Eradication of alien invasive species: surprise effects and conservation successes

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Abstract The growing number of biological invasions worldwide is now being accompanied by burgeoning successful alien species eradications on islands of increasing size, topography and habitat complexity. However, the extent of these achievements depends on the definition of success. In most cases, success or failure are measured in terms of the absence or presence of the target alien species. It is becoming increasingly evident that how the invaded ecosystems respond to eradications should also be assessed. This is because some eradications have been accompanied by unexpected population explosions of hitherto seemingly harmless (or undetected) introduced species, previously suppressed by the eradicated alien species. These unexpected chain reactions are sometimes referred to as "surprise effects". We conducted an eight year study of plant and animal communities in a simple insular ecosystem invaded by ship rats (*Rattus rattus*) and domestic mice (*Mus musculus*). We assessed these communities for potential surprise effects following rodent eradication. Next we eradicated the rats and mice following a protocol tailored to the presence of other introduced species. We then continued to monitor changes to the ecosystem, a step too often missing after eradication programmes. We then assessed the success of our eradication in terms of: 1) absence of the eradicated species; 2) recovery of the ecosystem; and 3) absence of surprise effects.

Keywords: *Rattus rattus*, *Mus musculus*, *Achyranthes aspersa velutina*, trophic relationships, island conservation, control strategy

INTRODUCTION

Increased success with alien species eradication from islands is probably one of the major achievements of the last decade in conservation biology (Courchamp *et al*. 2003; Genovesi, 2005; Brooke *et al*. 2007; Genovesi and Carnevali 2011). An expanding number of species of plants and animal are now successfully - sometimes routinely - removed from islands that are increasingly large, rugged and complex. In particular, islands that only ten years ago were regarded as ineligible for alien invasive mammal eradication because of low feasibility are included in large-scale multispecies removal programmes (Courchamp *et al*. 2003).

Despite the increasing range of invasive species eradicated from islands, there has not been a parallel increased understanding of the ecological effects of such eradications. Instead, there is still a disconnection between these management programmes and studies of their consequences at the ecosystem level. Generally, removal of a pest species has undisputed benefits to the extant native biota, but empirical observation shows that these benefits can vary dramatically and unpredictably, and there may even be unexpected adverse consequences (Courchamp *et al*. 2003).

Exotic species interact with native species as well as among themselves, creating complex direct and indirect effects involving competition, predation and facilitation that can be difficult to comprehend, let alone to predict. For example, the removal of one exotic species can favour the expansion of others that were previously suppressed by the species removed. Thus, in addition to improving our abilities to eradicate exotic species, it is also important to characterise their role in invaded trophic webs in order to avoid these unexpected or "surprise effects". An illustration is the removal of herbivorous aliens such as rabbits and goats, which can lead to a release of exotic plants. In the absence of browsing, the exotic species may then out-compete native plants, leading to an explosion of weeds. In one such example on Sarigan Island (Mariana Islands), goats and pigs were removed in order to reverse the loss of forest, reduce erosion, and protect endangered native fauna (Kessler 2002). However, the removal of alien mammals allowed the introduced vine *Operculina ventricosa* to thrive and spread so rapidly, part of the island became overgrown by vines, with unknown consequences for the future of the whole ecosystem. Introduced mammals had previously held the vine at such low density that pre-operation monitoring did not reveal its presence. There are other examples with different trophic relationships (e.g., prey-predators or competitors, Courchamp *et al*. 1999; Caut *et al*. 2007). These surprise effects are not the rule, but as they may lead to additional ecological damage, it is important to anticipate them. The outcomes of change within these already perturbed trophic webs are not entirely intuitive and intervention as dramatic as species eradication should, where necessary, be preceded by careful empirical and theoretical studies of the whole ecosystem. Sometimes, the presence of a few individuals of a species that may appear of minor importance can mask powerful interspecific interactions.

Here, we describe a long-term project on Surprise Island (New Caledonia). Our goal was to define a rational methodology to manage invasive populations in insular ecosystems where there may be surprise effects when an introduced species is eliminated. Specifically, our approach followed three successive steps. First, we undertook complete floristic and faunistic surveys of the island. We also studied diet of the focal introduced species, which was the ship rat (*Rattus rattus*), a major invasive species, (Jones *et al*. 2008), that had allegedly been on Surprise Island for several decades. We also undertook demographic studies of key species in order mainly to assess population sizes of species most likely affected by the rats. This allowed us to develop hypotheses about trophic webs and the direct or indirect effects of the focal alien invasive species.

The second part of our programme was to construct and analyse mathematical models of the dynamics of populations that interact within the trophic webs reconstructed from our field studies based on parameters from data obtained in the field (see Courchamp and Caut 2005; Caut *et al*. 2007). These models presented a number of possible consequences of the elimination of the rats, focussing on representative tri-specific sub-systems, including potential surprise effects. Once we established the different system response possibilities, we eradicated the rats according to the methods and strategies dictated by the field conditions and predictions from the models (Caut *et al*. 2009).

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The third part of this study was long-term post-eradication monitoring of the entire ecosystem. In the present paper, we focus on steps one and three. We briefly outline our field methods and the insights these provided into changes of the ecosystem four years after rat eradication. We show how even the most careful programmes may struggle to avoid all repercussions of the removal of introduced species as pervasive as ship rats.

MATERIALS AND METHODS

Field site

The Entrecasteaux reef is approximately 230 km from the northern end of the main island of New Caledonia and constitutes four main islands, among which is Surprise (Fig. 1). This uninhabited island is ovoid, (about 800 m x 400 m), with a coast length of nearly 1800 m and an area of 24 ha. Each year, four years before the rat eradication (in 2005) and five years subsequently, we visited the island in November to assess the characteristics and short-term change of the plant and animal communities. Specifically, we collected data on: plant cover (different species), seabird abundance (different species), skink abundance, insect abundance (different families) and rat abundance/presence. We mapped the entire island, using a Thales GPS 6502sk/mk, focusing on the extent of the main vegetation units (about 25,000 GPS points). The GPS also provided geo-referenced points for year-by-year comparisons. Rat diet characterisation was performed with classic stomach content and faeces analyses as well as stable isotopic analyses. We will here provide information only on aspects directly relevant to plant communities. Additional details about the island and its ecosystems are provided elsewhere (Caut *et al*. 2008, 2009; Watari *et al*. 2011).

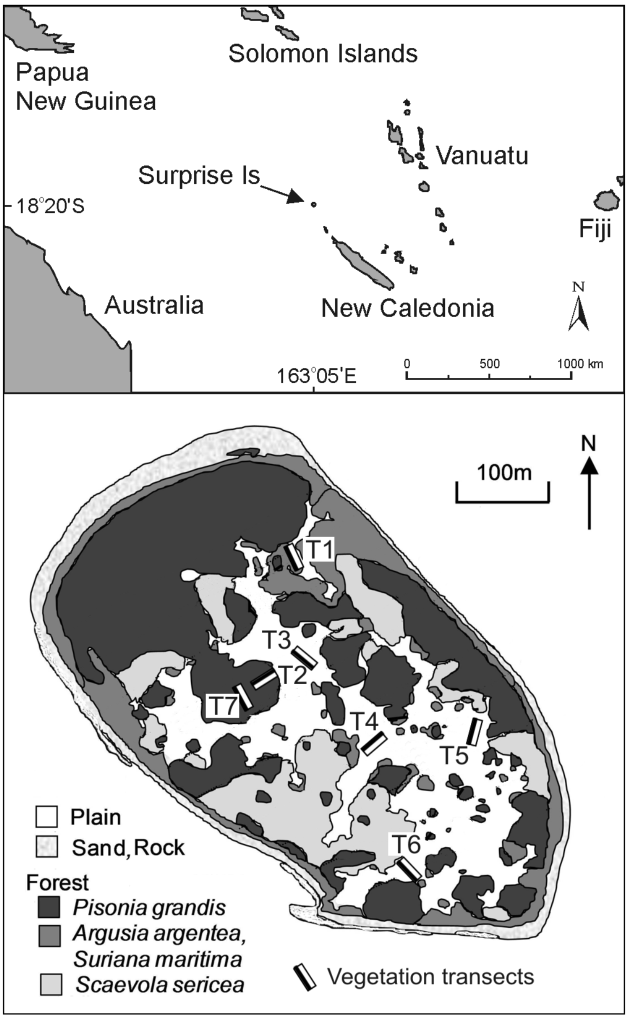

Fig. 1 Surprise Island showing the main vegetation units as well as the seven vegetation transects used to monitor the plant community changes. T1 to T7 are the seven plant transects. See key of the figure for more details.

Characterisation of the vegetation

We characterised the main vegetation units using: 1) five "plant plots" in each habitat unit within which species were identified in 20x20 m squares to assess the cover of each species present; 2) seven point-scale transects of 20 m to assess the cover of each species at different heights (Mueller-Dombois and Ellenberg 1974); and 3) geo-referenced annual photopoints for visual comparison of the plant communities. Samples of all plant species were collected for later identification of plant parts in rat stomach contents and faeces. In addition to constant visual observation, rats were regularly live-trapped along pre-established transects during yearly field sessions starting in 2001 and until their eradication in 2005. Details about the various vegetation types are available elsewhere (Caut *et al*. 2009).

Study of the rats' diet

Captured rats were killed, the stomach contents and faeces were removed and washed, and the fragmentary material obtained was compared with microphotographic reference collections of the epidermal tissues of Surprise Island plant species (120 different items) and animal prey. The relative contributions of plant items and animal prey were estimated for each stomach and faecal sample with a binocular microscope. Samples from livers of captured rats and samples from potential rat food items were collected for stable isotope analysis (Caut *et al*. 2008). Because the island was small and the vegetation types rather spread out and intermingled, we did not relate the diet to habitat. Too few individual mice were trapped for a quantitative diet analysis. Available data indicated, however, a potential overlap of diet, and a potential competition for watery plants (Caut *et al.* 2007).

Eradications

Given its size, eradication of rats from Surprise Island by trapping, as initially planned, would require 400 trapping stations on a 25 m grid (Pascal *et al*. 1996). However, we then discovered domestic mice (*Mus musculus*) on the island, which could undergo a population explosion should the rats be suddenly removed (Caut *et al*. 2007). This led to a changed rat eradication protocol to include the simultaneous removal of mice. Mice have been eradicated with bait stations at 25m on Mana Island (Hook and Todd 1992), but with their dominant competitors, ship rats, present on Surprise Island, mouse foraging ranges would likely be restricted. We calculated that eradication of mice by trapping would require a grid with trap and bait tubes every 5 metres; a total of 9800 stations over this small island. In addition to the cost and weighty logistics, this trap density would require significant damage to the plant communities and a major disturbance of seabirds. In addition, the numerous hermit crabs (*Coenobita* sp.) could lower trapping efficiency (or increase its cost), because the crabs can climb into bait stations to get the bait, and trigger traps. These logistic difficulties led us to switch from trapping to chemical control.

We used an anticoagulant poison that is target specific, will not affect other vertebrates, is harmless to invertebrates, and is widely used in France for rodent eradication. We used rodenticide bait blocks (3x3x1 cm, 25g) containing 0.005% bromadiolone (second generation anticoagulant toxicant), which is effective against rats and mice. Bait blocks were covered with paraffin wax to prolong their durability in a wet climate. We hand distributed the baits across the total surface of the island on a grid of 5x5 m. For access, we cut 38 transects (one every 15 metres) across the island (15 km of transects in the vegetation). On each of these 38 transects and every 5 metres, we dropped one bait block and tossed one at 5 metres to the left and another to the right. We repeated this process on days 0, 6, 11, and 18. About 950 kg (~40kg/ha) of rodenticide baits were used in total (250kg/session, ~11kg/ha). In parallel, traps were used to monitor rat activity just prior to, during, and after the eradication campaign (see also Caut *et al*. 2009).

Post-eradication surveys repeated the same methods used for all the ecosystem units (plants and animals) as in the pre-eradication phase (Caut *et al*. 2008, 2009).

RESULTS

Characterisation of vegetation

Our data revealed four contrasting vegetation units: 1) a ring of shrubs around the island dominated by 1 to 3 m high *Argusia argentea* and *Suriana maritima*; 2) a monospecific arboreal stratum of 3 to 10 m high *Pisonia grandis*; 3) scattered, dense patches of 1 to 3 m high *Scaevola sericea*; and 4) a central plain with more than a dozen main herbaceous species. Spatial coverage of the plant species present in each main vegetation unit based on plant plots and the point-scale transects is illustrated in Fig. 1. A limited stand of *Cassytha filiformis*, which is a potentially invasive plant native to Florida, was present on the island. Another notable exotic plant was *Colubrina asiatica* which was widely distributed over the island, although not dominating the vegetation cover.

Studies of the rats' diet

Rat digestive tracts contained 5202 identified fragments, 77% of which were of plant origin and included 17 of the 29 species of plants found on the island. *Pisonia grandis* was the most consumed plant (mostly as leaves), with 23% contribution of digestive tract contents and 74% presence in faeces of individuals (Fig. 2). Poaceae (grasses) contributed almost 11% to the diet of rats. About 18.6% of the stomach contents remained unidentified. Although widely distributed over the island, *Achyranthes aspersa* var. *velutina* amounted to only 4.67% of the rats' diet. We do not know how much this plant contributed to the diet of mice.

In total, animal remains formed 22% of the items present in the stomach contents (see also Caut *et al*. 2009). A significant component (35%) was ants, among which the only local species, *Pheidole oceanica*, was the most abundant. Ants found in rat stomach contents may have been ingested with the peanut butter bait, which attracted ants. If this were to be the case, ants would not have been a normal prey item of rats.

Eradications

After the eradication, trapping, tracking tunnels, wax tags, and hair tunnel devices deployed over the island confirmed the absence of rats on Surprise Island. Mice were eradicated at the same time as rats. If we follow the convention of confirmed absence for two consecutive years, we can claim a successful rodent eradication because both species have now been continuously absent for four years. Given the small size of the island and its remoteness, any rats or mice discovered in the future will most likely have come from a new introduction rather than from unnoticed survivors of the eradication programme.

The stand of *Cassytha filiformis* was removed to prevent post-eradication spread. Removal was not attempted for *Colubrina asiatica* due to its wide distribution over the island. Ant communities were left untouched as the local species predominated over the eight alien ant species in the two major habitats on the island (Cerdà *et al*. 2011): *Scaevola* shrubs and central plain. Furthermore, since *Pheidole oceanica* was the species most often eaten by rats, it was also the species most likely to increase in abundance. We did not witness any post-eradication spread of *Colubrina asiatica.* In contrast the indigenous *Achyranthes aspersa* became visibly more prominent over large parts of the island (Fig. 3).

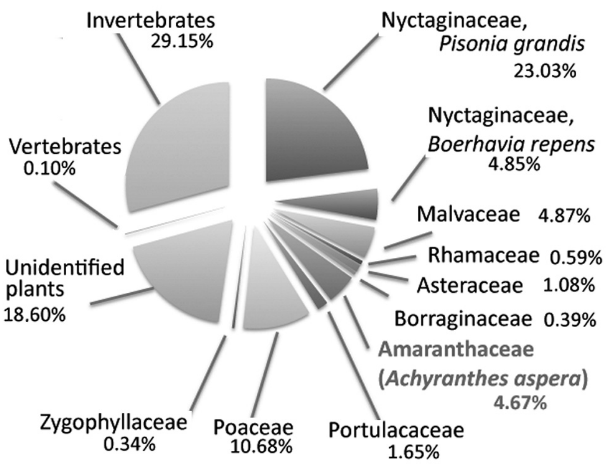

Fig. 2 Proportion of each item found in the stomach contents of rats invading Surprise Island. Note that *Achyranthes aspersa velutina* represents only 4.67% of all fragments found and are therefore not a major food item.

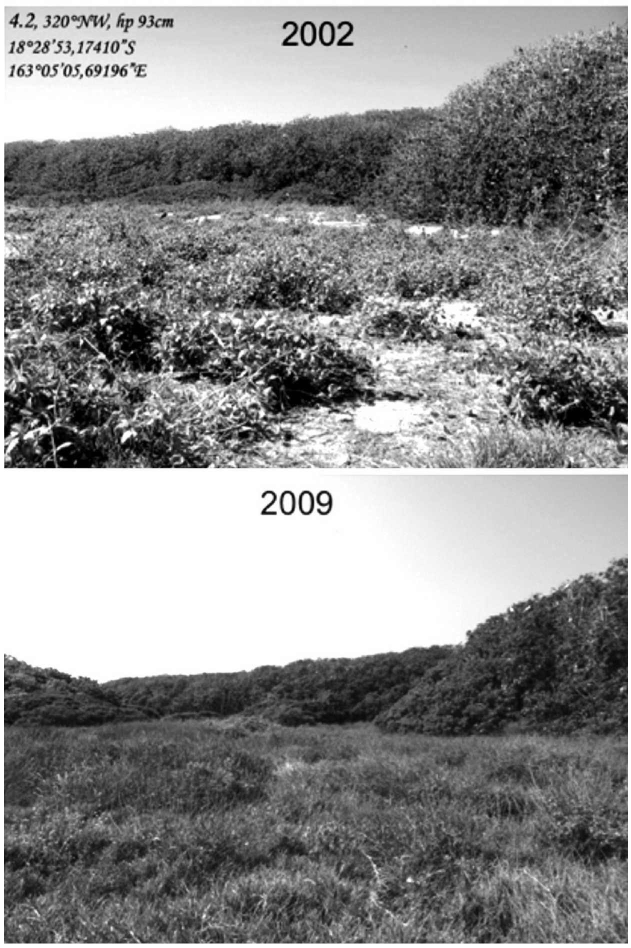

Fig. 3 Georeferenced photos of the central plain of Surprise Island, in 2002 (left side, three years before the rat eradication) and in 2009 (right side, four years after the rat eradication). The dramatic growth of *Achyranthes aspersa velutina* is clearly visible.

Based on the yearly surveyed transects, simple statistical comparisons from 2002 (before rat eradication) and 2009 (after rat eradication) showed that *Achyranthes* covered more space (U = 3 ; p = 0.0060, Fig. 4a), was taller where it was present (U = 57 ; p < 0.001, Fig. 4b), and was more abundant than the other plants (Yates corrected Chi-square $\chi^2 = 826.18$ p < 0.001 df = 1, Fig. 4c) in the absence of rats compared to when rats were present.

DISCUSSION

Our long-term study of a small and remote island with a simple ecosystem enabled us to predict and avoid competitor release of domestic mice and a potential upsurge of the introduced *Cassytha filiformis.* We also found no evidence of an explosion of another introduced plant, *Colubrina asiatica*, or of the several species of exotic ants. It is possible that ant community structure has changed, but no invasion has been observed. Following the rodent eradication, a local plant, *Achyranthes aspera velutina*, dramatically increased in height and coverage over the open spaces of the island and beneath *Pisonia grandis*. This was a very serious concern at first, as it was suspected that it could be the alien invasive *Achyranthes aspera* var. *aspersa*, released, directly or indirectly, by the rodent control. Positive identification of the plant as the local plant, which is heliophilous and generally the first to colonise after disturbances such as fire or cyclones (J.-Y. Meyer pers. comm.), suggests that the current explosion is normal and transitory. Seabirds may help disseminate the seeds of *Achyranthes aspersa velutina*, which stick to feathers (Fig. 5). Birds nesting on the ground in the central plain may in future be constrained by by this plant should its spread continue.

Fig. 5 Brown booby (*Sula leucogaster*) in *Achyranthes aspersa velutina* on Surprise Island. Photo by Yuya Watari, Nov 2009.

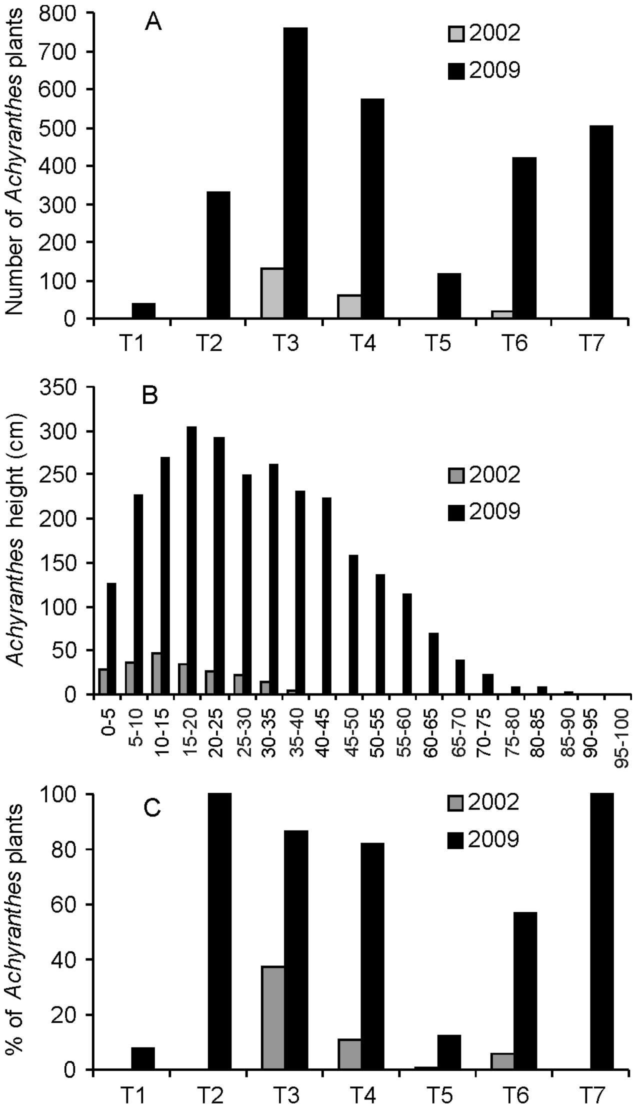

Fig. 4 Changes to *Achyranthes aspersa velutina* in 2002 (three years before the rat eradication) and in 2009 (four years after the rat eradication). A: number of times *Achyranthes aspersa velutina* was counted along the seven transects, showing that the plant was more abundant after rat eradication than it was before. B: height classes of *Achyranthes aspersa velutina* summed for all seven transects. This plant is on average taller after rat eradication than it was before. C: Proportion of *Achyranthes aspersa velutina* among all the plants present in the first metre of vegetation in the seven transects. This plant has outgrown the other plants since rat eradication.

We hope that the increase now being observed is part of a normal phase of expansion following disturbance and that it will be followed by a return to previous conditions or something similar.

The basic requirements for restoring an invaded island are relatively well known (e.g., Parkes 1990; Veitch and Bell 1990; Towns and Ballantine 1993; Towns *et al*. 1997; Atkinson 2001; Saunders and Norton 2001; Courchamp *et al*. 2003; Brooke *et al*. 2007). In addition to these, pre-eradication studies and post-eradication monitoring are important components of success. Removing any species from an ecosystem can have diverse desired and undesired consequences, so it is crucial to quantify and predict these effects. Indeed, the quantification of desired effects can lead to improved control methods as well as a better justification of control programme for biodiversity conservation. Adequate knowledge can also help predict and thus prevent undesired or previously unexpected effects. We strongly believe that criteria for the success of invasive alien species eradications should include the subsequent recovery of native species or ecosystems. If an invasive species is eradicated but the ecosystem becomes detrimentally affected by other erupting invasive species as a result of the eradication, the conservation programme should not be defined as a success. In other words, a programme cannot be qualified as a success if the proximate goal is reached (one management action) but the ultimate goal is not (species conservation). Eradication planning must therefore consider entire ecosystems and include assessments of the state of invaded ecosystems before drastic interventions such as the removal of deleterious invasive species (Thomas and Willis 1998). This step provides an estimation of the impacts of the invading species and enables predictions of the outcomes once eradication is completed. Such risk assessments need not be as detailed as ours for Surprise Island, but do require measures of the potential for other problematic alien invasive species to respond, so that, if necessary, they can be eradicated together, thus avoiding potential surprise effects such as chain reactions (e.g., Zavaleta *et al*. 2001). It is also necessary to implement the best control strategies qualitatively as well as quantitatively (Choquenot and Parkes 2001), according to local conditions. Of course, despite extensive study there can still be unexpected increases of invasive species following an eradication, but still with overall benefits to the natural ecosystem. In these cases, the eradication can be viewed as a success despite this surprise effect (Watari *et al*. 2011).

Sometimes, the risk of triggering a surprise effect might be worth taking in order to remove greater threats from particular invasive species. But when circumstances allow pre- and post- eradication surveys, the evidence gathered can provide lessons for other conservation programmes, help protect other ecosystems from invasions, and in the long run save money. Furthermore, scientific progress can be made out of what are essentially extraordinary situations. Biological invasions and alien species removals can both be viewed by theoretical ecologists as large scale experiments of trophic chain manipulations. Just as conservation practice has gained much from theoretical developments over the years, conservation biology can now be of tremendous help for fundamental ecology.

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