Information Facility (GBIF) and an EU-funded European Natural History Information Network are under way. To some extent, these top-down initiatives are in competition. It remains to be seen which will prove most useful and how such initiatives will mesh with bottom-up initiatives, such as the species analyst.

Museums are not only about pure science, they are also about educating the public. Obviously this is achieved by front-of-house exhibits. It is also achieved less obviously, for example by the service provided to publishers who produce ever more natural history books with wonderful plates painted by artists reliant on museum specimens. When the delegates scattered to the four corners of the world, few doubted that museums mattered very much – not just to the scientific few, but also to the worldwide many.

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Direct and indirect ecological effects of biological control

Historically, biological control has been a widely acceptable, 'green' approach to pest management. The need for biological control is not diminishing; not only are 'pests' still causing agricultural and forestry losses, but invasive species are also second only to habitat destruction as a threat to biodiversity. Recently, however, negative indirect and nontarget effects of biological control programmes have received increasing attention[1–5]. These criticisms are controversial[6] and evaluation has been hindered seriously by the lack of post-release monitoring[7]. If biological control is to continue as a reliable method of pest control, procedures must be developed for anticipating and reducing both direct and indirect impacts.

It was against this backdrop of public and scientific concern that the International Organization of Biological Control organized a recent symposium on assessing the ecological effects of biological control*.

What can go wrong?

Recently, two biological control agents, widely cited as flagship examples of successful biological control, have been found to be attacking nontarget hosts. Several speakers mentioned *Cactoblastis* moths, native to South America, which were introduced to Australia in the early 1900s to control exotic *Opuntia* cacti (Fig. 1). The rapid and dramatic success of this programme led to the redistribution of the moths to other parts of the world, including the Caribbean, from where they accidentally moved to Florida (and Georgia, according to Don Strong, University of California, Davis, USA). Here, they have been found to attack five native species of cacti, including the extremely rare semaphore cactus, *O. spinosissima*[8]. Although development is likely to be the major cause of the demise of the semaphore cactus, the death knell will be attributed to the moth *Cactoblastis cactorum*. However, the major concern is what will happen if (when?) *Cactoblastis* reaches the southwestern USA and Mexico, where the cactus flora is diverse and native cacti are grown commercially.

A second example of a successful biological control agent spilling over on to native plants involves the seed-feeding weevil *Rhinocyllus conicus*, which was introduced to North America to control exotic thistles from the genus *Carduus*. Now, beetles attack several native thistles of the genus *Cirsium* and reduce both seed production and the occurrence of a native picture-winged fly (*Paracantha culta*), which feeds on thistle seeds[3,6]. Svata Louda and Amy Arnett (University of Nebraska, Lincoln, USA) have dissected the relationship between *Cirsium canescens*, *R. conicus* and the native fly through experimental manipulation. Their results indicate a complex interaction in which there is not only direct competition for resources, but also the presence of *R. conicus* eggs and interference by weevil larvae cause *P. culta* to modify its behaviour. The attack of *Rhinocyllus* on nontarget plants was predicted from host-range data collected before their release (Andre Gassman, CABI Biosciences, Switzerland). A similar case can probably be made for *Cactoblastis*. However, the importance of the nontarget impacts of the introduced agents, particularly the spatial scale over which nontarget effects can be manifested, was underestimated.

Introduced predators can also influence native ecological interactions. The Asian ladybird *Harmonia axyridis*, was released in 1994 for aphid control in orchards in Eastern USA and rapidly dominated the system, even displacing another successful exotic predator, the sevenspot ladybird, *Coccinella septempunctata* (Mark Brown, USDA, Kearneysville, USA). Aphid control has been excellent, but an important early season predator, *Aphidoletes aphidimyza* (a cecidomyiid fly), declined simultaneously. However, there are also indications that native coccinellids might well be increasing.

Risk and benefit assessment

Identification of potential direct and indirect ecological impacts requires increasingly stringent assessment. Mark Lonsdale, David Briese and Jim Cullen (CSIRO, Canberra, Australia) pointed out that useful insights might be gained from risk analysis models. They stressed that benefit assessment should accompany risk assessment and communication of potential risk must involve wide-scale consultation rather than the traditional model of incontrovertible expert opinion. Don Strong, among others, pointed out that for many introduced pests biological control might be the only feasible solution – 'the last, best hope'. Doing nothing is not a neutral decision if the exotic pest is having economic or ecological impacts[6]; this might be particularly true in less developed countries where biological control is the only affordable and sustainable option. Peter Neuenschwander (International Institute of Tropical Agriculture, Cotonou, Benin) and Richard Markham

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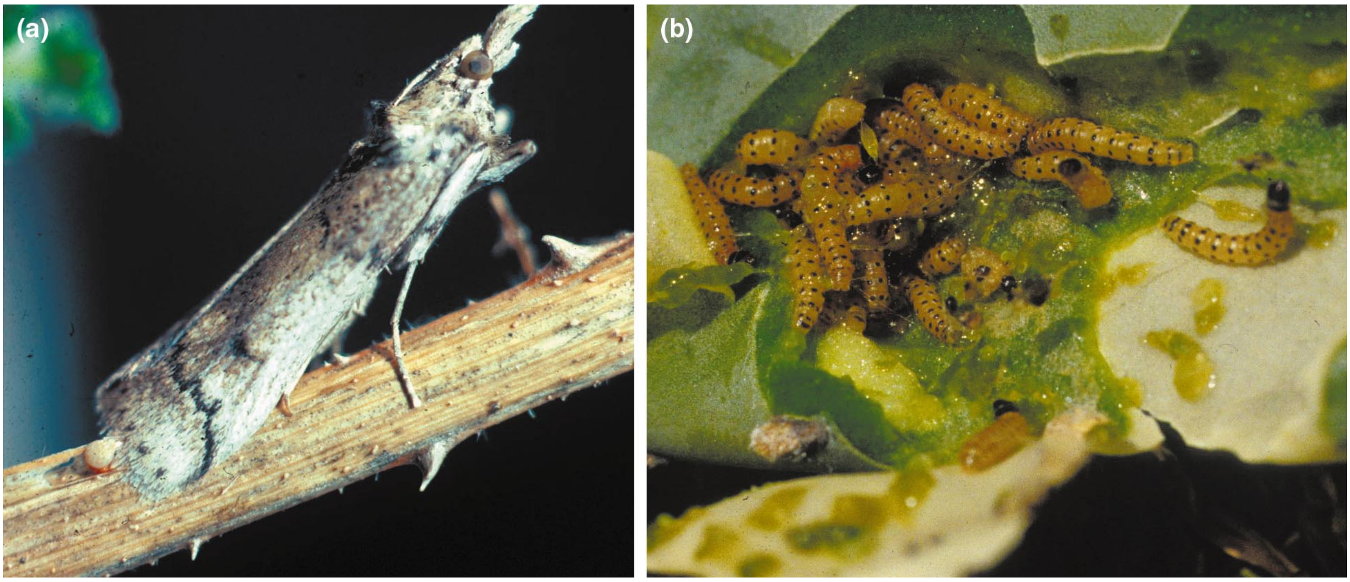

Fig. 1. *Cactoblastis* moths (a) were introduced from South America to Australia in 1925 to control prickly pear cacti. The gregarious larvae (b) destroyed cactus plants and were successful control agents. Recently, *Cactoblastis* have found their way into eastern North America where they are a potential threat to non-weedy cacti. *Photos by J. Myers.*

(IITA, Ibadan, Nigeria) stressed that if current standards had been applied, some of the highly successful and crucially important biological control programmes in Africa, whose impact has been monitored carefully, might not have gone ahead. This served to reinforce the message that biocontrol should not be overregulated.

By contrast, Strong and Pemberton cited the apparent lack of restraint in some recent biological control programmes, as demonstrated by the introduction of 31 species of natural enemies between 1986 and 1993 in the Russian Wheat aphid control programme in North America. These introductions included 12 species of ladybirds alone. In addition, agents known to have negative nontarget impacts, such as *Rhinocyllus* beetles and Asian ladybirds, have continued to be redistributed in a frenzy of biological control enthusiasm.

Host specificity

Accurate prediction of the host range of agents after release is at the heart of responsible biological control, but releasing essentially monophagous agents is not always an option. Peter McEvoy (Oregon State University, Corvallis, USA) outlined the history of host specificity testing, from expert opinion to centrifugal testing based on a phylogenetic framework[9] and to more recent approaches designed to identify taxonomically disjunct host distributions. He stressed that host range was constrained at different levels, from the genetic and physiologically based host range demonstrated in the laboratory, to the behaviourally and ecologically modified host range in the field.

Alec McClay (Alberta Research Council, Alberta, Canada) described his study of the chrysomelid beetle, *Lema cyanella*, released on Canada thistle, *Cirsium arvense*. Pre-release studies showed that *L. cyanella* preferred *C. arvense*, with limited feeding on most other *Cirsium* species. The release of *L. cyanella* in Canada was promoted on the grounds that rare host species would be less susceptible to attack than the more abundant pest species (resource concentration hypothesis)[10]. However, open-field experiments of *L. cyanella* showed serious damage to some rare, native, nontarget *Cirsium* species. McClay concluded that rarity does not protect a species from attack and released beetles were exterminated.

Biopesticides

Indirect ecological impacts potentially can occur with inundatively released control agents, such as pathogens, although this group is rarely discussed in this context. Mark Goettel (Agriculture Canada, Lethbridge, Canada) and Ann Hajek (University of Cornell, Ithaca, NY, USA) presented an overview of insect pathogens (viruses, bacteria, fungi and protozoa). Whether approaches to assessing nontarget effects of macrobials can be generalized to pathogens remains to be answered; laboratory host range can often be broad, but in the field far fewer insect hosts are likely to be infected. Equally, ecotoxicological methods adopted from chemical pesticides do not capture the biological nature of biopesticides. There is no evidence that inundative release of insect pathogens has resulted in long-term negative effects on nontargets, or even that pathogens introduced in this manner have established. However, we have little information on the long-term effects of pathogen application programmes.

Few studies have looked at the effect that introduced insect parasites have on the native fauna. Mary Barbercheck and Leah Millar (North Carolina State University, Raleigh, USA) have addressed this issue using nematodes. Nematode parasites of insects currently are exempt from regulation in most European countries and the USA. Barbercheck and Millar monitored the effect of introducing an alien species (*Steinernema riobrave*) on two endemics, *S. carpocapsae* and *Heterorhabditis bacteriophora*; initial results showed complex interactions. *Steinernema riobrave,* introduced into plots in a corn field once a year for three years, became established and was favoured by tilling, which adversely affected the native species, *S. carpocapsae*. Co-infection of a single host by two nematode species occurred in the laboratory but not in the field, and rarely was more than one species isolated from a soil core, indicating that heterogeneous spatial structures might promote coexistence of the different species in the field.

Is host range evolutionarily stable?

The risk of evolutionary host-range expansion is always of concern in biological control programmes. Rieks van Klinken (CSIRO-Entomology, Indooroopilly, Australia) found no evidence for host-range expansion among weed biological control agents. Reported host shifts were the result of new associations, sampling artifacts or ecological factors, such as changes in host densities. Similarly, Bob Pemberton (USDA-ARS, Fort Lauderdale, USA) showed, through a retrospective analysis of weed control projects in the USA, the Caribbean and Hawaii, that nontarget attacks were not a result of host changes in exotic agents, but of the presence of closely related native plants coexisting in the range of the weed. Michael Hochberg (Université Paris VI, France) addressed this issue from a theoretical perspective and explained why evolutionary host shifts should be unlikely, especially on to rare, nontarget, conserved species.

When are indirect impacts most likely?

Theoretical considerations of agent–host interactions indicate that partially successful biological control agents, for which both agent and host densities remain relatively high, are more likely to yield effects on nontarget hosts, competitive interactions with other organisms, and/or greater opportunities for evolutionary shifts in host choice or developmental phenology (Bob Holt, University of Kansas, Lawrence, USA). Along with Holt, Liam Lynch and colleagues (CABI Bioscience, Ascot, UK) investigated transient effects rather than the traditional equilibrium states of agent–host interactions. In the short-term, overflow of the control agent is likely if the carrying capacity of the target population is high, possibly resulting in local extinction of nontarget species. Thus, absolute, rather than relative, attack rates on different host species are important, underlining the need for no-choice, in addition to choice, experiments in host-range studies. With each biological control agent comes the possibility of nontarget impacts and, therefore, parsimony is the best approach[11], particularly because most biological control successes are achieved by a single agent[12,13].

The future

That biological control must remain a tool for combating agricultural, environmental and greenhouse pests was reinforced strongly at this meeting. Many of the presenters concluded that laboratory or contained-field host-range tests were a successful starting point. However, this needed to be complemented by knowledge of the biodiversity in the target area before release, including the impact of the target pest on biodiversity, as well as detailed, long-term, post-release monitoring. Furthermore, better understanding of the characteristics of successful biocontrol agents is a necessary prerequisite for reducing the number of unsuccessful species that are introduced. Additionally, the public needs to be better educated and more involved in the decision-making process. The techniques are available for making biological control more rigorous, but funding agencies must recognize that safe biological control requires more than just collecting agents from one habitat, dumping them in a new habitat and then hoping something positive will happen. In the USA alone it is estimated that invasive species cost $23 billion per year. Biological control has great potential for combating some of these costs and ecologists can help make it a more predictive science.

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