Neuenschwander P, Newman R, Norambuena H, Palmer WA, Pemberton R, Perez Panduro A, Pratt PD, Rayamajhi M, Salom S, Sands D, Schooler S, Schwarzländer M, Sheppard A, Shaw R, Tipping PW, van Klinken RD. Classical biological control for the protection of natural ecosystems. Biological Control 2010;54:S2–33.

20. Lange WJ, van Wilgen BW. An economic assessment of the contribution of biological control to the management of invasive alien plants and to the protection of ecosystem services in South Africa. Biological Invasions 2010;12: 4113–24.

21. Denslow JS, D'Antonio CM. After biocontrol: assessing indirect effects of insect releases. Biological Control 2005;35:307–18.

22. Mwangi E, Swallow B. Prosopis juliflora invasion and rural livelihoods in the Lake Baringo area of Kenya. Conservation and Society 2008;6(2):130–40.

23. Fish J, Chiche Y, Day R, Efa N, Witt A, Fessehaie R, Johnson KG, Gumisizira G, Nkandu B. Mainstreaming Gender into Prevention and Management of Invasive Species. Global Invasive Species Programme (GISP), Washington, DC, USA and Nairobi, Kenya; 2010. 64 pp.

24. UN (United Nations) (2010) Nagoya protocol on access to genetic resources and the fair and equitable sharing of benefits arising from their utilization to the convention on biological diversity. Available from: URL: http://treaties.un.org/doc/source/signature/2010/ch-xxvii-8-b.pdf

25. Andres LA. The economics of biological control of weeds. Aquatic Botany 1977;3:111–23.

26. Harris P. Cost of biological control of weeds by insects in Canada. Weed Science 1979;27:242–50.

27. Bigler F, Bale JS, Cock MJW, Dreyer H, Greatrex R, Kuhlmann U, Loomans AJM, van Lenteren JC. Guidelines on information requirements for import and release of invertebrate biological control agents in European countries. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 2005;1(1):10.

28. Barratt BIP, Howarth FG, Withers TM, Kean JM, Ridley GS. Progress in risk assessment for classical biological control. Biological Control 2010;52:245–54.

29. Hinz H.L, Schwarzländer M, Gassmann A, Bourchier RS. Successes we may not have had: a retrospective analysis of selected weed biological control agents in the United States. Invasive Plant Science and Management 2014;7:565–79.

30. Paynter Q, Fowler SV, Hayes L, Hill RL. Factors affecting the cost of weed biocontrol programs in New Zealand. Biological Control 2015;80:119–27.

31. Winston RL, Schwarzländer M, Hinz HL, Day MD, Cock MJW, Julien MH (editors). Biological Control of Weeds: A World Catalogue of Agents and Their Target Weeds, 5th ed. USDA Forest Service, Forest Health Technology Enterprise Team, Morgantown, West Virginia; 2014. FHTET-2014-04. 838 pp.

32. Cock MJW. Risks of non-target impact versus stakeholder benefits in classical biological control of arthropods: selected case studies from developing countries. In: Van Driesche RG, editors. Proceedings of the International Symposium on Biological Control of Arthropods, Honolulu, Hawaii, 14–18 January 2002. United States Department of Agriculture, Forest Service, Morgantown, WV; 2003. p. 25–33. FHTET-2003-05, 573 pp.

33. Winotai A, Goergen G, Tamò M, Neuenschwander P. Cassava mealybug has reached Asia. Biocontrol News & Information 2010;31(2):10N–1N.

34. Cock MJW, Ellison CA, Evans HC, Ooi PAC. Can failure be turned into success for biological control of mile-a-minute weed (Mikania micrantha)? In: Spencer N, editor. Proceedings of the X International Symposium on Biological Control of Weeds, Bozeman, Montana, July 4–14 1999. Montana State University, Bozeman, Montana, USA; 2000. p. 155–67.

Case Study 1
Cassava mealybug, *Phenacoccus manihoti* (Matile-Ferrero) (Hemiptera, Pseudococcidae)

Lead author: Sarah E. Thomas (CABI UK)

The following brief summary of one of the most important, successful and well-documented biological control programmes is based primarily on Herren and Neuenschwander [1], and Neuenschwander [2, 3]. Cassava (*Manihot esculenta* Crantz; Euphorbiaceae) is a crop of South American origin now grown as an important staple in many parts of the tropics. In Africa, cassava is an essential staple crop providing carbohydrates for several hundred million people. It can be grown in poor soils, is resistant to most pests, the roots provide starch and the leaves can be harvested and eaten boiled, it is easily propagated by cuttings, and can be grown as an intercrop, and because the fully formed roots can be left in the ground for long periods, it is an important food source when other food is scarce [4].

The Pest Problem

A new species of mealybug, was first observed in Zaire (Democratic Republic of Congo) and Congo (Republic of Congo) in the 1970s (Figure 1). It was described in 1977 as *Phenacoccus manihoti* Matile-Ferrero from African material, and subsequently became known as the cassava mealybug (Figure 2). Until its discovery in Africa, this species had never been recorded causing damage anywhere in the world. *P. manihoti* was found to be specific to cassava and the damage it causes includes stunting, leaf distortion and loss, dieback and weakening of stems used for crop propagation, all of which have an impact on the tuber yield.

P. manihoti reproduces parthenogenetically and its life cycle consists of an egg, three nymphal instar and the adult. The development period of egg to adult lasts approximately 33 days. The most favoured sites for oviposition are the terminal shoot tips, lower leaf surfaces and leaf petioles. Except for the first instar crawlers, all instars prefer the lower surfaces of fully expanded leaves, from where they move slowly to the stems and shoot tips. At low population densities, therefore, the insect is most abundant in the shoot tips. This newly discovered pest, unchecked by natural enemies in Africa, found ideal conditions to multiply explosively and cassava crops were devastated, causing crop losses of up to 80%. It quickly spread throughout all cassava producing regions, becoming the most important pest on cassava and threatened the food security of over 200 million people (Figure 3).

> Following its introduction in the 1970s, cassava mealybug quickly spread throughout all cassava producing regions of Africa, becoming the most important pest on cassava and threatened the food security of over 200 million people.

The Biological Control Programme

Because it was specialized on cassava, it was assumed that the pest's origin, like cassava, was neotropical. Since it had not been recorded in that region, it was presumed that it was under good natural biological control, and there was a good opportunity for a classical biological control programme for the mealybug.

In order to tackle this pest, it was soon recognized that a large collaborative programme would be necessary and an international research programme began involving field exploration, quarantine, rearing, release, laboratory and field research, monitoring, coordination, training, awareness building and impact studies. Exploration for natural enemies began with the International Institute for Tropical Agriculture (IITA) searching in Central America and the Commonwealth Institute of Biological Control (CABI) surveying in the Caribbean and Northern South America, but *P. manihoti* was not found. Later, surveys were extended to Paraguay, Bolivia and Brazil, and CIAT (Centro Internacional de Agricultura Tropical) and EMPRAPA (Empresa Brasileira de Pesquisa Agropecuária) became involved. It was only when *P. manihoti* was found in Paraguay (and subsequently parts of Bolivia and southwestern Brazil) that effective, host-specific natural enemies were found by CABI and IITA scientists.

Eighteen species of natural enemies were discovered in the area of origin of the cassava mealybug in Paraguay [1]. CABI arranged for these beneficial agents to be quarantined in the UK, initially at the Natural History Museum, London, and then at CABI's new quarantine unit. There, they were reared through a generation and were sent to IITA for further study, mass-rearing and release.

Neuenschwander [2] provides a comprehensive list of the releases of exotic parasitoids and predators made in Africa by IITA and its national collaborators between

Figure 1 Cassava mealybug was first discovered in Zaire in 1977 (photograph: D.J. Greathead, CABI).

Figure 2 Cassava mealybugs are about 1 mm long (photograph: G. Goergen, IITA, http://www.ecoport.org).

Figure 3 The newly introduced cassava mealybug destroyed cassava plants throughout the cassava growing belt of Africa (photograph: D.J. Williams, CABI).

Figure 4 Biological control agents for cassava mealybug were first collected in Bolivia in 1981 (photograph: F.D. Bennett, CABI).

Figure 5 *Anagyrus lopezi* was the effective biological control agent that brought cassava mealybug under control in Africa (photograph: A.H. Wood, CABI).

1981 and 1995. The highly-specific, neotropical parasitoid *Anagyrus lopezi* (De Santis) (Hymenoptera: Encyrtidae) was the most successful of these which established in a total of 26 African countries (Figure 4). *Anagyrus diversicornis* (Howard), another exotic parasitoid, failed to establish and the coccinellids *Hyperaspis notata* Mulsant (introduced) and *Diomus hennesseyi* (Fursch) (redistributed within Africa), were only established locally.

By the end of the decade, *A. lopezi* had spread and established across many ecological zones throughout the mealybug infested areas of tropical Africa, and was the primary agent that controlled the mealybugs by 95% so that today cassava grows with little mealybug damage (Figure 5).

This successful programme brought a sustainable and environmentally friendly solution for the cassava mealybug without any health hazards and with no costs to the farmer.

Figure 6 Following the successful biological control of cassava mealybug, African farmers such as this lady in Ghana can once again grow cassava with confidence (photograph: Neil Palmer, CIAT, commons.wikimedia.org, CC BY-SA 2.0).

Evaluation of Impact

For the farmers of Africa, the economic impact of *A. lopezi* on cassava mealybug has been exceptional and the biggest benefits are attributed to DR Congo, Nigeria, Ghana, Tanzania, Mozambique and Uganda. Throughout Ghana and Cote d'Ivoire, yield losses were reduced significantly by *A. lopezi*. Increased yields were estimated as 2.5 t/ha which was used by Norgaard [5] to further estimate the economic impact of this biological control agent.

A number of estimated benefit:cost analyses have been carried out for the biological control of the cassava mealybug. Norgaard [5] estimated a ratio of 149 : 1, but this analysis did not consider variation between different cassava producing countries, or agro-ecological zones and assumed that the benefits of the biological control programme would cease entirely within 25 years as other resistant varieties, cultural practices, etc. took over (Figure 6). This conservative scenario is therefore considered to be reasonable and least-favourable [6].

A more comprehensive study was undertaken by Zeddies *et al*. [7] who calculated costs and benefits for the programme over 40 years for 27 different African countries, the speed of impact of *A. lopezi* in different agro-ecological zones and four different loss replacement value scenarios. Benefit:cost ratios calculated based on additional cassava production varied from 199 : 1 (based on world market price) to 371 : 1 to 738 : 1 (based on the variation in average prices within Africa, where considerable cassava is traded at a higher value than the world market). Other loss replacement value scenarios gave a wide variety of benefit:cost ratios between 170 : 1 and 1592 : 1. However, even if the more conservative calculation based on market price alone is used; these calculations illustrate the substantial net benefits of this very successful biological control programme. Furthermore, they do not take into consideration, aspects such as eliminating the need to use insecticides to control the pest, with their associated risks to human and environmental health, nor the strengthening of national capability in pest management which proceeds in parallel with implementation [3].

For the farmers of Africa, the economic impact of *A. lopezi* on cassava mealybug has been exceptional. Benefit:cost ratios for the programme calculation based on additional cassava production varied from 199 : 1 to 738 : 1.

References

1. Herren HR, Neuenschwander P. Biological control of cassava pests in Africa. Annual Review of Entomology 1991;36:257–83.
2. Neuenschwander P. Biological control of the cassava mealybug in Africa: a review. Biological Control 2001;21:214–29.
3. Neuenschwander P. Biological control of cassava and mango mealybugs in Africa. In: Neuenschwander P, Borgemeister C, Langewald J editors. Biological Control in IPM Systems in Africa. CABI Publishing, Wallingford, UK; 2003. p. 45–59.
4. Cock JH. Cassava. New Potential for a Neglected Crop. Westview Press, Boulder, Colorado, USA; 2005. 192 pp.
5. Norgaard RB. The biological control of cassava mealybug in Africa. American Journal of Agricultural Economics 1988;70:366–71.
6. Alene AD, Neuenschwander P, Manyong VM, Coulibaly O, Hanna, R. The Impact of IITA-Led Biological Control of Major Pests in Sub-Saharan African Agriculture. A Synthesis of Milestones and Empirical Results. Impact Series, IITA, Ibadan, Nigeria; 2005. pp 26.
7. Zeddies J, Schaab RP, Neuenschwander P, Herren HR. Economics of biological control of cassava mealybug in Africa. Agricultural Economics 2001;24:209–19.

Case Study 2
Mango mealybug, *Rastrococcus invadens* Williams (Hemiptera, Pseudococcidae)

Lead author: Kathryn M. Pollard (CABI UK)

In the wetter parts of West Africa, a large proportion of households are rural and almost all of these have mango trees growing around their homes producing fruit for consumption. Mangoes are also grown as a cash crop for the domestic market, and the annual national crop in Bénin has been estimated at US$65 million [1]. The fruit is high in sugar and vitamins, especially vitamins A and C. In towns, it is a valuable dessert fruit, and in rural areas, it can replace whole meals during working days in the field. Almost all producers interviewed (99%), said they consumed mango fruits, and most (87%) underlined the added importance of mango for combating diseases [1]. The trees are also valued for their shade, which facilitates social functions (Figure 1). By the mid-1990s mango production in West and Central Africa was drastically threatened by the damage caused by the mango mealybug, *Rastrococcus invadens* Williams, which posed a serious threat to livelihoods in this region (Figure 2).

The Pest Problem

The mango mealybug is native to South-East Asia and it is believed to have been introduced into West Africa on contaminated plant material. It was first reported in Togo and Ghana in 1981, and soon caused serious damage to the fruit trees [2]. This pest was initially identified as *Rastrococcus spinosus* (Robinson), a closely related species which also causes damage to fruit trees, in particular mango, but was later re-identified as *R. invadens* [2]. Both adults and immature stages of the mango mealybug cause damage to plant leaves, fruit and inflorescences. Minor damage is inflicted by feeding on the plant and sucking the sap, but more damage is caused by the excretion of honeydew. This honeydew falls onto the leaves and fruit below, leading to the formation of a black sooty mould (*Cladosprium* sp.) which prevents growth, causes premature leaf drop and restricts photosynthesis resulting in a decrease in fruit production, weight, size, sugar, fat and carbohydrate levels [3, 4] (Figure 3). Crop losses due to the mango mealybug were often not calculated as the damage caused was self-evident. However, based on average production figures from 1986 to 1999, which in turn are based on estimates from the producers, the annual yield losses of mango as a result of the mango mealybug in Bénin were estimated to be 89% [1].

Crop losses due to the mango mealybug were often not calculated as the damage caused was self-evident. However, annual yield losses of mango as a result of the mango mealybug in Bénin were estimated to be 89%.

R. invadens is polyphagous and has been reported to feed on 45 plant species from 22 families including horticultural and ornamental plants and shade trees. However, the mango mealybug has a strong preference for mango, banana and citrus fruits. Before reaching the adult stage, mango mealybug goes through three instars. Adult females live on average 89 days and produce an average of 160 crawlers in its lifetime. The development time of *R. invadens* is strongly influenced by its host plant with mango identified as the most preferred host [5].

When it first became established, control of mango mealybug was typically attempted by the use of insecticides, pruning or more drastically, felling of infected trees. Nevertheless this was often unsuccessful as subsequent re-infestation from nearby hosts often occurred [2].

The Biological Control Programme

Studies in Togo and Bénin revealed a complex of natural enemies of *R. invadans* including 14 species of indigenous predators and one parasitoid. These however, had little impact on populations of *R. invadens.* In 1986 the Food and Agriculture Organization (FAO), the Government of Togo and CABI (as the International Institute of Biological Control) initiated a biological control programme for the control of *R. invadens.* Natural enemy surveys were conducted in the native range, in India and Malaysia. Surveys in India found three parasitic wasps, two entomopathogenic fungi and several predators. In contrast, no potential biocontrol agents were found during surveys in Malaysia. Two encyrtid parasitoids *Gyranusoidea tebygi* Noyes and *Anagyrus mangicola* Noyes (which were described as new for this programme) were prioritized for further testing as they were seen to cause significant mortality in the field, and past records indicate successful control of mealybugs with encyrtid parasitoids. *G. tebygi* attacks young mealybugs (first and second instars) of both sexes whilst *A. mangicola* attacks older females (third and fourth instars). As these parasitoids occupy separate ecological

Figure 1 The shade of mango trees provide an important social focus in many African villages – here in DR Congo where weekly meetings discuss issues that need to be tackled (photograph: Rishma Maini, DFID, commons. wikimedia.org, CC BY-SA 2.0).

Figure 2 Mango mealybug, an exotic pest in West Africa (photo: © G. Goergen, IITA).

Figure 3 Mango mealybugs on leaf under surface and heavy infestation of sooty mould on the upper surfaces, which reduce photosynthesis (photograph: P. Neuenschwander, from CABI CPC).

Figure 4 *Gyranusoidea tebygi*, one of the effective natural enemies introduced to control mango mealybug in West Africa (photo: © G. Goergen, IITA).

niches, it is possible for both species to coexist in the field [6]. Detailed studies in quarantine facilities at CABI in the UK found the parasitoids to be specific and capable of infecting the mealybug on a range of host plants and therefore potential biocontrol agents for release [3].

G. tebygi was first released in Togo in 1987 (Figure 4). The following year it was sent to International Institute for Tropical Agriculture (IITA) in Bénin, who carried out mass rearing and supported affected countries to make releases. Due to its successful establishment and control of *R. invadens*, it was later released in Bénin, Gabon, Ghana, Nigeria, Sierra Leone and DR Congo, and spread naturally to Congo and Cote d'Ivoire, without being released in these countries. From 1991 onwards, the second parasitic wasp, *A. mangicola*, was released in combination with *G. tebygi* in Bénin, Gabon and Sierra Leone to target localized 'hotspots' of *R. invadens*. Despite *G. tebygi* and *A. mangicola* being attacked by several indigenous hyperparasitoids in Africa, the performance of the biocontrol agents are not significantly affected and control of the mango mealybug has proved successful.

Evaluation of Impact

After release and establishment of these agents, fruit production was seen to dramatically increase and mangoes came back onto the market [6]. For example, in Bénin 10 years after the biological control programme, fruit production was seen to have increased by 142% compared with production before the introduction of the pest, due to increased yield and an increase in the number of trees planted [1]. This figure was based on producer estimates in Bénin from 1986 (prior to the release of the biocontrol agents) to 1999 (after successful release and establishment). Farmers also noticed a significant reduction in the population of mango mealybugs on their plants. In Bénin, the percentage of trees infested with *R. invadens* decreased from 31% in 1989 to 17.5% in 1991 and the average number of mealybugs per 48 leaves decreased from 9.7 to 6.4 females within this same time frame [7].

> After release and establishment of the biological control agents, fruit production was seen to dramatically increase and mangoes came back onto the market.

Initial economic assessments estimated that in Togo a saving of US$370/ha were obtained by farmers of grafted trees and in Bénin mango production increased fourfold for local varieties of mango and tenfold for grafted trees [5]. The biological control programme ran for 9 years at an estimated total cost of US$3.66 million. Estimates of the benefits of the biocontrol programme over 20 years in Bénin alone amount to US$531 million, when taking into account the increase in yields only [1]. This figure however, accounts only for the economic benefits accrued up until 1999 and therefore would be significantly higher today. In addition to this, it does not consider non-economic impacts such as those on livelihoods and the environment. For example, the return of mango trees as an ornamental shade tree or place of worship, the increased source of energy and vital nutrients (vitamins A and C), the use of mangoes in local medicine and the prevention of soil erosion by the root system. Using figures presented earlier, a benefit:cost ratio of 145 : 1 can be calculated for Bénin alone. This figure increases significantly to 808 : 1 when taking into account the benefits accrued by producer surpluses throughout Sub-Saharan Africa [8].

References

1. Bokonon-Ganta AH, de Groote H, Neuenschwander P. Socio-economic impact of biological control of mango mealybug in Benin. Agriculture, Ecosystems and Environment 2002;93:367–78.
2. Agounké D, Agricola U, Bakonon-Ganta HA. *Rastrococcus invadens* Williams (Hemiptera: Pseudococcidae), a serious exotic pest of fruit trees and other plants in West Africa. Bulletin of Entomological Research 1988;78:695–702.
3. Agricola U, Agounké D, Fishcer HU, Moore, D. The control of *Rastrococcus invadens* Williams (Hemiptera: Pseudococcidae) in Togo by the introduction of *Gyranusoidea tebygi* Noyes (Hemiptera: Encyrtidae). Bulletin of Entomological Research 1989;79:671–78.
4. Moore D. Control of the fruit tree mealybug, *Rastrococcus invadens*. Outlooks on Pest Management 2005;16(5):222–4.
5. Moore D. Biological control of *Rastrococcus invadens*. Biocontrol News and Information 2004;25:17–27.
6. Neuenschwander P. Evaluating the efficacy of biological control of three exotic homopteran pests in tropical Africa. Entomophaga 1996;41:405–24.
7. Bokonon-Ganta AH, Neuenschwander P. Impact of the biological control agent *Gyranusoidea tebygi* Noyes (Hymenoptera: Encyrtidae) on the mango mealybug, *Rastrococcus invadens* Williams (Homoptera: Pseudococcideae), in Benin. Biocontrol Science and Technology 1995;5:95–107.
8. Hill G, Greathead D. Economic evaluation in classical biological control. In: Perrings C, Williamson MH, Dalmazzone S, editors. The Economics of Biological Invasions. Edward Elgar, Cheltenham, UK; 2000. pp. 208–25.

Case Study 3
Pink hibiscus mealybug, *Maconellicoccus hirsutus* Green (Hemiptera, Pseudococcidae)

Lead authors: Kathryn M. Pollard and Sarah E. Thomas (CABI UK)

Trade is an important component of the economy of many Caribbean islands. In 1996, trade restrictions were implemented within the Caribbean to prevent the spread of the invasive, pink hibiscus mealybug, *Maconellicoccus hirsutus* Green [1]. This had a significant impact on the agricultural sector in several countries. For example, despite not being a host for pink hibiscus mealybug, the export of onions from St Kitts and Nevis declined significantly and has never fully recovered; in 1996, 476 tonnes of onions were exported which decreased to 64 tonnes by 1999 [2].

The Pest Problem

Pink hibiscus mealybug is polyphagous, feeding on plants from 76 families and over 200 genera. It will infect forest trees, vegetables including cabbage, cucumber, tomatoes and ornamental plants such as ginger lily, hibiscus, palm and *Heliconia* (Figure 1). The most commonly affected plants are within the families *Malvaceae*, *Fabaceae* and *Moraceae*. Therefore, the effects of pink hibiscus mealybug were seen across on a number of sectors including the agricultural, forestry and horticultural sectors (Figure 2). Pink hibiscus mealybug has piercing and sucking mouthparts to attack new growth, young shoots, fruits and flowers. When feeding within the phloem, it injects a toxin, which causes leaf malformations such as crinkling, curling and stunting, swelling at the growth points and the production of fewer and smaller fruits. As individual plants become more heavily infected, the mealybugs move towards healthy tissue from the shoot tips down towards the trunk [3]. Heavy infestations may therefore result in total leaf loss and whole plant death (Figure 3) [1]. In addition to this, the production of honeydew on leaves and fruit by the mealybug promotes the growth of a black sooty mould which can reduce photosynthesis, weaken the plant and make fruit unattractive. Its broad host range means that this polyphagous species can spread rapidly through not only agricultural land but also through forests and home gardens [4] making management of this species more difficult.

Pink hibiscus mealybug is native to southern Asia and has spread dramatically throughout the world. It is now present in Oceania, Africa, North, South and Central America and the Caribbean [5]. It was first identified in India in 1908 where it spread to Egypt in 1912. It is only within these countries that it been reported as a serious threat [1]. The first reports of pink hibiscus mealybug in the Western hemisphere were in Hawaii in 1984 and in Grenada in 1994, although it is believed to have been introduced to the Caribbean a few years earlier. Wind, rain, animals, import of contaminated plant produce, vehicles and other human activities are all thought to have been responsible for its spread. A strong association between the spread of the pink hibiscus mealybug and the main route of human traffic between islands has been identified [4]. A female mealybug can lay between 84 and 654 eggs which hatch in 6–9 days. Females have three instars and males four instars and under warm conditions, the mealybug may complete a generation in 5 weeks giving rise to multiple generations per year [3]. The crawlers are motile, dispersing naturally towards areas of new growth or over longer distances by wind, or accidentally carried by humans and animals. The most common means of dispersal is through the movement of infected plant material into new areas. In Grenada, economic losses of US$3.5–10 million were estimated for the growing period of 1996–1997 [6].

The use of chemicals and cultural methods, such as crop burning, to control pink hibiscus mealybug were heavily relied upon. Nevertheless, these methods were often ineffective due to re-infestation from neighbouring plants. In addition to this, the waxy coating on the mealybug rendered it resistant to water based insecticides. In an attempt to prevent spread to neighbouring islands, quarantine systems were upgraded and training in plant protection, with a focus on early prevention and detection was provided to non-infested countries [7]. Consequentially, trade restrictions were implemented within the Caribbean restricting movement of produce from an infected country. A public awareness campaign via the television, radio and newspapers was instigated and aimed to provide more general knowledge to the public and prevent the spread of plant material between islands [8]. Nevertheless, by 2001 pink hibiscus mealybug had spread to 25 territories within the Caribbean [4].

> Trade is an important component to the economy of many Caribbean islands. In 1996, trade restrictions were implemented within the Caribbean to prevent the spread of the invasive, pink hibiscus mealybug, with significant impact on the agricultural sector in several countries.

Figure 1 Pink hibiscus mealybugs (Bugwood.org: Jeffrey W. Lotz, Florida Division of Plant Industry, Florida Department of Agriculture and Consumer Services).

Figure 2 Blue mahoe (*Hibiscus elatus*), is an important watershed tree in Grenada; it was badly affected by pink hibiscus mealybug infestations until biological control was implemented (photograph: Krzysztof Ziarnek, Kenraiz, Wikipedia, CC BY-SA 3.0).

Figure 3 White patches of infestation of pink hibiscus mealybug on trunk of samaan tree; this tree was killed (photograph: Jeffrey W. Lotz, Florida Department of Agriculture and Consumer Services; Wikipedia, CC3.0).

In 1995, a biological control programme against pink hibiscus mealybug was initiated in Grenada through the Food and Agriculture Organisation (FAO) and executed by CABI from its centre in Trinidad. By 1996 the programme had been developed into a regional programme including all 13 countries within the Caribbean. Biological control programmes were joint efforts involving National Programmes with the assistance of FAO, the Caribbean Agricultural Research and Development Institute (CARDI), CABI (as CABI Bioscience), Instituto Interamericano de Cooperación para la Agricultura (IICA), United States Department of Agriculture (USDA) and l'Institut national de la Recherche agronomique (INRA, France) [4]. Earlier surveys in India and Egypt had revealed a complex of over 30 species of natural enemies from 11 families [5]. Pink hibiscus mealybug had also been the target of a biological control programme in Egypt, was the target of ongoing augmentative efforts in India, and was fortuitously controlled in Hawaii when it was introduced with its natural enemies. Using this information, *Anagyrus kamali* Moursi, a solitary encyrtid parasitoid, was the first natural enemy to be released into the Caribbean for pink hibiscus mealybug [1].

Table 1 Natural enemies released within the Caribbean (after [4])

Country	Number of natural enemies releases			
	Crytolaemus montrouzieri	*Scymnus coccivora*	*Anagyrus kamali*	*Gyranusoidea indica*
British Virgin Islands	18 000	–	9500	–
Curaçao	–	–	2000	–
Grenada	2000	1925	25 000	1500
Guyana	56 000	–	15 240	–
Montserrat	500	500	9250	–
St Kitts and Nevis	206 300	1300	66 000	32 000
St Lucia	406 000	–	44 525	–
St Vincent	85 416	–	25 330	–
Trinidad and Tobago	30 000	9000	43 670	–

This parasitoid has been reported to feed on several other mealybug species in Jordan and India, but research found that pink hibiscus mealybug is its preferred host [9]. Female parasitoids lay their eggs in 40–60 adult mealybugs, and the resultant parasitoid larvae grow and develop inside the host. Although female adults are preferred for oviposition, eggs may also be laid in earlier instars. In addition to this, the direct piercing of the mealybugs for feeding also inflicts damage [5]. Its narrow host range made this parasitic wasp suitable as a biological control agent. It was exported from China, to CABI's quarantine unit in the UK. After the elimination of contaminants and hyperparasitoids it was transferred to CABI's Trinidad centre for mass rearing with the Ministry of Agriculture Land and Marine Resources, before release in Grenada in 1995, Trinidad and Tobago in 1996 and the Caribbean islands. Parasitoids were also provided to the USDA for release into St Kitts and Nevis.

A number of additional biological control agents were also released into the Caribbean including a second encyrtid parasitoid, *Gyranusoidea indica* Shafee, Alam and Agarwal and two coccinellid beetles, *Cryptolaemus montrouzieri* Mulsant and *Scymnus coccivora* Ramakrishna Ayyar (Table 1). *Cryptolaemus montrouzieri* was released into all but one of the pink hibiscus mealybug infested countries and, with the ability to feed on 3000–5000 mealybugs during its lifetime; it is thought to be responsible for the initial decline in pink hibiscus mealybug populations. On the other hand, maintenance of low population levels of pink hibiscus mealybug is attributed to *A. kamali* (Figure 4).

Figure 4 The effective parasitoid of pink hibiscus mealybug *Anagyrus kamali* (Bugwood.org: Jeffrey W. Lotz, Florida Department of Agriculture and Consumer Services).

Evaluation of Impact

Since the release of the biological control agents into the Caribbean, the number of host plants on which pink hibiscus mealybug has been recorded has decreased dramatically and is now limited to *Hibiscus* spp. [10]. Losses due to pink hibiscus mealybug experienced by each country varied dramatically. In particular, losses to Grenada were much higher than other countries such as St Kitts and Nevis, as pink hibiscus mealybug was first recorded here and increased and inflicted damage for several years before biological control was implemented.

The USDA estimated that economic losses caused by pink hibiscus mealybug exceeded US$3.5 million a year in Grenada and US$125 million a year in Trinidad and Tobago [4]. In addition to this, losses of US$67 000 in St Lucia, US$3.4 million in St Vincent and the Grenadines and US$300 000 in St Kitts and Nevis were estimated [1]. As pink hibiscus mealybug failed to invade areas of production, estimates of losses were never calculated for Guyana. Nevertheless as a result of trade restrictions there was a significant negative impact to the economy [1].

Singh [11] conducted a comprehensive analysis of the benefits and costs of the pink hibiscus mealybug programme in Trinidad and Tobago alone, taking into consideration social, economic and environmental perspectives. This was compared with a baseline study which determined the magnitude, characteristics and spatio-temporal distribution of pink hibiscus mealybug from 1995 to 1997. The economic benefits and costs may be direct or indirect. The direct benefits included damage and losses avoided within home gardens and orchards,

Table 2 The benefits arising from the successful biological control of pink hibiscus mealybug in Trinidad and Tobago (after [11]; converted at 2004 rate TT$1=US$0.1615)

Item of benefit	Value in US$ million in 2004
Commercial farming	33.6
Home gardens and orchards	2.6
Commercial forests	4.4
Household property-gardens and landscape	1.4
Total	41.1

aesthetics/environment of household properties, commercial farming, commercial forestry and public parks, and the natural environment. The indirect benefits included the losses avoided with respect to exports of fresh produce. The direct economic costs included the Ministry staff costs and foreign exchange costs associated with the import of materials and supplies and the cost of capital equipment. The economic returns were calculated using a discounted rate of 10% as the social opportunity costs of capital, the value of the 30-year (1996–2024) streams of benefits and costs of the pink hibiscus mealybug programme were estimated to the direct economic/ environmental benefits and costs. In 2004, a value based on the 1995–1997 dollar value of total benefit was TT$254.69 million (see Table 2).

The economic cost was valued at TT$32.015 million, including expenditures incurred up to the end of 1997 and previsions for future management of pink hibiscus mealybug. This, therefore gives a benefit:cost ratio of 8 : 1 for Trinidad and Tobago for the period 1998–2004 and a net benefit of TT$222.675 million. It should be noted that this estimate is likely to be an underestimate as benefits to biodiversity etc. are difficult to quantify and have not been included. Potential benefits to the environment were highlighted as the prevention of environmental degradation in terms of biodiversity loss, and secondary impacts such as soil erosion, reduced water yield due to a loss of trees, increased cost of water treatment as a result of higher sediment loads and flooding due to higher run off rates. Other indirect benefits include the benefits of using biological control as opposed to chemical control, i.e. reduced health risk for the population on Trinidad and a decrease in likelihood of non-target effects on native insect species.

Since spreading throughout the Caribbean, pink hibiscus mealybug is now present within Southern California, Mexico and Florida where it would have posed a serious a problem were it not for the availability of biological control agents. Initial studies have suggested that should pink hibiscus mealybug become established, the overall annual costs to the US economy (including costs of both control and damages) would be US$700 million with a global cost of US$5 billion [12]. The USDA, Animal and Plant Health Inspection Service programme was initially set up to implement biological control within the Caribbean. However, in addition to this they were tasked with preparing for when pink hibiscus mealybug reached the USA [13]. It is for this reason that within a few weeks of the discovery of pink hibiscus mealybug in these countries, the biological control agents were introduced preventing the large-scale damages as seen within some of the Caribbean countries.

> Based on the Caribbean experience, within a few weeks of the discovery of pink hibiscus mealybug in USA and Mexico, the biological control agents were introduced preventing the large-scale damages seen in some of the Caribbean countries.

References

1. Kairo MTK, Pollard GV, Peterkin DD, Lopez VF. Biological control of the hibiscus mealybug, *Maconellicoccus hirsutus* Green (Hemiptera: Pseudococcidae) in the Caribbean. Integrated Pest Management Reviews 2001;5:241–54.
2. McComie LD. Challenges to the plant health systems in St Kitts and Nevis, 2000. [Online] Available from: URL: http://www.open.uwi.edu/sites/default/files/bnccde/sk&n/conference/papers/LDMcComie.html (accessed 15 January 2015).
3. EPPO (European and Mediterranean Plant Protection Organization). Data sheets on quarantine pests – *Maconellicoccus hirsutus*. OEPP/EPPO Bulletin 2005; 35:413–5.
4. Sagarra LA, Peterkin DD. Invasion of the Carribean by the hibiscus mealybug, *Maconellicoccus hirsutus* Green [Homoptera: Pseudococcidae]. Phytoprotection 1999;80:103–13.
5. CABI ISC (Invasive Species Compendium). *Maconellicoccus hirsutus*; 2014. [Online] Available from: URL: http://www.cabi.org/isc/datasheet/40171 (accessed 16 October 2014).
6. Meyerdirk DE, Warkentin R, Attavian B, Gersabeck E, Francis A, Adams M, Francis G. Biological Control of Pink Hibiscus Mealybug Project Manual. United States Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine & International Services, Riverdale, Maryland, USA; 1998. 194 pp [paginated in sections].
7. Kairo MTK, Barrow R, Persad C, Pollard GV. Dealing with extant or imminent threats: a Caribbean experience with building capacity for classical biological control. In: Mason PG, Gillespie DR, Vincent C, editors. *Proceedings of the Third International Symposium on Biological Control of Arthropods*, Christchurch, New Zealand, 8–13 February 2008. FHTET-2008-06. United States Department of Agriculture, Forest Service, Morgantown, West Virginia, USA; 2008. p. 506–13.
8. IUCN (Invasive Species Specialist Group). *Maconellicoccus hirsutus* (pink hibiscus mealybug) management and control, 2010. [Online] Available from: URL: http://www.issg.org/

database/species/reference_files/machir/machir_man.pdf (accessed 17 November 2014).

9. Sagarra LA, Vincent C, Stewart RK. Suitability of nine mealybug species (Homoptera: Pseudococcidae) as hosts for the parasitoid *Anagyrus kamali* (Hymenoptera: Encyrtidae). Florida Entomologist 2001;84:112–6.

10. Michaud JP. Three targets of classical biological control in the Caribbean: success, contribution, and failure. In: Van Driesche RG, editors. *Proceedings of the International Symposium on Biological Control of Arthropods*, Honolulu, Hawaii, 14–18 January 2002. FHTET-2003–05. United States Department of Agriculture, Forest Service, Morgantown, West Virginia, USA; 2002. p. 335–42.

11. Singh RH. The economic case for the regional safeguarding of agriculture and the environment: the experience of the pink hibiscus mealybug control programme in Trinidad and Tobago. In: Klassen W, Davis CG, Evans EA, Lauckner B, Adams H, Kairo MTK, editors. *Facilitating Safer U.S.-Caribbean Trade: Invasive Species Issues Workshop*, Port of Spain, Trinidad and Tobago, West Indies, 2–4 June 2004. PRTC 05-02. University of Florida Institute of Food and Agricultural Science, Gainesville, Florida, USA; 2005. p. 77–85.

12. Ranjan R. Economic impacts of pink hibiscus mealybug in Florida and the United States. Stochastic Environmental Research and Risk Assessment 2006;20:253–362.

13. Miller DR. Identification of the pink hibiscus mealybug, *Maconellicoccus hirsutus* (Green) (Hemiptera: Sternorrhyncha: Pseudococcidae). Insecta Mundi 1999;13:189–203.

Case Study 4
Orthezia bug, *Insignorthezia insignis* (Browne) (Hemiptera, Ortheziidae)

Lead author: Matthew J.W. Cock (CABI UK)

The following case study has been synthesized from Booth *et al*. [1] and Fowler [2, 3]). The British Dependent Territory of St Helena is a small South Atlantic island with a highly degraded, but internationally significant, terrestrial flora. The endemic gumwood, *Commidendrum robustum* (Roxb.) DC. (Asteraceae) is an important part of this remnant flora and the national tree of St Helena. Gumwood once formed much of the extensive woodland that used to cover the higher regions of the island but by the 1990s was restricted to two stands of around 2000 trees (Figure 1).

The Pest Problem

Orthezia scale, *Insignorthezia insignis* (Browne) until recently known as *Orthezia insignis*, but see Kozár [4] (Hemiptera, Ortheziidae) is native to South and Central America, but is now widespread through the tropics. It was accidentally introduced into St Helena in the 1970s or 1980s, and became a conspicuous problem when it started feeding on gumwood in 1991 (Figure 2).

Once the gumwood trees became infested in 1991, an increasing number of trees were being killed each year and at least 400 had been lost by 1993 (Figure 3). Orthezia bug damages its host primarily through phloem feeding but the colonization of the honeydew that orthezia bug excretes by sooty moulds has a secondary effect through the reduction of light transmission for photosynthesis. Because orthezia bug is polyphagous, and large populations could be maintained on other hosts such as lantana weed (*Lantana camara* L., Verbenaceae), it spreads easily onto the relatively rare gumwood trees. Gumwoods are susceptible to orthezia bug and if nothing had been done, it is most probable that gumwood would have become extinct in its natural habitat (Figure 4).

> The endemic gumwood tree is an important part of the unique St Helena flora, and once formed much of the extensive woodland that used to cover the higher regions of the island. Gumwood trees are very susceptible to the introduced orthezia bug and faced extinction in their natural habitat.

The Biological Control Programme

CABI (as the International Institute of Biological Control) assisted the Government of St Helena to carry out a biological control programme against this pest. There was already an indication that a suitable biological control agent might be available. Between 1908 and 1959, the predatory coccinellid beetle, *Hyperaspis pantherina* Fürsch had been released for the biological control of *O. insignis* in Hawaii, four African countries and Peru. Substantial control was reported after all the releases. A collection of *H. pantherina* was obtained from Kenya where it had been introduced to control orthezia bug on the introduced ornamental, jacaranda (*Jacaranda mimosifolia* D.Don, Bignoniaceae) and it was cultured and studied in UK quarantine. These studies showed that reproduction of the beetle is dependent on the presence of orthezia bug, that *H. pantherina* normally lays eggs directly onto adult females of *O. insignis* and that the first two instars of the larvae are frequently passed inside the ovisac of the female host, after which the host itself is often consumed. An assessment of the St Helena fauna showed that there did not seem to be any related indigenous species (although there were quite a few exotic pest scales present), so it was concluded that introduction of this predator would not only be safe in terms of effects on non-target organisms, but also would be likely to control the orthezia bug, and save the gumwoods.

In 1993, *H. pantherina* was imported, cultured and released in St Helena from June 1993 until February 1994 (Figure 5). It rapidly became established and numbers increased from 1994. Although at least 20 biological control agents have been released against insect pests of agriculture in St Helena prior to 1993, the release of *H. pantherina* was the first to be quantitatively monitored.

Evaluation of Impact

The monitoring data showed a correlation between scale infestation levels and tree death, and a negative correlation between the increase in *H. pantherina* and decrease in orthezia bug. Mean orthezia bug numbers per 20 cm branchlet decreased from >400 adults and nymphs in September 1993 to <15 in February 1995 when sampling

Figure 1 Gumwood forest in the hills of St Helena.

Figure 2 Adults with fluted egg sac and nymphs of orthezia bug, *Insignorthezia insignis* (photograph: JMK, Manie van der Schijff Botanical Garden, Pretoria, commons.wikimedia.org, CC BY-SA 3.0).

Figure 3 Orthezia bug infestation on gumwood, St Helena.

stopped. Though these data are correlative, the success of *H. pantherina* as a biological control agent for orthezia bug on St Helena is consistent with its past record in Hawaii and Africa [1]. Orthezia bug outbreaks have not been reported on St Helena since 1995, and culturing of *H. pantherina* was discontinued because insufficient orthezia bug could be found in the field to use for rearing the predator. In February 1995, there was still extensive blackening from sooty moulds on the surviving trees, but the gumwoods were showing signs of recovery with new growth appearing that were mostly uninfested by orthezia bug. It appears that the predator was effective just in time to prevent death of most trees. *H. pantherina* appears to have saved the field population of a rare endemic plant from extinction.

This is probably the first case of biological control being implemented against an insect in order to save a plant species from extinction. Gumwood is a key species for St Helena natural woodland, and essential for plans to conserve and re-establish natural habitats on this unique island. Restoration projects, to encourage natural gumwood regeneration by controlling weeds in and around the two relict stands, were able to proceed once biological control of orthezia bug was achieved. A large programme to establish a millennium forest of gumwoods on a previously wooded site on the island began in 2000, and orthezia bug infestations were not observed.

> The introduced predator was effective just in time to prevent death of the remaining gumwoods trees on St Helena, saving the field population of this key woodland plant. This is probably the first case of biological control being implemented against an insect in order to successfully save a plant species from extinction.

Figure 4 Sick and dying (right) gumwood trees infested with orthezia bug, St Helena.

Figure 5 The ladybird beetle *Hyperaspis pantherina* was introduced into St Helena and brought the orthezia bug under control, saving the gumwoods.

Because this project was built on existing knowledge based on the previous successful introductions of the predator, it was relatively straightforward to plan and implement a successful biological control project. Nevertheless, it was necessary to evaluate the risks to non-target organisms, as these had not been critically considered in previous introductions. Using CABI's network of regional centres, obtaining material of *H. pantherina* for culture and supply was quite straightforward. The costs of CABI's inputs were of the order of UK£30 000 at the time and were covered by the UK's Department for International Development. The costs of the St Helena Department of Agriculture to culture, release and monitor the predator have not been documented, but would probably have been comparable.

A *post hoc* stakeholder analysis [5] suggested that the following key stakeholder groups were interested in the biological control of orthezia bug:

- Conservationists, particularly those concerned with the preservation of St Helena's globally important flora and fauna;
- the agricultural industry in St Helena, particularly those concerned with crops likely to be affected by orthezia bug;
- garden owners, as some ornamental plants are adversely affected by orthezia bug;
- landowners whose land is infested by lantana weed, since this alien invasive plant is also attacked by orthezia bug, which can be quite damaging to lantana, possibly offering some control; and
- the British Government, which is responsible for the dependency of St Helena, as the control of orthezia bug would help them meet their obligations under the Convention on Biological Diversity.

The motivation for implementing this project was to save the gumwood, the incidental benefits to agriculture and gardens and any possible change in the status of lantana weed were not assessed. The success in saving the gumwoods is clear in qualitative environmental terms.

References

1. Booth RG, Cross AE, Fowler SV, Shaw RH. The biology and taxonomy of *Hyperaspis pantherina* (Coleoptera: Coccinellidae) and the classical biological control of its prey, *Orthezia insignis* (Homoptera: Ortheziidae). Bulletin of Entomological Research 1995;85:307–314.
2. Fowler SV. Biological control of an exotic scale, *Orthezia insignis* Browne (Homoptera: Ortheziidae), saves the endemic gumwood tree, *Commidendrum robustum* (Roxb.) DC. (Asteraceae) on the island of St. Helena. Biological Control 2004;29:367–374.
3. Fowler SV. The successful control of *Orthezia insignis* on St. Helena island saves natural populations of endemic gumwood trees, *Commidendrum robustum*. In: Hoddle MS (compiler). *Second International Symposium on Biological Control of Arthropods, Davos, Switzerland, September 12–16, 2005*. Forest Health Technology Team, Morgantown, West Virginia, USA; 2005. USDA Forest Service Publication FHTET-2005-08, p. 52–63.
4. Kozár F. Ortheziidae of the World. Plant Protection Institute, Hungarian Academy of Sciences, Budapest, Hungary; 2004. 525 pp.
5. Cock MJW. Risks of non-target impact versus stakeholder benefits in classical biological control of arthropods: selected case studies from developing countries. In: Van Driesche RG, editor. Proceedings of the International Symposium on Biological Control of Arthropods, Honolulu, Hawaii, 14–18 January 2002. United States Department of Agriculture, Forest Service, Morgantown, WV; 2003. FHTET-2003-05, p. 25–33.

Case Study 5
Brown peach aphid, *Pterochloroides persicae* (Cholodkovsky) (Hemiptera, Aphididae)

Lead author: Matthew J.W. Cock (CABI UK)

The Pest Problem

In 1993, an aphid attacking fruit trees, particularly peach and almond, was first reported in Yemen and was identified as *Pterochloroides persicae* (Cholodkovsky) or brown peach aphid [1]. This aphid probably originates from East-Central Asia and dispersed westwards along traditional trade routes in past centuries, along with its host trees. In recent decades, it has spread westwards and southwards into Europe and the Middle East. By the mid-1990s it had spread through Yemen and was inflicting severe losses on the country's 70 000 farmers who grew fruit tree crops for sale and home consumption. Yields and fruit quality were affected and in some areas the aphids were causing tree decline (Figure 1). Chemical control meant spraying every 2 weeks which was costly and had environmental and health implications. A Food and Agriculture Organization of the United Nations (FAO) emergency response project was set up with the General Department of Plant Protection (GDPP), Republic of Yemen, in collaboration with the Yemeni–German Plant Protection Project.

The Biological Control Programme

Pt. persicae had not previously been the subject of a biological control programme, so CABI (as the International Institute of Biological Control) was tasked to survey for *Pt. persicae* and research potential biological control agents. A literature survey and assessment of prospects [2] was followed by surveys in Pakistan where brown peach aphid is indigenous [3]. Literature searches indicated that an aphidiine parasitoid, *Pauesia antennata* (Mukerji), was the most commonly recorded and predominant natural enemy of *Pt. persicae* in Central Asia. Extensive surveys in Pakistan indicated that it was the only parasitoid of late instars/adults there. As it also had similar biological attributes to other aphid parasitoids that have been successful in classical biological control programmes, it was prioritized for further study.

Cultures of both the aphid and the parasitoid were established at CABI in Pakistan and the CABI quarantine facility in the UK, and research conducted on their biology, ecology and rearing, host specificity, other potential risks and likely impact of *Pa. antennata*. A dossier was prepared [4] and submitted via FAO to the Government of Yemen. Clearance for introduction of the parasitoid was received in December 1996.

There is rather little documentation of the release programme in 1997 and its impact thereafter, but fortunately during this period, an MSc student at Sana'a University in Yemen, Ahmed Saif Abdul-Hak, was conducting research, which included studying the population dynamics of *Pt. persicae* in Yemen and later the effects of the introduced parasitoid on aphid populations [5], summarized in [6]. His results indicated that before *Pa. antennata* was released, *Pt. persicae* was present throughout the year, reproducing parthenogenetically at all surveyed sites. Populations increased from mid-September through to the end of July with peak populations recorded from the beginning of May to mid-July. Female alates produced at the end of April/beginning of May dispersed to other orchards. Abdul-Hak's studies also indicated that indigenous natural enemies were limited to generalist predators which were clearly not keeping the exotic aphid in check.

Pa. antennata was imported to the GDPP laboratories in Sana'a at the end of January 1997 and a rearing colony established. By July the GDPP had reared more than 65 000 parasitoids, and over 50 000 of these were released in the field [7] (Figure 2). At the peak of production 1000 parasitoids a day were being released. Releases were concentrated at three main sites around Sana'a and within 2 months the aphid populations in these areas, and beyond, had completely collapsed as a result of parasitoid attack: within 2 months, Abdul-Hak was finding parasitism rates of approximately 40–90% in orchards within 25 km of Sana'a. The parasitoid was found at farms more than 50 km away from release sites 2 months after release and 120 km away 4 months later. The release programme was extended to the south and south-east to increase dispersal, and successful country-wide control was achieved as the parasitoid spread and established in Yemen (Figure 3). Just under 350 000 parasitoids were released in all.

> Parasitoid releases against brown peach aphid were concentrated around Sana'a and within 2 months the aphid populations in these areas, and beyond, had completely collapsed as a result of parasitoid attack.

Figure 1 Brown peach aphid secreting honeydew (photograph: Eran Finkle, https://www.flickr.com/photos/finklez/3551064470, CC BY 2.0)

Figure 2 Release container for *Pauesia antennata*, the introduced biological control agents for brown peach aphid in Yemen (photograph: M.J.W. Cock, CABI).

Figure 3 Scientists from General Department of Plant Protection, Republic of Yemen, and the Yemeni–German Plant Protection Project inspect parasitoid releases against brown peach aphid in Yemen (photograph: M.J.W. Cock, CABI).

Abdul-Hak's data indicated that after parasitoids were released, *Pt. persicae* populations decreased dramatically, except in orchards where farmers continued to use chemicals. He also cited a fall in pesticide use in stone- and pome-fruit orchards country-wide from 22 to 2.5 tonnes between 1995, at the height of the outbreak, and 1998, by which time *Pa. antennata* had controlled the pest; the cost of pest control also fell nine-fold in the same period. However, he reported a potential hyperparasitoid problem: two pteromalid species newly recorded for Yemen were identified from *Pa. antennata*. Although hyperparasitism was less than 30% in 1997 and caused no problems in that year, in 1998, it exceeded 75% and even 80% in places and thus became a problem. The approach was to treat trees in affected areas with pesticide and release fewer *Pa. antennata*; hyerparasitism subsequently fell back to around 30%. There seems little room for doubt that the introduction of *Pa. antennata* led to the successful biological control of brown peach aphid.

Evaluation of Impact

The classical biological control programme was proclaimed a success in Yemen: the front page of the *Yemen Times* for 6–12 October 1997 carried the headline, 'Over 7.6 million trees saved: a biological enemy for the peach stem aphid introduced in Yemen'. Although the benefits have not been quantified, they are evident from the qualitative information available. Livelihoods and incomes were preserved, avoiding the use of substantial amounts of insecticides, for the 70 000 farmers who grew fruit tree crops for sale and home consumption. If we accept the figure of 7.6 million fruit trees saved, that is a little over 100 trees per farmer, the loss of which would have been significant.

> Headline in the *Yemen Times*, 6–12 October 1997: 'Over 7.6 million [peach] trees saved: a biological enemy for the peach stem aphid introduced in Yemen'.

References

1. Harvey AW, Abdul-Moghni, AA. New aphid pest infesting fruit-trees in Yemen. FAO Plant Protection Bulletin 1994;42(4):220.
2. Kairo MTK, Poswal MA. The brown peach aphid, *Pterochloroides persicae* (Lachninae: Aphididae): prospects for IPM with particular emphasis on classical biological control. Biocontrol News and Information 1995;16(3):41N–7N.
3. Poswal MA. Biological Control of Brown Peach Aphid. Unpublished report. PARC-IIBC Station, International Institute of Biological Control, Rawalpindi, Pakistan; 1996. 19pp.

4. Cross AE and Poswal MA. Dossier on *Pauesia antennata*: biological control agent for the brown peach aphid, *Pterochloroides persicae*, in Yemen. CABI Working Paper 5, 2013. 23 pp. Available from: URL: http://www.cabi.org/uploads/cabi/expertise/CABIWP5-Pauesia-antennata.pdf
5. Abdul-Hak AS. The biological control of giant brown bark aphid Pterochloroides persicae (Cholodk.) on stone-fruit trees in the Republic of Yemen. MSc thesis, Department of Plant Protection, Faculty of Agriculture, Sana'a University, Yemen; 2000.
6. Cock MJW. Revisiting peach aphid biocontrol in Yemen. Biocontrol News and Information 2013;34(4):31N–3N.
7. IIBC [International Institute of Biological Control]. Annual Report 1997. CAB International, Wallingford, UK; 1998. 135 pp.

Case Study 6
Banana skipper, *Erionota torus* Evans (Lepidoptera, Hesperiidae)

Lead author: Matthew J.W. Cock (CABI UK)

Often referred to as banana skippers, *Erionota torus* Evans and *Erionota thrax* (Linnaeus) are two very similar species of *Erionota*, a genus indigenous to South-East Asia. A recent review by Cock [1] showed that there has been considerable confusion between the two in the applied entomological literature (unattributed information in the following case study is based on references in Cock [1]). This confusion is exemplified in the case of Mauritius, where the introduced banana skipper was identified as *E. thrax*, and under this name was the target of a successful biological control programme, but examination of museum specimens shows that the species in Mauritius is *E. torus* (Figure 1).

The Pest Problem

E. torus is indigenous in mainland South-East Asia, from northern India to Peninsular Malaysia, and has become established in Mauritius (1970), Okinawa, Japan (1971), the southern Philippines (before 1984), Taiwan (1986) and the western Ghats of India (2014). *E. thrax* occurs in four subspecies and is indigenous from north-east India to the northern Philippines and Indonesia as far east as North Moluku. Subspecies *thrax* has become accidentally established in Saipan (late 1960s), Guam (1956), Hawaii (1973), Papua New Guinea (PNG, 1986) and the Andaman Islands, India (1990), although Cock [1] suggests that the identification of the last record needs checking.

The food plants of *E. thrax* and *E. torus* are restricted to species of *Musa* (bananas, plantain, Manila hemp) and their relatives. The larvae construct a distinctive leaf roll shelter by cutting a long arc from the edge of a banana leaf and rolling the flap thus created into a tube in which they shelter. Feeding and pupation is within successive tubes, and the larva grows to more than 5 cm (Figure 2). The loss of leaf area due to feeding and shelter construction is significant, and severe leaf loss and defoliation occur when larvae are numerous (Figure 3).

When *E. torus* appeared in Mauritius, it was identified and reported as *E. thrax*. It immediately started to cause severe damage to backyard bananas, although plantation bananas (Cavendish dwarf variety) were not initially affected [2].

The Biological Control Programme (Mauritius)

The Ministry of Agriculture and Natural Resources contacted CABI for help with biological control, and together CABI and the ministry implemented a biological control programme of what they believed was *E. thrax*.

Already, parasitoids were known to attack *E. thrax* in South-East Asia, as CABI taxonomists had named and described *Ooencyrtus erionotae* Ferrière (Encyrtidae), an egg parasitoid from peninsular Malaysia, and *Apanteles erionotae* Wilkinson (Braconidae), a larval parasitoid from peninsular Malaysia and Sumatra as a result of, and largely based on, material submitted to CABI's identification service. The former species is now considered a synonym of *Ooencyrtus pallidipes* (Ashmead), and the latter is treated as the combination *Cotesia erionotae* (Wilkinson).

CABI's Dr Rahman A. Syed, based in Sabah, East Malaysia, studied the parasitoid natural enemies of *E. thrax* (*E. torus* does not occur there) and sent shipments of selected parasitoid species to Mauritius [3–7]. No host-specificity studies were made at this time, although it would have been known that these parasitoids did not attack known Hesperiidae pests. *O. pallidipes* and *C. erionotae* became established and quickly gave excellent control [8]. However, as a result of the 1975 cyclone, pest and parasitoid numbers crashed, and although the pest briefly resurged, it subsequently remained present only in very low numbers [8]. Although parasitoids were not recovered after the cyclone, nevertheless it seems most likely that the introduced biological control agents persist, continuing to keep the pest at very low numbers, doing no economic damage.

The Biological Control Programme (elsewhere)

Based on the research already done by R.A. Syed, when *E. thrax* appeared in Hawaii, a biological control programme was immediately started [9]. In 1973 *O. pallidipes* was introduced from Guam (where it seemed to be an accidental introduction itself), and in 1974 *C. erionotae* was introduced and released, initially from Thailand (early 1974) and then from CABI Sabah, Malaysia (late 1974). The control was rapid, and the strain of *C. erionatae* from Thailand was probably already established and bringing the pest under control before that from Sabah was released. In 1974, *C. erionotae* cultures of the Thailand strain were

Figure 1 Adults of the banana skipper fly at dusk and are attracted to light (M.J.W. Cock, CABI).

Figure 2 Larvae of the banana skipper grow to 5 cm and are covered with white waxy powder (M.J.W. Cock, CABI).

Figure 3 Banana skipper larvae make large leaf rolls in which they shelter and feed; the leaf area lost to making the shelter is greater than that lost to feeding (M.J.W. Cock, CABI).

sent from Hawaii to Guam and from Guam to Saipan in 1974–1975, in both cases giving good control [9]. In their 1989 review of the biological control of banana skipper, Waterhouse and Norris [9] reported that local entomologists were not aware of any non-target attack by the introduced parasitoids, although no structured surveys were made. Both parasitoids were also sent from Hawaii to Taiwan for the control of *E. torus*; they were released in 1987 and both became established [10]. Although the impact has not been fully assessed and reported, Teruya [11] found *E. torus* to have 'a low pest status', infestation ranging from 0.1 to 7% with an average of 4%, but he did not find the introduced parasitoids.

E. thrax may have spread into Irian Jaya before 1983 as it appeared by the border in north-western mainland of PNG in 1983, and then spread rapidly through the island over 5 years, and started to colonize the other islands of PNG [12]. It spread together with its egg-parasitoid, *O. pallidipes*. However, control was not adequate with the egg parasitoid alone, and so *C. erionotae* from Guam was introduced after quarantine safety tests [13], which showed that three commercially important species of Papilionidae and an indigenous palm-feeding Hesperiidae pest were not suitable targets. This rapidly resulted in good control of the pest.

Evaluation of Impact (PNG)

The programme in PNG was supported by the Australian Centre for International Agriculture Research (ACIAR), who subsequently funded assessments of the benefits to PNG and Australia [14] and the impact on poverty in PNG [15]. The following is summarized from their reports.

Extrapolating from several studies on defoliation and fruit loss indicates that more than 16% defoliation will cause measureable loss of yield, and 50% defoliation will cause 28% yield loss. As the banana skipper spread in PNG, it destroyed an average of some 60% of banana leaves (Figure 4), leading to both a serious delay in fruit maturation and reduced weight of banana bunches. After *C. erionotae* was introduced and established, there was a reduction in the estimated average leaf damage from 60 to 5%.

Bananas are an important subsistence food crop in PNG, grown in all parts of the country up to 2200 m altitude and account for around 8% of PNG's staple food crop production. For 26% of the population, bananas make up at least 10% (by value) of their food consumption.

The first study recognized that banana is the second most important staple crop in PNG, but did not attempt to assess the socio-economic impact of 30% losses of such an important food crop, for livelihoods, food security, social stability, etc. Instead, the study attempted to assess economic values based on potential lost production.

Figure 4 Banana skipper outbreak in Papua New Guinea (photograph: C. Dewhurst, Papua New Guinea Oil Palm Research Association, Inc – retired).

Using the estimated production value of bananas in PNG to the year 2020 (a 30 year period was used based on the assumption that the positive effects of the biological control agent will last at least that long), the losses due to banana skipper each year were calculated at 30% of crop, of which 95% was saved by the biological control introduction. Using a discount rate of 5% per year over the 30 year period, the net present value of lost production that would have been due to *E. thrax* amounts to approximately A$301.8 million. The value of damage prevented by biological control is estimated at A$201.6 million.

> Bananas are an important subsistence food crop in PNG, grown in all parts of the country up to 2200 m altitude and account for around 8% of PNG's staple food crop production. The losses due to banana skipper in PNG each year were calculated at 30% of crop, of which 95% was saved by the biological control introduction.

The reduction of banana skipper abundance by 90% in southern PNG has correspondingly reduced the chance of adults invading not only Australian islands in the Torres Strait but also the Australian mainland. The successful biological control program in PNG has therefore provided significant benefits to banana production in Australia. Assuming similar levels of damage in Australia as in PNG, these benefits were estimated to be $223 million to the year 2020.

The assessment of benefits did not consider the social and cultural uses of banana leaves, nor the possible benefits in Irian Jaya, to which the parasitoid almost certainly spread. Apart from these aspects, the 1998 value of total benefits from the ACIAR project is A$424.7 million (A$201.6 million to PNG and A$223.1 million to Australia). This compares with the 1998 value of the cost of the ACIAR project of $0.70 million, giving a benefit:cost ratio of 607 : 1 and an internal rate of return of 190%.

Poverty through income deprivation is a significant problem in PNG. Estimates from a 1996 household income survey suggested that around 30% of the PNG population have household incomes below the poverty line (i.e. income is not sufficient to sustain 2200 calories/day of food consumption and cover the cost of essential non-food items). PNG's continued poor economic performance since 1996, suggests that the extent of poverty was higher, perhaps significantly higher, when Bauer *et al.* [15] did their study. Most income-poor households live in rural areas and rely heavily on subsistence agriculture. It follows that measures that raise the productivity of subsistence agriculture, or avoid losses in subsistence agricultural production that would otherwise occur, could make a significant contribution to poverty reduction in PNG. Roughly 700 000 banana growers live in poverty, as do around 1 million banana consumers. The biological control of *E. thrax* has had a significant beneficial impact on the effective incomes of most PNG households by improving the supply of bananas and by lowering the price of bananas to purchasers.

Subsistence banana growers are the major beneficiaries. The real improvement of their incomes depends on the relative contribution of bananas to their diet and the extent to which they would have diverted resources from banana growing to other crops if the pest had not been controlled. It was considered that with 30% crop losses there would be relatively little diversion, considering the investment already made to establish banana plants. The improvement in income due to biological control measures against the banana skipper would put around 15 000 people (assuming no diversion of resources to other crops) to 6000 people (assuming 30% diversion) above the poverty line who would otherwise have been below it. Every subsistence banana producer will experience an increase in income between 0.9 and 2.2%. This means that poverty among all banana producers is reduced. These estimates assume that all production is consumed in the household, whereas growers who sell some of their surplus product at the market will receive a larger benefit in terms of increased income and consumption prospects.

> The improvement in income due to biological control measures against the banana skipper would put around 6000–15 000 subsistence banana producers above the poverty line who would otherwise have been below it.

The successful implementation of the project has also contributed to lower urban banana prices, in that the fall in supply of bananas caused by the pest would have forced banana prices up. By how much, depends on the price elasticity of demand for bananas, a parameter that is not known with certainty in PNG. The more responsive the price elasticity of demand, the more likely that even a small increase in prices caused by a reduction in banana production, will cause consumers to switch to other sources of food. Even with a price elasticity at the more responsive end of the likely range, banana prices are likely to have risen by around 15% had the biological control of the skipper not been achieved. Preventing this increase in market prices for bananas of around 15% by the introduction of the biological control measures resulted in around 28 000 purchasers of bananas living just above the poverty line when they otherwise would have been below it.

These estimates of numbers seem small when compared with the 1.4 million people considered to be below the poverty line in PNG. However, this head count ratio measure takes no account of the amount by which people fall short of the poverty line or are above it. Since the program has prevented a banana shortage and price rise, all banana consumers will benefit from more affordable bananas. The banana skipper control program has increased effective incomes across all income levels of banana producers and banana consumers.

Evaluation of Impact (Mauritius)

The project in PNG differed from that in Mauritius, in that we now know that the species in Mauritius is *E. torus* not *E. thrax*. We do not know whether the two species would have caused equal damage without biological control, but given the similar biology and ecology of the two species, this seems a reasonable assumption. In addition, the egg parasitoid that spread with *E. thrax* in PNG probably provided a degree of control before the introduction of the larval parasitoid. Hence, with neither parasitoid present in Mauritius, the damage was likely to be greater. On the other hand, it was stated that although tall varieties of banana in backyards in Mauritius were severely affected, rural plantations of Cavendish dwarf varieties were not affected (J. Monty in [9]). This situation may have only been temporary since Cavendish varieties are affected by *E. thrax* and/or *E. torus* in Malaysia [16], or it may indicate a difference between the two *Erionota* spp. However, a year after *E. torus* was discovered in Mauritius, parasitoids were already being released and effective control was rapidly achieved, so there is no data on what the damage would have been to commercial plantations. In the absence of better data, 30% potential crop loss in Mauritius seems plausible.

Hence, we can attempt a rough calculation of the annual benefits of biological control of *E. torus* for Mauritius, using figures from 2011 [17]. In 2011, bananas (including backyard production) were estimated to occupy 497 ha (6.6% of 7484 ha of food crops production) and produce an annual harvest of 10 544 tonnes. All banana production is eaten locally in Mauritius, and about 8 kg of bananas are consumed per capita per year. The wholesale price of bananas has fluctuated at around 28 000 Rp/tonne for several years [18]. The Mauritius Rupee is currently about 50 to UK£, but the general trend is a slowly weakening Rupee. Hence, the 2011 benefit of biological control of *E. torus* in wholesale banana values is the annual crop (10 544 tonnes) $\times$ price per tonne (Rp 28 000) $\times$ potential loss due to *E. torus* (30%) $\times$ reduction in loss due to biological control (95%), i.e. Rp 84 million, or UK£ 1.7 million. If this benefit were discounted at 5% per year over 30 years as for the PNG study, it would be worth £26.7 million at 2011 values.

This approach does not attempt to quantify the reduced risk of transfer of *E. torus* to nearby countries, of which La Réunion (part of France) is closest at 220 km. Boats and airplanes are likely pathways, particularly if loaded under floodlights which could attract the night-flying adults. Air Mauritius flies locally to Reunion and Rodrigues Is, as well as to Australia, India, Kenya, Madagascar and South Africa (http://www.airmauritius.com/).

The A$700 000 cost of the biological control programme in PNG included the construction of a quarantine facility for safety tests as well as the cost of obtaining *C. erionotae*, and rearing and releasing it over a wide area. The cost of the studies that CABI carried out in Sabah is no longer available, but the work was carried out by Dr Syed over 4 years as a relatively small part of the 5–7 projects that he worked on in Sabah, with up to three technical assistants (CIBC 1970-1974; see under Syed in references). We suggest that CABI's work for Mauritius involved at the very most six scientist months and six technician months using facilities provided by the Sabah Department of Agriculture, maybe 20 identifications of parasitoids and perhaps 10 shipments of parasitoids to Mauritius, which at today's costs would be a total of about UK£43 000 (without any overheads). The cost of describing and naming the two parasitoids in today's prices might be of the order of 0.5 taxonomist months or £7000, assuming the taxonomist was already familiar with the fauna (as Ferrière and Wilkinson were), giving a total of about £50 000 (without overheads). In addition to this would have been the scientist and technician time for rearing, release and follow-up of the parasitoids in Mauritius using an existing facility. If this cost is estimated at a further £50 000, giving a total cost of £100 000, then this indicates a benefit:cost ratio of 53 : 1 for the programme in Mauritius alone.

A retroactive study to improve this assessment would need to address the following:

1. That one or both parasitoids remain present in Mauritius and cause sufficient mortality to explain the continuing very low level populations of *E. torus*.
2. A more rigorous analysis of the economics of banana production, sales and consumption in Mauritius, and a full economic analysis similar to that of Waterhouse *et al.* [14].

References

1. Cock MJW. A critical review of the literature on the pest *Erionota* spp. (Lepidoptera, Hesperiidae): taxonomy, distribution, food plants, early stages, natural enemies and biological control. CABI Reviews 2015;10(7):1–30.
2. Monty J. Notes on a new insect pest in Mauritius: the banana leaf-roller *Erionota thrax* L. (Lepidoptera, Hesperiidae). Revue Agricole et Sucrière de l'ile Maurice 1970;49:107–109.
3. Syed RA. Biological control of *Erionota thrax* (for Mauritius). Commonwealth Institute of Biological Control, Annual Report; 1970. p. 96.
4. Syed RA. Biological control of *Erionota thrax* (for Mauritius). Commonwealth Institute of Biological Control, Annual Report; 1971. p. 110–111.
5. Syed RA. Biological control of *Erionota thrax* (for Mauritius). Commonwealth Institute of Biological Control, Annual Report; 1972. p. 81.
6. Syed RA. Biological control of *Erionota thrax* (for Mauritius). Commonwealth Institute of Biological Control, Annual Report; 1973. p. 81.
7. Syed RA. Supply of parasites of *Erionota thrax* (for Mauritius and Hawaii). Commonwealth Institute of Biological Control, Annual Report; 1974. p. 84.
8. Monty J. Entomological news from the Agricultural Services of the Ministry of Agriculture, Natural Resources and the Environment. Revue Agricole et Sucrière de l'ile Maurice 1977;56(3):107–109.
9. Waterhouse DF, Norris KR. 8. *Erionota thrax* (Linnaeus). In: Waterhouse DF, Norris KR, editors. Biological Control Pacific Prospects – Supplement 1. Australian Centre for International Agricultural Research, Canberra, frontispiece +; 1989. pp. 89–99.
10. Lo KC. Biological control of insect and mite pests on crops in Taiwan – a review and prospection. [In Chinese with English abstract, tables and references]. Symposium on the Biological Control of Agricultural Insects and Mites. Formosan Entomologist, Special Publication; 2002;3:1–25.
11. Teruya T. A brief report about the distribution of the banana skipper, *Erionota torus Evans in Taiwan*. [In Chinese with English tables and summary]. Okinawa Agriculture 1997;32(1):62–67.
12. Sands DPA, Sands MC, Arura M. Banana skipper, *Erionota thrax* (L.) (Lepidoptera: Hesperiidae) in Papua New Guinea: a new pest in the South Pacific region. Micronesica, 1991;3(Supplement):93–98.
13. Sands DPA, Bakker P, Dori FM. *Cotesia erionotae* (Wilkinson) (Hymenoptera: Braconidae), for biological control of banana skipper, *Erionota thrax* (L.) (Lepidoptera: Hesperiidae) in Papua New Guinea. Micronesica 1993;(Suppl. 4):99–105.
14. Waterhouse D, Dillon B, Vincent D. Economic benefits to Papua New Guinea and Australia from the biological control of banana skipper (*Erionota thrax*) ACIAR Project CS2/1988/002-C. Impact Assessment Series 12. Australian Centre for International Agricultural Research, ACIAR, Canberra, Australia; 1998. 36 pp.
15. Bauer M, Pearce D, Vincent D. Saving a Staple Crop: Impact of Biological Control of the Banana Skipper on Poverty Reduction in Papua New Guinea. ACIAR project CS2/1988/002-C. *ACIAR Impact Assessment Series*, No 22. Australian Centre for International Agricultural Research, Canberra, Australia; 2003. 23pp.
16. Okolle JN, Ahmad AH, Mansor M. Infestation and parasitism of banana skipper (*Erionota thrax*) (Lepidoptera: Hesperiidae) in relation to banana leaf age, and surface and distance from field edge. Asian and Australasian Journal of Plant Science 2009;3(1):61–65.
17. Ministry of Finance & Economic Development. Digest of Agricultural Statistics 2011. Ministry of Finance & Economic Development, Mauritius; 2012. 157 pp. http://www.gov.mu/portal/site/cso/menuitem.046106bcbc449145c18d5c10a0208a0c/?content_id=00a1924de23eb010VgnVCM1000000a04a8c0RCRD
18. Index Mundi. Bananas Monthly Price – Mauritius Rupee per Metric Ton. 2014. Available from: URL: http://www.indexmundi.com/commodities/?commodity=bananas&months=60&currency=mur

Case Study 7
Black sage, *Varronia curassavica* Jacq. (Boraginales, Cordiaceae)

Lead author: Matthew J.W. Cock (CABI UK)

This weed biological control target has long been known as *Cordia curassavica* (Jacq.) Roem and Schult. (=*C. macrostachya* (Jacq.) Roem and Schult.) and placed in the Boraginaeae. Gottschling *et al.* [1] confirmed that Cordiaceae, based on *Cordia* and related genera, is a valid monophyletic family, and it is recognized on the Angiosperm Phylogeny Website [2]. Miller and Gottschling [3] resurrected the genus *Varronia* for about 100 species from the New World tropics, which had for many years been treated as an infrageneric group within *Cordia*, so the correct name for this weed is now *Varronia curassavica* Jacq., although its common name in Trinidad, black sage, will be used here.

The Pest Problem

The following account of the biological control programme in Mauritius is adapted from Greathead [4], Cock [5] and the sources to which they refer. This hardy shrub is native to the Neotropical region, including Trinidad where it is known as black sage (Figure 1). Black sage is believed to have reached Mauritius from Guyana in about 1860 in shipments of sugar cane plants. An abundant production of seeds in the absence of natural enemies and the dispersion of the seeds by fruit feeding birds, especially the bulbul *Pycnonotus jocosus* (L.) (Pycnonotidae) soon led to its spread through the island. It encroached gradually on the secondary vegetation to become an exclusive dominant of large areas of grassland and scrubland under a wide range of rainfall conditions. Thus, large tracts became covered in a dense scrub at the expense of the existing vegetation, destroying grazing land and making it difficult to collect the leaves of the wild aloe *Furcraea foetida* (L.) Haw. (Asparagaceae) which are a source of fibre.

> Following its introduction into Mauritius, black sage encroached gradually on the secondary vegetation to become an exclusive dominant of large areas of grazing land and scrubland under a wide range of rainfall conditions.

The Biological Control Programme

Mauritius

Biological control was considered by the Department of Agriculture in 1939 but action was delayed by World War II, until in 1944 studies were begun on the plant in Trinidad (at the Imperial College of Tropical Agriculture), including a survey of its insect enemies, to acquire ecological data for comparison with those obtained in Mauritius. In 1946 the work was taken over by the CABI (as the Commonwealth Institute of Biological Control, CIBC), when Dr F.J. Simmonds was transferred to Trinidad from the wartime headquarters in Canada.

Simmonds studied the biology and host-specificity of two chrysomelid beetles, *Physonota alutacea* Boheman [6] and *Metrogalleruca obscura* Degeer (=*Schematiza cordiae* Barber) [7, 8]. Extensive tests in both Trinidad and Mauritius showed that both species are completely host specific. In 1947, shipments of parasitoid-free stocks were made to Mauritius by air mail: ten shipments totalling 550 dormant *P. alutacea* adults were sent during the dry season and 13 shipments totalling 5249 fully grown larvae and prepupae of *M. obscura* [9, 10]. Cultures of both were established.

First 21 000 adults, 4000 larvae and 280 egg masses (approximately 7000 eggs) of *P. alutacea* were released between June 1947 and May 1948 but successful establishment was not achieved. Interference with larval feeding by ants appeared to be the chief reason for failure [9]. Attention was then turned to *M. obscura* and about 18 000 adults were released at 18 localities between March 1948 and February 1949. Subsequently 60 000 adults were collected from the field between February and April 1949 and redistributed. The population build-up during the 1948–49 hot season was dramatic and by June complete defoliation and suppression of flowering occurred over large areas of scrub. By mid-1950, much of the scrub was dying and the continued severe defoliation was reducing its competitive power [10].

As it was felt that a seed destroying insect was likely to play a part in controlling recolonization by black sage, work was done in Trinidad on the complex of Hymenoptera feeding in the fruits. Several eurytomids were reared from the inflorescences, and of these a eurytomid, *Eurytoma attiva* Burks (=*Eurytoma* sp. nr. *howardii*) was ascertained to be phytophagous and the others to be parasitic. *Eurytoma attiva* was studied and recommended as safe for introduction on the grounds of its very close relationship with its host, and its galling action indicating its specificity. This species was released in Mauritius without any host specificity tests. Between September 1949 and April 1950 about 2.5 million black sage fruits were sent to Mauritius by air after drying and application

Figure 1 A flowering short of black sage (photograph: Marcia Stefani, commons.wikimedia.org, CC BY 2.0).

of fungicide to prevent decay. These were held under quarantine in emergence boxes and the daily emergences carefully sorted. Males of all *Eurytoma* spp. (which could not be accurately determined to species while alive) and female *E. attiva* were retained and bulked in jars. All other insects were destroyed. Bulked *Eurytoma* were released every few days. The numbers obtained were small; only 1300 females and 900 males were released. By May 1950, establishment was confirmed at the first release site and to avoid further risks the remaining stock of black sage fruits was destroyed. The first colony was used for distribution of *E. attiva* to other sites where it soon became established. As *M. obscura* had already substantially controlled black sage by the time *E. attiva* was released its contribution to control has not been accurately assessed, however Williams [11] considered its part likely to be important in stabilizing control as the two species have complementary effects on the plant.

Wiehe [12] assessed the situation in 1960 at the end of the biological control programme. Although scrubs composed dominantly of black sage are still to be seen in certain localities, they are of small extent and show no tendency to spread. They are generally remnants of more extensive scrub which survived the sweeping early attacks of *M. obscura* and, probably owing to some favourable local combination of environmental factors, have been able to persist. Otherwise, black sage growths are not dense now and the plant is a subordinate constituent of the lowland scrubs and thickets of the island. A distinguishing feature of these communities in former days was the almost impenetrable undergrowth formed by black sage. This has now almost completely disappeared, black sage being of comparatively rare occurrence and coexisting with other species of the same life form, such as *Lantana camara* L., which are now able to compete successfully with it. Similarly, on waste lands, along hedgerows and on stone heaps in sugarcane fields, where, for over a quarter of a century, black sage was often the exclusive dominant, its status has now been relegated to that of an occasional species. Finally, the grasslands that occur around the coast and in parts of the uplands of Mauritius are now almost free from black sage. It may be concluded, therefore, that the secondary succession of vegetation has now reverted to its former course. Forty years later, the situation does not seem to have changed, and Fowler *et al.* [13] in their review of weed biological control in Mauritius refer to it as under 'continuing, fully successful biological control'. Any benefits in terms of reduced competition with indigenous plants has not been assessed, and it seems likely that is less than might have been expected because many other introduced plant species have also proved to be highly invasive [14].

For the last 40 years, in disturbed areas of Mauritius where, for over a quarter of a century, black sage was often the exclusive dominant, its status has now been relegated to that of an occasional species. The grazing lands that occur around the coast and in parts of the uplands are almost free from black sage.

Malaysia

Black sage was introduced into the Singapore Botanic Garden by 1897, and by 1954 was noted to have spread through much of peninsular Malaysia, due to its use as an urban hedge plant. It only started to come into prominence as an agricultural weed in the early 1960s. When the biological control programme was initiated, Ung *et al.* [15] and Simmonds [16] summarized the problem as follows. Distribution was still patchy, being virtually absent from many forest or tree-crop planted areas, but the plant had been observed to be spreading and on the increase. In Sungei You (80 km north-west of Kuala Lumpur), Butterworth and Klang there were large patches of black sage serious enough to warrant concern. More than 2000 ha of valuable agricultural land under coconut in Sungei Yu were rendered unproductive due to heavy encroachment by black sage (Figure 2). Although coconut palms in this area were between 5 and 10 years old, the majority still did not yield any fruit, their growth seriously impaired due to competition with black sage. In this area, black sage reached a height of 1.5–3.0 m and growth was so dense that passage through parts of the holding was nearly impossible and only the tips of coconut fronds were visible. Although not explicitly stated, it seems this infestation in Sungei Yu was a trigger for a biological control programme to be undertaken, perhaps seen as a harbinger of things to come in other agricultural areas.

The biological control programme is summarized from the accounts by Ung *et al.* [15], Ung and Yunus [17],

Figure 2 Infestation of black sage amongst young coconut palms, Malaysia (photograph: P.A.C. Ooi, CABI/Universiti Tunku Abdul Rahman).

Figure 4 Adults of *Metrogalleruca obscura*, the defoliating biological control agent of black sage (photograph: F.D. Bennett, CABI – retired).

Figure 3 Larva of *Metrogalleruca obscura*, the defoliating biological control agent of black sage (photograph: P.A.C. Ooi, CABI/Universiti Tunku Abdul Rahman).

Figure 5 Adult of *Eurytoma attiva* on flowers of black sage (photograph: P.A.C. Ooi, CABI/Universiti Tunku Abdul Rahman).

Simmonds [16] and Ooi [18, 19]. *M. obscura* from Trinidad and *E. attiva* from Mauritius were imported in 1977 (Figures 3–5). Further host specificity tests were made before 8600 *M. obscura* and 7500 *E. attiva* were released at eight sites at Sungei Yu (Selangor) in September 1977 – March 1978, and *E. attiva* was also released at Kuala Lumpur. Establishment of both species occurred immediately. *E. attiva* rapidly spread throughout the peninsula and in early 1979 was found attacking 33–81% of fruits in samples from every state. *M. obscura* spread more slowly, but causing extensive defoliation (Figure 6). In June 1978, a total of 240 acres of black sage at Sungei Yu had been 'denuded of leaves', which increased to 1380 acres by October 1978. No detailed assessment of the impact of this programme was subsequently published, but by 1992, Mohamed *et al.* [20] were able to write that black sage 'no longer constitutes a serious weed problem'.

Sri Lanka

The biological control programme against black sage in Sri Lanka is briefly documented by Simmonds [21]. Black sage was known to be present in Sri Lanka by 1885, and by the 1970s it was widespread, threatening to become ubiquitous. In 1972 it was seen covering extensive areas over about 1000 sq miles, 'the main areas being the Mahaillupullamma to Anaradhapura area and northwards, the east coast between Kallar and Pottuvil and inland towards Amparai, at Dematogoda and Kalaniya near Colombo, with several isolated bushes in the city itself. It was also seen around several towns in the western coconut areas.'

In June 1978, Simmonds [21] arranged for *M. obscura* and *E. attiva* to be imported from Malaysia and several modest releases were made. In July–August 1980, Simmonds found both insects well established with extensive defoliation and heavy seed attack. He concluded that it 'is reasonable to assume that over most of the affected areas, the aggressiveness of (black sage) will be much

Figure 6 A bush of black sage completely defoliated by *Metrogalleruca obscura* (photograph: P.A.C. Ooi, CABI/ Universiti Tunku Abdul Rahman).

reduced, that it will no longer pose a problem to the cultivation of land left idle for several years, and biological control of (black sage), as elsewhere, will be completely successful'. His prediction is most likely correct, as there have been no further reports of black sage as a weed in Sri Lanka (CAB Abstracts).

Black sage was brought under effective biological control in Sri Lanka before it became a significant problem.

Implications for other countries

The effective biological control agents may well have spread or been spread within South-East Asia since 1978, but this has not been documented. They will probably have spread into Thailand and perhaps further into Myanmar and the Mekong delta. There is a record of *M. obscura* from Brunei (1981 specimen in the Natural History Museum, London; [22]), suggesting that it is also present on the island of Borneo.

Evaluation of Impact

Mauritius

In CABI CPC [22], it is stated that the 'total cost of the (black sage) project to the Mauritius and British governments is estimated to be about R 80 000 (£2500) (J.R. Williams, Mauritius Sugar Industry Research Station, Reduit, Mauritius, personal communication to M.L. Cox, CABI, 1996). It is difficult to know how to interpret this figure, and the true cost may be obscured by the fact that the salary costs of the entomologists involved (F.J. Simmonds and J.R. Williams) were at that time already covered by CABI and Mauritius, respectively; i.e. the number may only refer to the direct costs.

It may be useful to cross-reference with an estimate of the costs with hindsight. The preliminary phase involved some student research at ICTA and a visit by P.O. Wiehe from Mauritius to Trinidad, which led to the subsequent implementation of a full project.

The scope of the exploratory and host-specificity phase of programme in Trinidad can be guessed at from Simmonds' published outputs, and an examination of the list of unpublished reports compiled by the CIBC West Indian Station in 1964. Simmonds must have worked on this project from 1946 to at least 1950, probably with 1–3 full-time technical support staff (about £13 000 each per annum). Although, he was obviously involved in a variety of other initiatives, as his usual prolific output of reports indicates, this was probably his main project. Simmonds would have been in his 30s then, and went on to become the Director of CIBC in 1958, a post he held until retirement nearly 20 years later [23]. It would be reasonable to suggest that his contribution represents at least three scientist-years of a mid-career scientist (£30 000/year), i.e. approximately £230 000 in total for staff costs.

Similarly, J.R. Williams ran the rearing, release and monitoring phase of the programme in Mauritius. Judging by his publication record in CAB Abstracts, he would have been at the beginning of his distinguished career in Mauritius. Biological control of black sage seems to have been his main activity from 1947 to 1952, but he was working on other biological control projects against insect pests. It seems reasonable to suggest that his inputs represent at least four scientist years of an early-career scientist (approximately £14 400 for a national scientist today), with support by 2–3 or more full time technical staff (approximately £5500 for a junior technician to £8400 for a senior technician), i.e. approximately £141 000 in total for staff costs.

As shipments were by airmail, the direct costs of shipments would have been relatively low, but if the project were being done today probably fewer consignments would be sent using airfreight rather than air mail, say 15 shipments at £300 each. Based on preserved material in the CABI insect collection (now in the University of the West Indies Zoological Museum) and the United States National Museum, identifications were made by taxonomists of the United States Department of Agriculture (USDA) and CABI (as Commonwealth Institute of Entomology) of many of the insects that Simmonds studied. It is difficult to know how many identifications were made (Simmonds did not publish an account of the natural enemies of black sage), but 100 identifications is certainly possible, which if charged at today's costs might well cost more than £15 000. In addition, *M. obscura* was described as *S. cordiae* Barber for this investigation [24], although subsequently synonymized under *M. obscura*. There would have been local travel costs at each end of the project, and Simmonds also made observations in Central America, although this may have been combined with other duties. At today's costs, this might amount to about £20 000–30 000 over the lifetime of the project. So, overall, allowing an overhead of 33% on all costs, it would probably cost around £525 000 to carry out this programme today. As this is about 200 times greater than J.R. Williams' estimate of the cost at 1950 sterling values, this suggests that Williams did not include full costs. By comparison, applying the formula derived by Paynter *et al.* [25] for the cost of weed biological control programmes in New Zealand, the programme could have cost about £900 000 in New Zealand, suggesting that our estimate is probably of the right order.

It is not possible to assess the benefits at this time except descriptively, based on the stated impact of the weed before the successful and complete biological control in Mauritius, Malaysia and Sri Lanka. In Mauritius, black sage was clearly having a significant impact on large areas of grassland and scrubland under a wide range of rainfall conditions, where it became an exclusive dominant. Today we would call this a key species or ecosystem engineer. In 1958, 140 100 acres (30.3% of the total land area) of Mauritius were classified as 'meadows, grassland, scrub, grazing grounds and waste lands' although much of this is too steep to be usable and only a relatively small proportion would be classified as grazing land [26]. Currently, 25% of Mauritius land area classified as forest, scrub and grazing lands [27]. In 2001 only 4% of the total land area was considered permanent grazing land [28]. Much of the land in these categories would have been at risk of dominance by black sage (Figure 6).

Malaysia

The costs for the programme in Malaysia would have been significantly less. The external inputs were provided by F.J. Simmonds visiting twice for perhaps a total of 1 month, plus consignments of the biological control agents from Mauritius (maybe £10 000). In Malaysia, additional host range testing was carried out, following by a rearing, release and monitoring programme over about 1 year (maybe £36 000). This may have amounted to a total cost of £70 000 including a 33% overhead. Applying Paynter *et al.*'s [25] formula for New Zealand costs suggests a figure of £200 000.

The infestations in Malaysia were probably mostly at an earlier stage, and it is difficult to predict what the potential impact would have been over time if biological control had not been implemented. At best, it can be anticipated that there would have been substantial additional weeding costs in the extensive plantations of oil palm and rubber, which accounted for 23 and 45%, respectively, of all agricultural land in the whole of Malaysia in 1980 when agriculture was 23% of GDP, compared with 63 and 20% in 2005 when agriculture was 6% of GDP [29].

Sri Lanka

The programme in Sri Lanka would have been significantly cheaper than that in Malaysia. The infestation in Sri Lanka seems to have been at an early stage too, but the observations from Malaysia do suggest that the impact of black sage would have been substantial without the intervention with biological control.

References

1. Gottschling M, Miller JS, Weigend M, Hilger HH. Congruence of a phylogeny of Cordiaceae (Boraginales) inferred from ITS1 sequence data with morphology, ecology, and biogeography. Annals of the Missouri Botanical Garden 2005;92:425–37.
2. Stevens PF. Angiosperm Phylogeny Website. Version 12, July 2012 [and more or less continuously updated since]; 2014. Available from: URL: http://www.mobot.org/MOBOT/research/APweb/ (accessed 18 September 2014).
3. Miller JS, Gottschling M. Generic classification in the Cordiaceae (Boraginales): resurrection of the genus *Varronia* P. Br. (Cordiaceae). Taxon 2007;56(1):163–9.
4. Greathead DJ. A Review of Biological Control in the Ethiopian Region. Technical Communication No 5. Commonwealth Institute of Biological Control. Commonwealth Agricultural Bureau, Farnham Royal, UK; 1971. 162 pp.
5. Cock MJW (editor). A Review of Biological Control of Pests in the Commonwealth Caribbean and Bermuda up to 1982. Technical Communication No. 9, Commonwealth Institute of Biological Control. Commonwealth Agricultural Bureaux, Farnham Royal, UK; 1985. 218 pp.
6. Simmonds FJ. Insects attacking *Cordia macrostachya* (Jacq.) Roem. & Schult, in the West Indies. 1. *Physonota alutacea* Boh. (Coleoptera, Cassididae). Canadian Entomologist 1949;81(8):185–99.
7. Simmonds FJ. The effective control by parasites of *Schematiza cordiae*, Barber, in Trinidad. Bulletin of Entomological Research 1948;39(2):217–20.
8. Simmonds FJ. Insects attacking *Cordia macrostachya* (Jacq.) Roem. and Schult, in the West Indies. II. *Schematiza cordiae* Barb. (Coleoptera, Galerucidae). Canadian Entomologist 1950;81(11):275–82.
9. Williams JR. The introduction of *Physonota alutacea* Boheman (Col., Cassid.) into Mauritius. Bulletin of Entomological Research 1950;40(4):479–80.
10. Williams JR. The control of the black sage in Mauritius by *Schematiza cordiae* Barb. (Col., Galerucid.). Bulletin of Entomological Research 1951;42:455–63.
11. Williams JR. The control of black sage (*Cordia macrostachya*) in Mauritius: the introduction, biology and bionomics of a species of *Eurytoma* (Hymenoptera, Chalcidoidea). Bulletin of Entomological Research 1960;51(1):123–33.
12. Wiehe PO. Notes on the present ecological status of *Cordia macrostachya* in Mauritius. Bulletin of Entomological Research 1960;51(1):132–3.
13. Fowler SV, Ganeshan S, Mauremootoo J, Mungroo Y. Biological control of weeds in Mauritius: past successes revisited and present challenges. *Proceedings of the*

X International Symposium on Biological Control of Weeds, Bozeman, Montana, USA, 1999 July 4–14. Montana State University, Bozeman, USA; 2000:43–50.

14. Strahm W. Invasive species in Mauritius: examining the past and charting the future. In: Sandlund OT, Schei PJ, Viken A, editors. Invasive Species and Biodiversity Management. Kluwer, Dordrecht, The Netherlands; 1999. p. 325–47.
15. Ung SH, Yunus A, Chin WH. Biological control of *Cordia curassavica* (Jacq) R. and S. in Malaysia by *Schematiza cordiae* Barb. (Coleop.: Galerucidae). Malaysian Agricultural Journal 1979;52(2):154–165.
16. Simmonds FJ. Biological control of *Cordia curassavica* (Boraginaceae) in Malaysia. Entomophaga 1980;25(4):363–4.
17. Ung SH, Yunus A. The present status of the biological control of *Cordia curassavica* in Malaysia. *Proceedings of the 5th International Symposium on Biological Control of Weeds*. Commonwealth Scientific and Industrial Research Organization, Australia; 1981. 489–98.
18. Ooi PAC. *Eurytoma attiva* Burks (Hym., Eurytomidae) attacking *Cordia curassavica* (Jacq.) R & S in Kedah and Perlis, Malaysia. I. Biology of *E. attiva* and distribution of *C. curassavica*. Malaysian Agricultural Journal 1980;52(4): 71–7.
19. Ooi PAC. *Eurytoma attiva* Burks (Hym., Eurytomidae) attacking *Cordia curassavica* (Jacq.) R. & S. in Kedah and Perlis, Malaysia. II. Incidence of *E. attiva*. Malaysian Agricultural Journal 1981;53(1):1–8.
20. Mohamed AZ, Lee BS, Lum KY. Developing a biological control initiative in Malaysia. In: Ooi PAC, Lim GS, and Teng PS, editors. Proceedings of the 3rd International Conference on Plant Protection in the Tropics, Genting Highlands, Malaysia, 20–23 March 1990. Malaysian Plant Protection Society, Kuala Lumpur, Malaysia; 1992. p. 59–62.
21. Simmonds FJ. Control of *Cordia curassavica* in Sri Lanka. Biocontrol News and Information 1981;2:2.
22. CABI CPC (Crop Protection Compendium). *Metrogaleruca obscura*. In: Crop Protection Compendium. CAB International, Wallingford, UK; 2015. Available from: URL: http://www.cabi.org/cpc (accessed 7 July 2015).
23. Blight D, Ibbotson R. CABI: A Century of Scientific Endeavour. CABI, Wallingford, UK; 2011. 171 pp.
24. Barber HS. A new *Schematiza* on *Cordia* in Trinidad (Coleoptera: Chrysomelidae). Journal of the Washington Academy of Science 1947;37:242–3.
25. Paynter Q, Fowler SV, Hayes L, Hill RL. Factors affecting the cost of weed biocontrol programs in New Zealand. Biological Control 2015;80:119–27.
26. Meade JE, Foggon G, Houghton H, Lees N, Marshall RS, Roddan GM, *et al.* The Economic and Social Structure of Mauritius. Routledge, London & New York; 1961. xviii + 246 pp.
27. Statistics Mauritius. Digest of Environmental Statistics 2012. Mauritius Ministry of Finance and Economic Development, Port Louis, Mauritius; 2013. 142 pp.
28. Mauritius. *Thematic Working Group Land and Land Use Final Report August 2001*; 2001. 35 pp. Available from: URL: http://www.mrc.org.mu/Documents/Thematic/LandReport.pdf
29. Olaniyi AO, Abdullah AM, Ramli MF, Sood AM. Agricultural land use in Malaysia: an historical overview and implications for food security. Bulgarian Journal of Agricultural Science 2013;19(1):60–9.

Case Study 8
Rubber vine, *Cryptostegia grandiflora* Roxb. ex R. Br. (Gentianales, Apocynaceae)

Lead author: Kathryn M. Pollard and Sarah E. Thomas (CABI UK)

CABI played an important role in one of the biggest success stories for classical biological control in Australia in recent years.

The Pest Problem

Rubber vine, *Cryptostegia grandiflora* Roxb. ex R. Br., is a perennial woody climber or vine which may also grow as a sub-shrub in open situations. Native to south-west Madagascar, rubber vine occurs as a riverine plant and in previously disturbed areas. It is a summer growing, perennial weed with large, showy purple flowers (Figure 1). Seed pods contain 200–250 seeds which are readily dispersed by wind and water and remain viable after 8 months of drought [1].

Rubber vine was introduced into Australia in the 1860s as an ornamental plant and has since spread dramatically throughout Queensland. It has been described as the single biggest threat to natural ecosystems in tropical Australia and by 1991 it was estimated to be present across 34 million ha in Queensland, with the potential to spread into the Northern Territory and to Brisbane [2]. For this reason, it is declared a Weed of National Significance [3]. Rubber vine can smother trees and pastures and will often form impenetrable thickets along streams, out-competing native flora, decreasing biodiversity and increasing erosion due to decreased ground cover [4] (Figure 2). The Queensland cattle industry was severely affected as rubber vine restricts access to water, reduces grazing, increases mustering problems and is toxic. Although, it is highly poisonous, rubber vine is extremely unpalatable and thus grazing animals usually avoid it; however, in dry years significant losses can occur when forage is scarce [5].

Rubber vine is relatively easy to control using chemical methods but these can be costly, ranging from A$600 to 2000/ha for herbicide and labour costs (depending on the herbicide) to ground treat a dense infestation (3000–5000 plants/ha) [6]. Reduced grazing and managed burns are also used but these methods however are uneconomical over a large scale [7]. For this reason, in 1985, the Queensland Department of Lands initiated a biological control programme for control of rubber vine.

The Biological Control Programme

Focus was initially given to an entomological survey of rubber vine but studies found very few of these insects to be highly specific [7]. As a result, two mycological surveys were carried out. CABI's surveys in Madagascar (the native range) revealed a rust pathogen, *Maravalia cryptostegiae* (Cummins) Ono, to be a promising biocontrol agent. In the field, this pathogen was ubiquitous and in a number of cases caused total leaf defoliation of many plants. As a result, this pathogen was described as 'the most widespread and damaging pathogen' of rubber vine' [7]. By targeting the leaves of rubber vine plants the rust pathogen causes premature leaf drop resulting in a reduction in vigour and seed production (Figure 3).

The pathogen was selected from the north of Madagascar and was shipped to the UK where, under quarantine conditions, extensive studies on the pathogenicity, life cycle and host range of the rust were carried out. Host range studies tested over 70 species for their susceptibility towards the rust pathogen. However, one endemic species, *Cryptolepis grayi* P.I. Forst., was found to support sporulation of *M. cryptostegiae* although with fewer uredinia which were delayed in development when compared with that on rubber vine. Nevertheless, when the results were presented to the relevant authorities it was decided that the 'threat posed by the weed to the biodiversity of northern Queensland, as well as to livestock, far outweighed the risk of the rust attacking an indigenous plant species' [8]. For this reason, *M. cryptostegiae* was released in Australia in 1993. Unfortunately, the susceptibility of *C. grandiflora* in the field was much lower than expected and previously seen under quarantine conditions. In addition to this *C. madagascariensis* Bojer ex Decne., another invasive but less prevalent Madagascan rubber vine species was found to be severely affected by the rust [8]. It is believed that a number of different pathotypes of *M. cryptostegiae* exist and that the pathogenicity of the strain tested in quarantine had been artificially extended to include *C. grandiflora* when testing under optimal conditions [9]. For this reason, a second strain was obtained from south-west Madagascar from *C. grandiflora* was released into Australia in 1994 after screening in the UK. As hoped, this strain was highly damaging towards the target

Figure 1 Because of its attractive flowers and foliage, rubber vine from Madagascar has been widely introduced in the tropics as a garden ornamental (photograph: H.C. Evans, CABI).

Figure 2 Infestations of rubber vine smothering and displacing riverside vegetation, Queensland, 1977 (photograph: H.C. Evans, CABI).

C. grandiflora in Australia with *C. madagascariensis* being less susceptible [8]. No symptoms of infection were observed on *C. grayi* in the field so the apparent susceptibility has been attributed to a laboratory artefact or false positive.

Evaluation of Impact

Although predicted to take 10 years, most of the weed was controlled within 7 years. Symptoms of infection can be readily seen in the field in the form of yellow rust spores on the underside of leaves (Figure 4). Since the release of the second strain of *M. cryptostegiae*, the number of live plants and stems per hectare across Queensland has declined significantly (by up to 90% at some sites). As a result of this, a significant reduction in seed production can be seen, and in a number of instances

Figure 3 Early and late infection of rubber vine rust (photographs: H.C. Evans, CABI).

Figure 4 Advanced field infection of rubber vine rust, shortly before defoliation of the rubber vine, Queensland, Australia (photograph: H.C. Evans, CABI).

seedling establishment has reduced from 178/hectare to almost zero [4].

The main economic impact from *C. grandiflora* invasion was the direct loss of pasture, with dense infestations reducing livestock carrying capacity by up to 100%. By 1995, as a result of rubber vine infestations, the annual cost to the grazing industry in terms of lost beef production due to the loss of pasture was estimated to be more than A$18 million [10, 11]. In addition, the invasion of water courses and river banks impeded access for stock to water and difficulties in mustering. These increased management costs have been estimated at US$15 million per annum to the northern Queensland beef industry alone [10]. Since *C. grandiflora* has the potential to infest nearly 600 000 km^{2}of northern Australia [12] and at the time of the biological control programme was only infesting 40 000 km^2 [13], then the number of landholders and costs incurred would have increased substantially without biological control.

The area infested with rubber vine was estimated to be approximately 378 500 ha in 1984. Without biological control rubber vine was predicted to spread at a rate of 6% per annum, while biological control, introduced in 1995, is estimated to be reducing the level of infestation by 3% per annum. The benefits of this programme are believed to be between A$295 and 528 million [4]. This figure when converted to 2004/05 dollars is based on estimated costs for the control of rubber vine ($10.32/ha), the reduced carrying capacity of land ($16.56/ha); increased mustering costs ($4.81/ha) and cattle losses ($4.40/ha).

The costs of the biological control programme between 1984 and 2004 are A$3.4 million and returned benefits with a net present value of $232 million and a benefit:cost ratio of 109, at a discount rate of 8% [2]. However, this estimated benefit:cost analysis does not include the many benefits that have been incurred both environmentally and socially, for example, the reduced displacement of native plant species including those to a World Heritage conservation area which was previously at threat, reduced soil erosion, better access to streams, reduced toxicity from chemical control and reduced health risks.

Rubber vine is a problem in several other tropical countries including parts of eastern and southern Africa, Brazil, Mexico, Panama and Cuba, so there is huge scope to control it in these countries, by releasing the same, very effective pathogen biological control agent.

References

1. Weber E. Invasive Plant Species of the World: a Reference Guide to Environmental Weeds. CABI, Wallingford, UK; 2003. viii + 548 pp.
2. Palmer B, Vogler W. Cryptostegia grandifolia (Roxb.) R. Br. – rubber vine. In: Julien M, McFadyen R Cullen J, editors. Biological Control of Weeds in Australia. CSIRO, Melbourne, Australia; 2012. p. 190–7.
3. Thorp JR, Lynch R. Determination of Weeds of National Significance. National Weeds Strategy Executive Committee, Launceston, Australia; 2000. Available from: URL: http://www.weeds.org.au/docs/WoNS/
4. Page AR, Lacey KL. Economic Impact Assessment of Australian Weed Biological Control. Technical Series no. 10, CRC for Australian Weed Management, Adelaide, Australia; 2006. 151 pp.
5. Parsons WT, Cuthbertson EG. Noxious Weeds of Australia. Inkata Press, Melbourne, Australia; 1992. 692 pp.
6. Mackey AP (editor). Rubber vine (*Cryptostegia grandiflora*) in Queensland. Queensland Department of Natural Resources & Mines, Brisbane, Australia; 1996. 25 pp.
7. Evans HC. Studies on the rust *Maravalia cryptostegiae*, a potential biological control agent of rubber-vine weed (*Cryptostegia grandiflora*, Asclepiadaceae: Periplocoideae) in Australia, I: life-cycle. Mycopathologia 1993;124(3): 164–74.
8. Evans HC. Evaluating plant pathogens for biological control of weeds: an alternative view of pest risk assessment. Australasian Plant Pathology 2000;29:1–14.
9. Evans HC, Tomley AJ. Greenhouse and field evaluations of the rubber vine rust, Maravalia cryptostegia, on Madagascan and Australian Asclepiadaceae. In: Moran VC, Hoffmann JH, editors. Proceedings of the IX International Symposium on Biological Control of Weeds. University of Cape Town, Cape Town, South Africa; 1996. p. 165–9.
10. ARMCANZ (Agriculture and Resource Management Council of Australia and New Zealand) Weeds of National Significance. Rubber Vine (Cryptostegia grandiflora) Strategic Plan. National Weeds Strategy Executive Committee, Launceston, Australia; 2000. 16 pp.
11. Walton C. Reclaiming Lost Provinces. A Century of Weed Biological Control in Queensland. Department of Natural Resources and Mines, Brisbane, Australia; 2005. 104 pp.
12. Chippendale JF. The potential returns to research into rubber vine (Cryptostegia grandiflora R. Br.) in north Queensland. MSc Thesis, University of Queensland, Brisbane, Australia; 1991. [Alternatively refer to (J.P. Chippendale in Tomley & Evans 2004)]
13. Tomley AJ, Evans HC. Establishment of, and preliminary impact studies on, the rust, Maravalia cryptostegiae, of the invasive weed, Cryptostegia grandiflora in Queensland, Australia. Plant Pathology 2004;53(4):475–84.

Case Study 9
Leafy spurge, *Euphorbia esula* (L.) (Euphorbiaceae)

Lead author: Hariet L. Hinz, CABI (Switzerland)

The Pest Problem

Infestation history and problems

Euphorbia esula or leafy spurge, a perennial herb of Eurasian origin, was first reported in the state of Massachusetts in 1827 [1]. By 1933, the plant was found in 19 USA states and several Canadian provinces and was considered a threat to rangeland in the northern Great Plains of the USA ([2] and references therein). By 1949, leafy spurge had dispersed to all Canadian provinces except Newfoundland, and by 1979 the plant occurred in 30 USA states. In 1997, leafy spurge was estimated to infest 2 million ha (4.94 million acres) across 35 states ([1] and references therein). Most widely infested areas include the Prairie provinces in Canada [3] and western and central USA [4].

Leafy spurge is a deep rooted perennial that reproduces by seed and vegetative root buds. It is found primarily in untilled agricultural land (pasture, rangeland, hayland and idle cropland) and in other untilled land (road ditches, shelterbelts, wildlife areas, around lakes and rivers, and in parks) [5]. It contains white sticky latex which is toxic to cattle. However, leafy spurge is rarely eaten by cattle and they avoid leafy spurge-infested pasture despite the presence of palatable grasses [6]. In addition, leafy spurge is an aggressive competitor that is able to outcompete rangeland grasses and forbs [7]. Thus, the primary economic impacts of leafy spurge are reductions in available forage and therefore reduced cattle production on infested rangeland.

However, leafy spurge also has adverse ecological impacts in North America. In a study conducted in mixed-grass prairie in Manitoba, Canada, infestations by leafy spurge significantly reduced cover of native species as well as native species richness [8]. Most native species were absent where leafy spurge was most abundant and species richness declined from 11 outside the infestation to three at the centre [8]. In another study in Theodore Roosevelt National Park in North Dakota, leafy spurge infested grassland habitats were shown to reduce native ungulate use of these sites. For instance, bison use of leafy spurge infested grassland averaged 83% less in comparison with uninfested sites. This was either attributed to lower forage production and/or avoidance of leafy spurge infested grasslands [9].

Conventional control methods

Successful leafy spurge control requires killing the root system and associated vegetative buds ([6] and references therein). Chemical control can reduce top growth of leafy spurge and gradually decrease the underground root system [6], but it has not proven to be effective in achieving sustained long-term control [1]. In addition, leafy spurge control with herbicides cannot be used in sensitive environments and is usually not economic on range and untilled land [5, 6]. Both sheep and goats are used in weed control programmes to reduce flowering and seed production and to retard the spread of leafy spurge [4]. However, once the animals are removed, the plant begins to regrow to its original densities [6].

The Biological Control Programme

On behalf of the Canadian Department of Agriculture, CABI in Switzerland (as IIBC European Station) started surveys for biological control agents for leafy spurge in 1961 in western Europe, and extended surveys to central and south-eastern Europe in 1973 [10]. Based on work conducted at the CABI Centre in Switzerland, 12 agents were screened and released in North America between 1970 and 1988, including five flea beetles in the genus *Aphthona* (Coleoptera: Chrysomelidae) (Figure 1). All five beetle species are univoltine. Adults feed on leafy spurge foliage and flowers and may completely defoliate shoots at high densities, though this damage has little or no impact on the weed [7]. Females lay eggs just below the soil surface on or near the base of leafy spurge shoots. Newly hatched larvae begin feeding on the fine roots, and progressively larger roots as they develop. Larval mining contributes to plant mortality by disrupting water and nutrient transport and may provide entry points for soil born fungal pathogens [10]. Of the five species, *Aphthona nigriscutis* Foudras and mixed populations of *Aphthona czwalinai* (Weise) and *Aphthona lacertosa* Rosenhauer reached the highest population densities and have so far proven to be the most successful agents released (Figure 2) [11].

In a study conducted in North Dakota, a mixed population of *A. czwalinai* and *A. lacertosa* reduced leafy spurge density by over 95% within 4 years of release [12]. Similar reductions in the stem densities of leafy spurge were

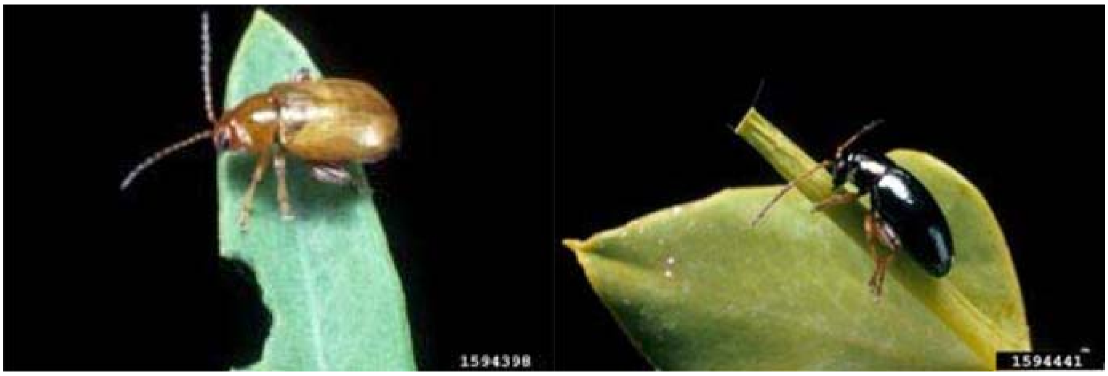

Figure 1 Adult *Aphthona nigriscutis* (left) and *A. lacertosa* (right) beetles – two of the most successful *Aphthona* spp. used for the biological control of leafy spurge (photograph: Mark Schwarzländer, University of Idaho).

Figure 2 High density of *Aphthona lacertosa* beetles on leafy spurge (photograph: Monika Chandler, Minnesota Department of Agriculture).

found by Kirby *et al.* [13] 6 years after release. In a study conducted in Montana and South Dakota, where 3000 insects of each species were released in permanently marked plots in 1998, mean foliar cover and density of leafy spurge were 83–90% and 73–78% less than pre-release values, respectively, 6 years later [14]. At eight release sites in Fremont County, Wyoming, *A. nigriscutis* reduced mean cover of leafy spurge from 59% to less than 20% from 5 years after release onwards, and to less than 10% from 15 years after release onwards (J.L. Baker *et al.*, unpublished data). Similarly, at several locations in Montana, *A. nigriscutis* has reduced leafy spurge densities to 5–30% of pre-release densities within 3–5 years [7]. More importantly, the beetles are able to persist at sites with low, remaining, levels of leafy spurge, thus maintaining control over many years [15, 16]. In a study at two sites in North Dakota, where all three species had been released in 1999, leafy spurge was reduced from an average of over 200 stems/m^2 to less than 8 stems/m^2 by 2004, and this level was kept or even further reduced by 2009 (Figure 3) [17, 18]. This is in stark contrast to other control measures, including herbicides, which need to be regularly repeated to maintain low levels of leafy spurge (see above). Stable coexistence between the biocontrol agent and the target weed at low densities is the optimal case scenario in weed biocontrol, leading to long-term, sustained control [19].

Reasons for the success include that the flea beetle larvae attack the 'Achilles heel' of leafy spurge, i.e. its root system, that flea beetle populations can increase rapidly and that a massive, area-wide re-distribution programme was established [12]. The latter was facilitated by the TEAM leafy spurge, an area-wide pest management programme financed by US Department of Agriculture – Agricultural Research Service [20]. Over 85 million beetles (from mixed populations) have been redistributed from North Dakota alone to various other states and Canada [12].

However, control may vary between sites, probably influenced by local characteristics such as soil texture, spring warming, density of leafy spurge and presence of soil-borne pathogens ([16] and refs therein). For instance, beetles have been shown to be less effective at controlling leafy spurge at very sandy sites (>80% sand) [6, 16]. Control of insects is also limited in very dense leafy spurge stands (>320 stems/m^2) [15], especially, if these are in riparian and other high-moisture habitats (e.g. irrigated areas) or in leafy spurge stands in shaded locations [7].

Integrated control

Some studies have shown that the most effective way to control leafy spurge is an integration of different control methods. For instance, incorporation of *Aphthona* beetles with herbicides has resulted in a more rapid and complete leafy spurge control than either method used alone, while a combination of *Aphthona* with sheep or goat grazing has resulted in a larger decline in leafy spurge production than insects alone and in weed density than grazing alone [6, 15].

Figure 3 A leafy spurge site at Big Stone National Wildlife Refuge (left image). A US Fish and Wildlife biologist noticed a large leafy spurge infestation during an aerial survey. Monika Chandler (Minnesota Department of Agriculture) released 25 000 *Aphthona lacertosa* in 2006. The beetles were released at five separate points (5000 each) within the infestation. In 2009, most of the spurge was killed and replaced with grass (right image) (photograph: Monika Chandler, Minnesota Department of Agriculture).

Evaluation of Impact

In 1999, Bangsund *et al.* assessed the economic benefits of biological control of leafy spurge in the northern Great Plains of the USA (Montana, North Dakota, South Dakota and Wyoming), incorporating earlier studies estimating the economic effects of leafy spurge (e.g. [21–25], etc.). The two key components of the bioeconomic model were: (1) estimating the impacts of leafy spurge on rangeland and (2) estimating impacts on wildland. Rangeland impacts included the negative effects of leafy spurge on livestock carrying capacity and subsequent economic effects on livestock producers and their expenditures. Wildland impacts included the effects on wildlife habitat productivity and subsequent effects on outdoor recreation activities as well as changes in soil and water conservation benefits.

The direct economic benefits of biological control on rangeland were based on assumed increases in grazing output. The principal use of rangeland in the northern Great Plains is for beef cattle production, with cow-calf herds being the predominant beef enterprise. Increases in grazing output were therefore assumed to lead to proportionate increases in cow-calf production. These changes were then used to estimate the direct economic impacts of biological control of leafy spurge on rangeland, i.e. changes in net income of stock producers and landowners and changes in producer expenditures. It was assumed that carrying capacity after biological control of leafy spurge was 75% of pre-infestation levels (since control will vary between sites [see above] and densities of leafy spurge might not always be reduced below an economic threshold).

The economic benefits of biological control on wildland were based on assumed increases in wildlife habitat productivity and soil and water conservation values. Decreases in cover and diversity of native species, especially native bunch grasses, associated with leafy spurge infestations, not only decreases the quality and attractiveness of the habitat for wildlife use, but may also negatively affect soil water retention and water quality and increase soil erosion [8, 26]. The direct economic benefits from biological control of leafy spurge infestations in wildland therefore include: (a) changes (increases) in wildlife-associated recreationist expenditures that have a positive impact on local suppliers of related goods and services and (b) changes (decreases) in user expenditures to mitigate damages from runoff and soil erosion. It was expected that wildland outputs would return to 100% of pre-infestation levels after biological control of leafy spurge.

Based on interviews with more than 25 scientists involved in leafy spurge research and biological control, the acreage of leafy spurge infestations was projected to increase until about the year 2000, at which time, the area infested in the four-state region was estimated to be about 760 000 ha (1.85 million acres). It was further expected (based on expert opinion) that about 65% of future leafy spurge infestations will eventually be controlled with biological agents by the year 2025. Control was defined as reducing the infestation density below economic thresholds.

Biological control was thus estimated to suppress leafy spurge infestations by a total of 522 000 ha (1 270 000 acres) in the northern Great Plains by the year 2025, 337 000 ha on rangeland and 185 000 ha on wildland, according to previous estimates on the distribution of leafy spurge between rangeland and wildland [22, 25]. On rangeland, the suppression was estimated to result in the recovery of about 320 000 animal unit months (AUMs) of grazing. One AUM is the average amount of forage needed to feed one animal unit (AU) for 1 month. This in return was estimated to have a value (based on grazing land rental rates) of $4.98 million in 1997 dollars. It was further estimated that the recovered grazing

Figure 4 The Dakota cattle industry has made multi-million dollar economic benefits from the biological control of leafy spurge (photograph: Scott Bauer, USDA Natural Resources Conservation Service, commons.wikimedia.org, public domain).

capacity would support an increase in the region's beef cow herds of about 39 400 cows and that this would lead to additional production expenditures of about $11.47 million. Thus, the total annual direct benefit of biological control of leafy spurge on rangeland in the year 2025 was estimated to be about $16.45 million (in 1997 dollars) or approximately $17.65 million in the year 2000 dollars corrected for inflation. The year 2000 was used as the base year for our further analysis (see below), since Bangsund *et al.* [2] assumed reductions in leafy spurge acreage from biological control from this year onwards.

On wildland, the suppression of leafy spurge was estimated to result in increased annual expenditures for wildlife associated recreations of about $1.8 million and a $785 000 annual increase in soil and water conservation benefits. The total annual direct benefit of biological control of leafy spurge on wildland was therefore estimated to be about $2.6 million (in 1997 dollars) or $2.79 million (in 2000 dollars).

The total direct economic benefits from biological control were thus estimated at $19.08 million ($20.47 million 2000 dollars) annually (Figure 4).

> In the northern Great Plains of the USA, the annual total direct economic benefit from biological control of leafy spurge was estimated at $20.47 million (at year 2000 values).

However this estimated benefit is for just 1 year, while the benefits of the biological control will have started to occur before 2025, and will continue into the future. Therefore, based on Bangsund *et al.*'s [2] predicted rate of control of leafy spurge, estimates were made of the benefits accrued from 2000 to 2025. Acreages infested in years between 2000 and 2025 were read from the predicted acreage graph (Figure 1 in [2]), and these acreages were subtracted from the total infested area to give the acreage controlled each year. The benefit estimated in 2025 for control of 513 950 ha (1 270 000 acres) was used to calculate, on a proportional basis, the benefit accrued in each year as the area controlled increased. Benefits were estimated for each year from 2000 to 2050 as it is expected that the control effects from the *Aphthona* beetles would continue at least that long.

The costs of developing and implementing the biological control programme for leafy spurge was not included by Bangsund *et al.* [2] and so no benefit:cost ratio was calculated. At CABI, the work on the *Aphthona* beetles started in 1977 and was completed in 1993, so it took 16 years in total, including initial surveys and shipments. Unfortunately, it proved to be impossible to trace back the amounts spent on the project. In the 1970s, it was estimated that the total cost of controlling a weed biologically in Canada was between Can$1.2 and 1.5 million [27]. This included post-release studies, additional screening in Canada and the assumption that five species would be screened and released. Since, exactly five *Aphthona* species were screened and released based on work at CABI and in addition, the first 10 years of the project were exclusively funded by Canadian sources, we used $1.5 million ($3.56 million 2000 dollars) as an estimate of the likely costs of screening and releasing the flea beetles.

Based on the estimated direct benefits and the control costs, a number of benefit:cost ratios were calculated, showing the variation caused by both the number of years considered and the discount rates used (Table 1). In all scenarios, it is evident that the benefits of using biological control far outweigh the costs of the research and development of the agents. A minimum benefit:cost ratio of 8.6 was calculated for this work, when considering only 5 years of maximum benefit (to 2030) and using a 15% discount rate. When using a 5% discount rate and considering the benefits much further into the future (to 2050, 25 years of maximum control) a benefit:cost ratio of 56 was obtained.

This assessment does not include benefits incurred prior to 2000. The three *Aphthona* beetles that contributed most to the control of leafy spurge, *A. czwalinai*, *A. lacertosa* and *A. nigriscutis* were released between 1987 and 1989 in the USA [28]. Considering that reductions below economic threshold levels occur within 3–6 years after release, at least some economic benefits are therefore missing in our analysis. One could argue that this is offset by costs involved in the re-distribution of beetles, however, since this was organized by field days, at sites with mass-outbreak populations, where people could collect insects for free (R. G. Lym, personal communication, 2014), we consider that these costs are minimal. Neither does it include benefits incurred in other parts of North America, for instance Canada. Bourchier *et al.* [3] estimated that 155 000 ha are infested with leafy spurge in

Table 1 Calculation of benefit:cost ratios for the biological control of leafy spurge under different assumptions

						Discounted benefit		
Discount rate	Year	Cost 2000$	Area infested (ha)	Area controlled (ha)	Benefit 2000$	5%	10%	15%
Benefit:cost ratio 2030						39.4	17.3	8.6
Benefit:cost ratio 2040						49.7	19.4	9.1
Benefit:cost ratio 2050						56.0	20.1	9.2
	2000	3 560 000	748 668					
	2005		728 434	20 234	806 772	632 127	500 942	401 108
	2010		566 560	182 109	7 260 945	4 457 590	2 799 409	1 794 795
	2015		384 451	364 217	14 521 890	6 985 277	3 476 425	1 784 660
	2020		299 467	449 201	17 910 331	6 750 215	2 662 257	1 094 326
Max control	2025		234 718	513 951	20 492 000	6 051 344	1 891 330	622 499
	2030		234 718	513 951	20 492 000	4 741 387	1 174 367	309 492
	2035		234 720	513 949	20 492 000	3 715 001	729 189	153 872
	2040		234 722	513 947	20 492 000	2 910 800	452 769	76 502
	2045		234 724	513 945	20 492 000	2 280 688	281 134	38 035
	2050		234 726	513 943	20 492 000	1 786 979	174 562	18 910
				Total benefits 2030		140 184 771	61 717 923	30 753 342
				Total benefits 2040		176 796 503	68 933 899	32 306 610
				Total benefits 2050		199 272 929	71 715 970	32 690 554

Canada, mainly in Manitoba. Levels of leafy spurge control using *Aphthona* spp. have been similar to the USA ([3, 13] and references therein).

Bangsund *et al.* [2] did calculate secondary benefits of control of leafy spurge, resulting from subsequent spending within the economy (e.g. the suppliers of livestock producers purchasing more goods and hiring workers to meet demand) as a spillover or side effect of the direct benefits. According to their estimates, secondary benefits amounted to about $39.3 million ($42.16 million 2000 dollars). However, these were not included in our benefit:cost analysis.

The economic study by Bangsund *et al.* [2] was conducted over 15 years ago. It would therefore be tempting to try and compare the projected area of leafy spurge suppressed by biocontrol with the current status of leafy spurge in the four-state-region investigated. However, this is not as trivial as it seems, since even at sites where leafy spurge biocontrol was successful, the plant is still present, though at much lower, non-economic levels. So the actual area covered by leafy spurge might not have decreased considerably, but rather its impact is significantly less. For instance, in Fremont County, Wyoming, leafy spurge acreage remained more or less constant between 1991 and 2011 at about 4000 ha (10 000 acres) although biological control of leafy spurge has been very successful (J. L. Baker, personal communication). However, in many areas where leafy spurge is present, plants are much smaller than before, single-stemmed and only 10–15 cm tall. To achieve 50% forage utilization by cattle, the level of leafy spurge canopy cover must be less than 10% [29]. This level of reduction in leafy spurge cover has been reported by numerous studies 3–6 years after release (see above). For North Dakota, it has been estimated that the area infested by leafy spurge went from over 600 000 ha (1.5 million acres) in the mid- to late-1990s to about 263 000 ha (650 000 acres) in 2014 (R. G. Lym, personal communication, 2014). This is a reduction of 57%, achieved by a combination of biocontrol, herbicide applications and grazing. Bangsund *et al.* [2] extrapolated a reduction of about 42% from biological control alone during the same time period. In North Dakota, the *Aphthona* spp. worked very well in about one-third of all infested areas and to a lesser degree in another third (R. G. Lym, personal communication, 2014). This again compares well with the estimated 65% of leafy spurge acreage controlled with biological control agents by the year 2015 in Bangsund *et al.* [2]. Overall, the predictions by Bangsund *et al.* [2] therefore appear realistic and we are confident about our calculated benefit:cost ratios.

References

1. Anderson GL, Delfosse ES, Spencer NR, Prosser CW, Richard RD. Biological control of leafy spurge: an emerging success story. In: Spencer NR, editor. Proceedings of the

X International Symposium on Biological Control of Weeds. Montana State University, Bozeman, Montana, USA; 2000. p. 15–25.

2. Bangsund DA, Leistritz FL, Leitch JA. Assessing economic impacts of biological control of weeds: the case of leafy spurge in the northern Great Plains of the United States. Journal of Environmental Management 1999;56:35–43.
3. Bourchier RS, Erb S, McClay AS, Gassmann A. *Euphorbia esula* (L.), leafy spurge, and *Euphorbia cyparissias* (L.), Cypress spurge (Euphorbiaceae). In: Mason PG, Huber JT, editors. Biological Control Programmes in Canada 1981–2000. CABI International, Wallingford, UK; 2002. p. 346–58.
4. Hansen RW, Spencer NR, Fornasari L, Quimby PC, Jr, Pemberton RW, Nowierski RM. Leafy spurge, *Euphorbia esula* (complex). In: Coombs EM, Clark JK, Piper GL, Cofrancesco AF, Jr, editors. Biological Control of Invasive Plants in the United States. Oregon State University Press, Corvallis, Oregon; 2004. p. 233–62.
5. Bangsund DA, Leitch JA, Leistritz FL. Economic Analysis of Herbicide Control of Leafy Spurge (*Euphorbia esula L.*) in Rangeland. Agricultural Economics Report No. 342. North Dakota State University, Fargo, USA; 1996. v + 35 pp.
6. Lym RG. The biology and integrated management of leafy spurge (*Euphorbia esula*) on North Dakota rangeland. Weed Technology 1998;12:367–73.
7. Hansen RW, Richard RD, Parker PE, Wendel LE. Commentary: distribution of biological control agents of leafy spurge (*Euphorbia esula* L.) in the United States: 1988–1996. Biological Control 1997;10:129–42.
8. Belcher JW, Wilson SD. Leafy spurge and the species composition of a mixed-grass prairie. Journal of Range Management 1989;42(2):172–5.
9. Trammell MJ, Butler JL. Effects of exotic plants on a native ungulate use of habitat. Journal of Wildlife Management 1995;59(4):808–16.
10. Gassmann A, Schroeder D. The search for effective biological control agents in Europe: history and lessons from leafy spurge (*Euphorbia esula* L.) and cypress spurge (*Euphorbia cyparissias* L.). Biological Control 1995;5:466–77.
11. Bourchier RS, Van Hezewijk BH. *Euphorbia esula* L., Leafy Spurge (Euphorbiaceae). In: Mason PG, Gillespie DR, editors. Biological Control Programmes in Canada 2001–2012. CABI International, Wallingford, UK; 2013. p. 315–20.
12. Lym RG, Nelson JA. Biological control of leafy spurge (*Euphorbia esula*) with *Aphthona* spp. along railroad right-of-ways. Weed Technology 2000;14:642–6.
13. Kirby DR, Carlson RB, Krabbenhoft KD, Muldal D, Kirby MM. Biological control of leafy spurge with the introduced flea beetles (*Aphthona* spp.). Journal of Range Management 2000;53:305–8.
14. Butler JL, Parker MS, Murphy JT. Efficacy of flea beetle control on leafy spurge in Montana and South Dakota. Rangeland Ecology and Management 2006;59:453–61.
15. Lym RG. Integration of biological control agents with other weed management technologies: successes from the leafy spurge (*Euphorbia esula*) IPM program. Biological Control 2005;35:366–75.
16. Larson DL, Grace JB, Larson JL. Long-term dynamics of leafy spurge (*Euphorbia esula*) and its biocontrol agent, flea beetles in the genus *Aphthona*. Biological Control 2008;47:250–6.
17. Cline D, Juricek C, Lym RG, Kirby DR. Leafy spurge (*Euphorbia esula*) control with *Aphthona* spp. affects seedbank composition and native grass reestablishment. Invasive Plant Science and Management 2008;1:120–32.
18. Setter CM, Lym RG. Change in leafy spurge (*Euphorbia esula*) density and soil seedbank composition 10 years following release of *Aphthona* spp. biological control agents. Invasive Plant Science and Management 2013;6:147–60.
19. Harley KLS, Forno IW. Biological Control of Weeds. A Handbook for Practitioners and Students. Inkata Press, Melbourne, Australia; 1992. xi + 74 pp.
20. Prosser CW, Anderson GL, Wendel LE, Richard RD, Redlin BR. TEAM leafy spurge: an areawide pest management program. Integrated Pest Management Reviews 2002;7:47–62.
21. Bangsund DA, Leistritz FL. Economic Impact of Leafy Spurge in Montana, South Dakota, and Wyoming. Agricultural Economics Report No. 275. North Dakota State University, Fargo, USA; 1991. 104 pp.
22. Bangsund DA, Baltezore JF, Leitch JA, Leistritz FL. Economic Impact of Leafy Spurge on Wildland in Montana, South Dakota, and Wyoming. Agricultural Economics Report No. 304. North Dakota State University, Fargo, USA; 1993. v + 32 pp.
23. Leistritz FL, Thompson F, Leitch JA. Economic impact of leafy spurge (*Euphorbia esula*) in North Dakota. Weed Science 1992;40:275–80.
24. Leitch JA, Leistritz FL, Bangsund DA. Economic effect of leafy spurge in the Upper Great Plains: methods, models, and results. Impact Assessment 1996;14:419–33.
25. Wallace NM, Leitch JA, Leistritz FL. Economic impact of leafy spurge on North Dakota wildland. North Dakota Farm Research 1992;49:9–13.
26. USDA-NRCS. Comparing warm-season and cool-season grasses for erosion control, water quality, and wildlife habitat. In: Conservation Practice Fact Sheet. Natural Resources Conservation Service (NRCS), Maryland, USA; 2014. 5 pp.
27. Harris P. Cost of biological control of weeds by insects in Canada. Journal of Weed Science 1979;27(2):242–50.
28. Winston RL, Schwarzländer M, Hinz HL, Day MD, Cock MJW, Julien MH (editors). Biological Control of Weeds: A World Catalogue of Agents and their Target Weeds. 5th ed. FHTET-2014-04. USDA Forest Service, Forest Health Technology Enterprise Team, Morgantown, West Virginia, USA; 2014. 838 pp.
29. Hein DG, Miller SD. Influence of leafy spurge on forage utilization by cattle. Journal of Range Management 1992;45:405–7.

Case Study 10
Water hyacinth, *Eichhornia crassipes* (Mart.) Solms (Pontederiaceae)

Lead author: Roger K. Day (CABI Africa) and Matthew J.W. Cock (CABI UK)

In many ways, water hyacinth (*Eichhornia crassipes* [Mart.] Solms) is one of the most difficult of classical biological control (CBC) programmes to evaluate because (1) the problems caused by water hyacinth are always multi-sectoral; (2) assessing the impact of the biological control agents is challenging because of factors such as climate, eutrophication, water movement, wind, the sinking of damaged plants, etc. and (3) the reduction of competiveness or cover by water hyacinth interacts with many of these factors, and other water plants to produce a dynamic situation which is difficult to compare with the situation earlier. It is also a global problem, and CBC has been implemented around the world with variable results.

The Pest Problem

Water hyacinth (Figure 1) is native to South America, but is now an environmental and social menace particularly throughout the Old World tropics, but also in many parts of the Americas and even Southern Europe. It affects the environment and humans in diverse ways [1]. Most of these are detrimental, although some are beneficial or potentially useful. Many of these effects are due to its potential to grow rapidly and produce enormous amounts of biomass, thereby covering extensive areas of naturally open water. Some of the negative aspects are as follows:

- A most striking and little understood effect of water hyacinth is on aquatic plant community structure and succession. Water hyacinth replaces existing aquatic plants, and develops floating mats of interlocked water hyacinth plants, which are colonized by several semi-aquatic plant species. As succession continues, floating mats dominated by large grasses may drift away or be grounded. This process can lead to rapid and profound changes in wetland ecology, e.g. shallow areas of water will be converted to swamps.
- In slow-moving water bodies, water hyacinth mats physically slow the flow of water, causing suspended particles to be precipitated, leading to silting.
- Reduced water flow due to clogging with water hyacinth can cause flooding and adversely affect irrigation schemes.
- Water hyacinth acts as a weed in paddy rice by interfering with germination and establishment.
- Water hyacinth is reported to cause substantially increased loss of water by evapo-transpiration compared with open water, although this has been challenged.
- Displacement of water by water hyacinth can mean that the effective capacity of water reservoirs is reduced by up to 400 m^3 of water/ha, causing water levels in reservoirs to fall more rapidly in dry periods.
- Water displacement, siltation of reservoirs and physical fouling of water intakes can have a major impact on hydroelectric schemes.
- Water hyacinth mats are difficult or impossible to penetrate with boats, and even small mats regularly foul boat propellers. This can have a severe effect on transport, especially where water transport is the norm.
- Infestations make access to fishing grounds increasingly time consuming or impossible, while physical interference with nets makes fishing more difficult or impractical. Some fishing communities in West Africa have been abandoned as a direct result of the arrival of water hyacinth.
- By absorbing and using nutrients, water hyacinth deprives phytoplankton of them. This leads to reduced phytoplankton, zooplankton and fish stocks.
- The large amounts of organic material produced from senescent water hyacinth decompose, and this leads to oxygen deficiency and anaerobic conditions under the floating water hyacinth mats. These anaerobic conditions have been the direct cause of fish death, and change the fish community by eliminating most species at the expense of species that can breathe air such as catfish (Clariidae).
- Stationary mats of water hyacinth also shade out bottom growing vegetation, thereby depriving some species of fish of food and spawning grounds.
- The conditions created by water hyacinth encourage the vectors of several human diseases, including the intermediate snail hosts of bilharzia (schistosomiasis) and most mosquito vectors, including those responsible for transmission of malaria, encephalitis and filariasis.
- In parts of Africa, water hyacinth mats are reported to provide cover for lurking crocodiles and snakes, putting those living adjacent at greater risk.

Figure 1 Water hyacinth has been widely introduced because of its attractive flowers (photograph: Colin Wilson, from CABI CPC).

In addition to these many negative aspects, there are some positive ones:

- Water hyacinth has direct effects upon water chemistry. It can absorb large amounts of nitrogen and phosphorus, other nutrients and elements. It is this ability to pick up heavy metals which has led to the suggestion that water hyacinth could be used to help clean industrial effluent in water.
- Given the enormous amount of biomass water hyacinth can produce, it has been suggested that it can be used as animal feed and as a source of biogas. Tests to date have not proved entirely satisfactory for either purpose.
- Derived compounds appear to have nematicidal properties leading to some patents.
- Communities living beside water hyacinth infestations naturally try and make use of this resource in different ways, e.g. for making ornaments and furniture, dried as cooking fuel, etc.

The diversity of impact means that the problems occur in the mandates of diverse ministries. There is considerable scope for delays following a new infestation, while the relevant government groups decide who is responsible for what in order to tackle water hyacinth.

The Biological Control Programme

The biological control programme against water hyacinth for the benefit of different parts of the world has involved several different national and international agencies in the survey for and assessment of biological control agents, as well as in implementation, and sometimes assessment of CBC. Efforts have been based on the national needs of developed countries and the urgent needs of developing countries. The national programmes of the USA, Australia and South Africa and CABI have been heavily involved in all aspects. Funding has been provided by national governments and by assistance agencies: Department for International Development (DFID, UK), Australian Centre for International Agriculture Research (ACIAR) and the World Bank. These efforts have only been loosely coordinated, but this has been sufficient to minimize duplication of effort.

CABI and the United States Department of Agriculture (USDA) started surveys for biological control agents in the 1970s, CABI with support from DFID (then Overseas Development Agency). Initially the more accessible parts of the Neotropics were surveyed, with a focus on insect potential biological control agents. Further surveys continued until the 1990s, with a stronger focus on plant diseases, particularly fungi as potential biological control agents, and extending surveys to some of the more inaccessible parts of South America. All active parties, including CABI were involved in host-range testing, and in due course, CABI also assisted national programmes in several countries to make decisions about introducing biological control agents, and then implement release programmes. DFID support was provided to assist Sudan in the 1970s and Malawi in the 1990s.

Sudan and South Sudan

The following summary of the 1980s biological control of water hyacinth in Sudan (now Sudan and South Sudan) is taken from Irving and Beshir [2], Bashir [3], Obeid [4] and Beshir and Bennett [5], as summarized in Hill *et al*. [6]. Water hyacinth was recorded from the Sudan in 1955–56, and was first noted as a serious weed in the White Nile system in 1958. It spread rapidly throughout the Sudd region from Juba (now in South Sudan) to the Jebel Aulia Dam, in Sudan, 40 km south of Khartoum (Figure 2). Deleterious effects which are summarized by Obeid [4] include:

- interference with river transportation including high operational and maintenance costs for ships;
- blockage of irrigation canals or pumps and access to water riverine settlements and recreation activities;
- water loss by evapo-transpiration;
- fishing losses; and
- the high cost of chemical control programmes.

To cope with the water hyacinth problem the Sudanese-Egyptian Joint Nile Committee initiated a control programme, the main thrust of which was based on herbicide

Figure 2 Water hyacinth accumulating on the left, behind the Jebel Aulia Dam, Sudan, August 1977 (photograph: D.J. Girling, CABI).

applications by aircraft and boats. Limited use was also made of mechanical and manual control. The main objectives were to maintain open water access for commercial steamer traffic and riverside villages. Resultant problems included difficult access due to bad roads and damage to crops by spray drift, as well as the cost of chemical treatments which were calculated to be about US$1.5 million/annum, totalling US$19 million over 15 years.

However, the solution to the problem was based upon biological control, initially as a cooperation between the Sudanese National Council for Research and the USDA, under which a weevil, *Neochetina eichornniae* Warner, was imported in December in 1976 and released May–July 1978, and subsequently, as a DFID (then Overseas Development Ministry)/Sudan Government project started in 1979 with assistance from CABI and USDA. A second weevil, *Neochetina bruchi* Hustache, was introduced in November 1979 and a stem boring crambid moth, *Niphograpta albiguttalis* (Warren), in 1980. Recoveries of *Neochetina eichornniae* were made from January 1980, of *N. bruchi* in April–May 1981, and of *N. albiguttalis* in 1982. It has been suggested also that pathogens attacking water hyacinth became more common after the biological control insects were established.

Since the early 1960s, there had been an annual accumulation of up to 11 350 ha of water hyacinth behind the Jebel Aulia Dam, which was seasonally treated with chemical herbicides. Since the establishment of biological control in 1982, there has been no accumulation of floating mats of water hyacinth behind the dam. The Ministry of Agriculture terminated its intensive spray programme in 1983, although a limited amount of manual clearing by the agricultural community continued in order to clear canals, etc. and some farmers continued to use water hyacinth as a mulch on their crops. Throughout the area the leaves of virtually every water hyacinth plant are scarred by the feeding marks of *Neochetina* spp. (Figure 3). Adults, plants are much less vigorous, have a lower dry weight, float lower in the water, and no longer form suitable colonization sites for other plants which used to form substantial islands on the floating platforms provided by healthy water hyacinth plants.

Figure 3 Adult and feeding damage of *Neochetina eichornniae*, one of the effective biological control agents used against water hyacinth (photograph: P.A.C. Ooi, CABI/Universiti Tunku Abdul Rahman).

> Since the early 1960s there had been an annual accumulation of up to 11 350 ha of water hyacinth behind the Jebel Aulia Dam, north of Khartoum, which was seasonally treated with chemical herbicides. Since the establishment of biological control in 1982, there has been no accumulation of floating mats of water hyacinth behind the dam.

However, the relative contributions of the three biological control agents have never been evaluated, and recent information on the status of water hyacinth in the South Sudan has not been available due to civil unrest. Nevertheless, the objective data regarding accumulation of water hyacinth behind the Jebel Aulia Dam has justified the view that this has been one of the success stories of biological control against water hyacinth.

Malawi

Water hyacinth is thought to have reached Malawi in the 1960s, probably from neighbouring countries where it was already present. Fishermen in the Lower Shire River in Southern Malawi suggest that it may have arrived during floods [7, 8]. It subsequently spread northwards up the Shire River, and by 1980 had reached the southern end of Elephant Marsh near Makhanga [9]. It was recorded from the northern end of the marsh in 1991 [10], and in 1995, it was found in the Upper Shire north of Mangochi [11], towards where the Shire flows out of the southern tip of Lake Malawi. In 1995, a small infestation was also found in the Lilongwe River which flows into Lake Malawi further

Figure 4 Biological control agent rearing facility beside the Shire River, Malawi (photograph: M.J.W. Cock, CABI).

north. At that time the weed was apparently absent from the Shire between Lake Malombe and Chikwawa, suggesting that it had been transported to the Upper Shire and the Lilongwe River, rather than having spread all the way up the Shire River. By 2001 it was found throughout the Shire, as well as at a number of other locations in different parts of the country [12].

In 1995, a control project was started, funded by DFID and implemented by CABI in collaboration with the Malawi Fisheries Department. There were four components, one of which was biological control. The project ended in March 1999 [13], but after around a year's gap, the biological control work continued until the end of 2001 under a much broader Environmental Management Project funded by the World Bank [14]. There is no record of biological control work having continued after the World Bank funding ended, and there is little information on the status of the biological control since that time.

Four biological control agents were introduced during the period 1996–2001: the weevils *Neochetina eichhorniae* and *N. bruchi*, a mirid, *Eccritotarsus catarinensis* (Carvalho), and a moth, *Niphograpta albiguttalis*. The mite *Orthogalumna terebrantis* Wallwork was found to be already present on water hyacinth in the Lower Shire in 1995, so no introductions were made, but it was re-distributed to new infestations as they were found.

The first introductions of *Neochetina* spp were in September 1996, hand carried from Zimbabwe. A total of 710 insects were released at Mvera (the northern end of Lake Malombe), and 510 were released at M'baluku (Mangochi), but most were used to establish a rearing facility at Makhanga in the Lower Shire. The first harvest was made in May 1997, and over a 3 year period a little over 100 000 weevils were harvested from that facility. Harvesting at the Makhanga rearing facility ceased in mid-2000, but another unit had been established at Mangochi in the Upper Shire in May 1997 (Figure 4), with the first harvests made early in 1998. By the end of 2001, almost a quarter of a million *Neochetina* spp. had been harvested at the Mangochi facility. In 2000, small rearing units were set up at Fisheries Department offices in Salima, from which over 5000 insects were subsequently harvested, and in Nkhotakhota which produced over 8000 insects. In 2001, single community-managed rearing pools were set up at six locations for local release of insects.

During the period 1996–2001 over 340 000 *Neochetina* spp. were released. Relatively more beetles were released in the Upper and Middle Shire because it was anticipated that once established, many insects would be washed downstream. The establishment and build-up of beetle populations in the Lower Shire showed that this strategy was successful.

Three small shipments of *E. catarinensis* were imported from South Africa in 1997–1999, but during 2000 and 2001 around 20 000 insects were imported in four shipments. The shipments were used to make releases and establish cultures, although only from September 2000 onwards was a continuous culture maintained. However, by later in 2001, large populations had built up on Chiwembe Dam in Blantyre (first releases were made there in April 2000), from where insects were harvested for redistribution. A total of over 30 000 insects were released from imports, cultures, and field collections, at sites in the Lower, Middle and Upper Shire, in Blantyre, and at sites along the edge of Lake Malawi.

N. albiguttalis larvae and pupae were also imported from South Africa over the period May 1997–April 2001, but five shipments only totalled 1220 insects. Over half of these were released directly to sites in the Middle and Upper Shire, while the others were used to start cultures. However, culturing proved difficult, so to increase the chances of survival, rather than harvesting insects, infested plants from the cultures were released. Thus it is not known how many insects were released, but the numbers were small.

Monitoring was conducted at ten sites from April 1998 to the end of 2001, and at a further five sites from mid-2000. Six were in the Lower Shire, three in the Middle Shire, three in the Upper Shire, and one each at Blantyre, Salima and Nkhotakhota. The aim was to monitor each site once in every 2 months, though this was not always possible, particularly for the Lower Shire sites in 2001 due to the high water levels. At each occasion 30 mature plans were assessed for plant size (6 parameters), *Neochetina* spp. (insects and damage), *E. catarinensis* (presence or absence of insects or damage) and *N. albiguttalis* (presence or absence of damage). Damage due to mites and pathogens was also recorded.

The main measurement for assessing *Neochetina* spp. populations was the number of feeding scars on leaf 2. In the Lower Shire this value peaked in 1999–2000 at around 15–35 scars per leaf, but in 2001 damage was less. However, sites in the Middle and Upper Shire were at their highest in 2000–2001, with similar numbers of feeding scars. No pattern was seen in the parameters for plant size and health, though at most sites the plants appear to have been stressed throughout the monitoring period, with the longest petiole generally around 30 cm, around half or less than the length of petioles at Chiwembe Dam in Blantyre. At most sites the petiole length was generally similar to or shorter than the root length, also suggesting the plants were short of nutrients, except at Chiwembe where the roots were usually much shorter than the petiole.

By 2001, *E. catarinensis* had established in Chiwembe Dam and large populations had built up, although there was no apparent reduction in the water hyacinth infestation. The dam is surrounded by informal settlements, probably leading to large nutrient inflows. Feeding marks of *E. catarinensis* were seen at other sites, but no evidence of establishment was seen. No evidence of establishment of *N. albiguttalis* was seen at any of the monitoring sites.

All the sites had been chosen due to their having significant infestations of water hyacinth, and during 2001, most had relatively low populations, except at Chiwembe Dam which remained with almost 100% of the water surface covered. However, at many sites there was proliferation of other plants, and Rother and Twongo [15] concluded that water hyacinth was probably facilitating a succession.

As far as we know, no work on implementation or assessment of biological control of water hyacinth has been undertaken in Malawi since 2001. However, it is clear that since then the problem of aquatic weeds in the Shire River has become more serious. Most of Malawi's electricity is generated from hydropower stations on the Shire. Preventing vegetation clogging the inlets, undertaking repairs to damage caused by floating weeds, and the resulting lost generation capacity are reported to be very costly, though it is suggested that by no means all the repairs are needed as a result of weed damage [16]. The contribution of water hyacinth to the aquatic weed problem, either directly or through facilitating the growth of other weeds, is not clear.

Under the Millennium Challenge Corporation compact with Malawi, plans have been developed to address the problem. The Environment and Natural Resources Management project has three components, one of which (weed and sediment management) will include restarting biological control of water hyacinth. However, observations by the consultants developing these projects show that 'a weevil population (though greatly reduced) persists, and there are indications that it continues to exert some pressure on the vigour of the water hyacinth infestation' [17].

ICF/CORE [18] reports that during site visits in March 2010, water hyacinth at Liwonde Barrage appeared to be at relatively low levels compared with those seen in December 2008. It was suggested that this could be due to biocontrol agents limiting growth, and water hyacinth at the barrage 'exhibited low but consistent evidence of feeding and damage', by the mite and the weevils, though the 'number of weevils observed were low'. It was also reported that at several power stations that water hyacinth was not the major water weed problem.

Overall biological control of water hyacinth in Malawi can be considered successful in as much as the programme was implemented as planned, and at least three biological control agents became established. However, although there are indications that water hyacinth is under a degree of biological control, data on the impact of the introduced biological control agents are not available, and water weeds as a whole continue to be a major problem. There is scope for studies to compare impacts of the weed problem today with what was observed in earlier studies during the DFID project, such as socioeconomics impacts on local communities [8] and biodiversity [15].

Bénin

Water hyacinth was first reported from Southern Bénin in 1977 and within 10 years had become a serious weed, affecting the lower reaches of the Ouémé and the Sô rivers [19]. The Ouémé flows all year, and the mats of water hyacinth are flushed out particularly during the flood in August, which brings the plants into the flood plain, where they get trapped when the water recedes. The smaller and shorter Sô river does not flow as strongly; it does not flush out as easily and is more prone to clogging by the weed, especially at the river bends.

Biological control of water hyacinth in Southern Bénin used a combination of the three host-specific agents: *N. eichhorniae* released in December 1991, followed by *N. bruchi* in March 1993, and *N. albiguttalis* in December 1993 [19]. All agents were imported by International Institute for Tropical Agriculture (IITA) from Australia (CSIRO, Commonwealth Scientific and Industrial Organisation), after quarantine at CABI, UK. They were mass reared at IITA's station in Cotonou, and released together with the Bénin Direction de Pêche (Ministry of Rural Development), with assistance from the project Projet Pêche Lagunaire, supported by the Gesellschaft für Technische Zusammenarbeit (GTZ).

In Bénin, monitoring started in 1991 and continued for more than 10 years. The weevils became established, spread from the release sites and now are found in all suitable habitats. After many years of uncertain impact, biological control, particularly by *N. eichhorniae*, was finally showing an impact and water hyacinth cover was being reduced early this century (Ajuonu and Neuenschwander unpublished in [20]).

Evaluation of Impact

Bénin

In 1999, a survey by De Groote *et al.* [20] of 365 men and women from 192 households in 24 villages in the target area, using participatory and quantitative methods, revealed that water hyacinth, although not eliminated, was perceived by the villagers as having been reduced from a serious pest to one of minor or moderate importance. According to their estimates of the impacts they perceived, at the peak of the infestation water hyacinth had reduced the yearly income of this population of about 200 000 by approximately US$84 million. Lost revenues for men were mostly in fishing, while women experienced lost revenues in trade, primarily food crops and fish. The reduction of water hyacinth cover through biological control was credited with an increase in income of US$30.5 million/year. The total cost of the control programme is estimated at a present value of US$2.09 million. Assuming the benefits are to stay constant over the next 20 years, a most conservative assumption, the accumulated present value would be US$260 million, yielding a respectable benefit:cost ratio of 124 : 1. This ratio was calculated for direct economic effects on the people of Southern Bénin only, and does not take into account improved levels of control which may have been achieved since the survey was carried out or indirect benefits, including an improvement in water quality and human health.

A 1999 survey of 192 households in 24 villages in the target area revealed that water hyacinth, although not eliminated, was perceived by the villagers as having been reduced from a serious pest to one of minor or moderate importance. The reduction of water hyacinth cover through biological control was credited with an increase in income of US$30.5 million per year for the population of 200 000.

Implications for other countries

Since 1971, two South American weevils, *N. eichhorniae* and *N. bruchi* have been widely introduced in Australia, Asia and Africa. Other agents such as *N. albiguttalis* and *E. catarinensis* have been released less widely. In some areas, they have provided substantial control, but this is not consistent in different areas. Water nutrient status, average temperature, winter temperatures and other factors probably affect the impact. Biological control of water hyacinth is still the subject of active research, and new biological control agents have been released in the last 5 years [21], so the final impact of the global efforts towards biological control will not be known for years to come.

The problems caused by water hyacinth are multi-faceted. As a result the objectives of control programmes are not always clearly defined. Effective management plans are needed which involve all local stakeholders in their development, together with inputs from specialists in all aspects of weed control and utilization. The principal options for control of water hyacinth are mechanical, chemical and biological control. Utilization should not be considered an effective control strategy by itself but is an important consideration for an integrated control programme. Biological control is the only permanent and sustainable control option, and as such it must be the basis of any control programme. It has proved to be an adequate control method on its own in several instances in developing countries (e.g. Sudan and South Sudan, Papua New Guinea, Bénin). Using currently available agents, it usually reduces biomass by 70–90%. The principal drawback with biological control of water hyacinth is the time required to achieve control. In tropical environments this is usually 2–4 years and is influenced by the extent of the infestation, climate, water quality and other control options. Because of the time taken to achieve full impact, biological control should be pursued as a matter of the greatest priority as soon as an infestation of the weed appears. Other control options will need to be integrated with the biological control. As the weed infestation increases, the capacity of the biological control agents to control it effectively and quickly diminishes, so that other interim means of control may be needed.

References

1. Wittenberg R, Cock MJW. Invasive Alien Species: a Toolkit of Best Prevention and Management Practices. CABI publishing, on behalf of the Global Invasive Species Programme, Wallingford, UK; 2001. 228 pp.
2. Irving NS, Beshir NO. Introduction of some natural enemies of water hyacinth to the White Nile, Sudan. Tropical Pest Management 1982;28:20–6.
3. Bashir MO. The establishment and distribution of natural enemies of water hyacinth released in Sudan. Tropical Pest Management 1984;30(3):320–3.
4. Obeid M. Water hyacinth, Eichhornia crassipes (Mart.) Solms in Sudan. In: Thyagarajan G, editor. Proceedings of the International Conference on Water Hyacinth: Hyderabad, India, February 7–11, 1983. UNEP reports and proceedings series no.7, Nairobi, Kenya; 1984. p. 145–60.
5. Beshir MO, Bennett FD. Biological control of water hyacinth on the White Nile, Sudan. In: Delfosse ES, editor. Proceedings of the VI International Symposium on Biological Control of Weeds. Agriculture Canada, Ottawa, Canada; 1985. p. 491–6.
6. Hill G, Cock M, Howard G. A Global Review of Water Hyacinth, its Control and Utilisation, Volume 15. SIDA Publications on Water Resources, Stockholm, Sweden; 1999a. 54 pp.
7. Harley KLS. Survey report of a project on exotic floating African water weeds. Unpublished report to the Commonwealth Science Council; 1991. p. 151–77.
8. Chimatiro S, Mwale D. A Participatory Rural Appraisal Study on the Socio-Economic Impact of Water Hyacinth on Local Communities of the Lower Shire Area, Malawi. Report to Department for International Development Renewable Natural Resources Knowledge Strategy

programme. Malawi Fisheries Department and CAB International, Kenya; 1998. 101p.

9. Blackmore S, Dudley CO, Osborne PL. An annotated checklist of the aquatic macrophytes of the Shire River, Malawi, with reference to potential aquatic weeds. Kirkia 1988;13:125–42.
10. Terry PJ. Water hyacinth in the Lower Shire, Malawi, and recommendations for its control. Report of a consultancy for ODA. 18 September – 5 November 1991.
11. Hill G, Day R, Phiri G, Lwanda C, Njaya F, Chimatiro S, Hill MP. Water hyacinth biological control in the Shire River, Malawi. In: Hill MP, Julien MH, Center TD, editors. Proceedings of the First IOBC Global Working Group Meeting for the Biological and Integrated Control of Water Hyacinth, Harare, Zimbabwe, 16–19 November 1998. Plant Protection Research Institute, South Africa; 1999b. p. 39–50.
12. Phiri PM, Day RK, Chimatiro S, Hill MP, Cock MJW, Hill MG, Nyando E. Progress with biological control of water Hyacinth in Malawi. In: Julien MH, Hill MP, Center TD, Jianqing D, editors, Biological and Integrated Control of Water Hyacinth Eichhornia crassipes. Proceedings of the Second Meeting of the Global Working Group for the Biological and Integrated Control of Water Hyacinth, Beijing, China, 9–12 October 2000, Volume 102, ACIAR Proceedings, Canberra, Australia; 2001. p. 47–52.
13. CABI. Control of Water Hyacinth in the Shire River, Malawi. Final Technical Report of Project R6392. 1999.
14. Day RK, Nando E, Phiri P. Biological Control of Water Hyacinth. Final Technical Report to the Malawi Fisheries Department. 2002.
15. Rother JA, Twongo T, . Water hyacinth in the Shire River: techniques for monitoring biodiversity impacts and a baseline survey. Unpublished report to DFID/Government of Malawi/ CABI for Lower Shire water hyacinth biological control project. 1999.
16. Mzuza MK, Chapola L, Kapute F, Chikopa I, Gondwe J. Impact of aquatic weeds in the Shire river on generation of electricity in Malawi: a case of Nkula falls Hydro-electric power station in Mwanza district, Southern Malawi. American Open Aquaculture and Fisheries Journal 2014;1:1–11.
17. Anon. (no date). Malawi Compact Environment and Natural Resources Management Project Description. Available from: URL: http://www.mca-m.gov.mw/files/ENRM_Project_Description.pdf. [Accessed on 29 November 2014].
18. ICF/CORE (ICF International/Core International, Inc.) Malawi Power System Project Studies. Revised final feasibility study report. Annex 6: Weed Management Report (public version). Millenium Challenge Corporation. 2011. Available from: URL: http://www.finance.gov.mw/index.php?option=com_docman&task=cat_view&gid=86&limit=50&limitstart=0&order=name&dir=DESC&Itemid=114. [Accessed on 29 November 2014].
19. van Thielen R, Ajuonu O, Schade V, Neuenschwander P, Aditế A, Lomer CJ. Importation, release, and establishment of *Neochetina* spp. (Curculionidae) for the biological control of water hyacinth, *Eichhornia crassipes* (Lil.: Pontederiaceae), in Benin, West Africa. Entomophaga 1994;39:179–88.
20. De Groote H, Ajuonu O, Attignon S, Djessou R, Neuenschwander P. Economic impact of biological control of water hyacinth in Southern Benin. Ecological Economics 2003;45:105–17.
21. Winston RL, Schwarzländer M, Hinz HL, Day MD, Cock MJW, Julien MH (editors). Biological Control of Weeds: A World Catalogue of Agents and their Target Weeds, 5th ed. USDA Forest Service, Forest Health Technology Enterprise Team, Morgantown, West Virginia; 2014. FHTET-2014-04. 838 pp.