REVIEW

Reassembling island ecosystems: the case of Lord Howe Island

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Abstract

Exotic species that invade remote islands, usually following human settlement, have had catastrophic effects on native biota. However, on islands it is increasingly feasible to eradicate key exotic species allowing extant native species to recover *in situ* or to return naturally. The practice of marooning threatened species on islands where the threat is absent, irrespective of whether the threatened species once occurred on the island, is well established. However, less focus has been given to the 'island' as the management unit on which to return extirpated species or related surrogates for extinct species. We use the example of Lord Howe Island as a case study to explore options for island restoration should the remaining critical exotic pests (rodents and perhaps owls in this case) be eradicated as planned. Lord Howe Island, in the south-west Pacific Ocean, is remote, biologically diverse, has a high degree of endemism, and was only discovered by humans in 1778. Consequently, the original and exotic biota and their interactions are all better known than for many islands with a more ancient human history. Two species of plants, nine terrestrial birds, one bat and at least four invertebrates have been lost from the island since 1778. One plant and two invertebrates could be returned as conspecifics. One plant and all the terrestrial birds that are extinct could be replaced by closely related species from elsewhere in the Pacific Ocean. Decisions on replacing extinct species with surrogates should be based on the taxonomic relatedness of the candidates for reintroduction: the same species before subspecies before genera, with functional replacement being a further filter on candidates that are not the same species. In our opinion, taxa with functional equivalence but without taxonomic relatedness would not be acceptable candidates for reintroduction.

Introduction

The arrival of humans on oceanic islands has led to the extinction of significant proportions of native biota (Franklin & Steadman, 1991). This has been particularly evident in the Pacific Ocean, where human settlement on the islands of Micronesia, eastern Melanesia and Polynesia began only about 3500 years ago and ended in the early 19th century with European settlement of the few islands not previously discovered by Polynesians. Early causes of insular extirpations and extinctions (the former being where a taxon is lost from the island but remains elsewhere, and the latter being where the whole taxon has been lost) included hunting, habitat modification, and predation and competition from the few species introduced by the first settlers – notably the kiore *Rattus exulans* (Atkinson, 1985). However, predation and competition from exotic biota were increasingly important threats to native biota after European arrival in the Pacific brought an extra array of culprits. Critical pests include ship rats *Rattus rattus*, Norway rats *Rattus norvegicus*, mice *Mus musculus*, cats *Felis catus*, goats *Capra hircus*, exotic invertebrates and many weeds (Veitch & Clout, 2002), and the process continues, especially from accidental establishment of species that travel with modern transport. To list but a few, Indian mynas *Acridotheres tristis*, brown tree snakes *Boiga irregularis*, Asian house geckos *Hemidactylus frenatus*, crazy yellow ants *Anoplolepis gracilipes*, giant African snails *Achatina fulica* and large numbers of weeds (often from garden escapes) all require active management to limit their spread between islands (Swarbrick, 1997).

Nevertheless, removal of some of the exotic biota is becoming increasingly feasible on islands, and at increasing scales (e.g. Soria, Gardener & Tye, 2002; Parkes & Murphy, 2003; Towns & Broome, 2003; Nogales *et al.*, 2004;

Campbell & Donlan, 2005). Successful eradication of key pests allows managers to consider five management scenarios to restore native biodiversity. First, the eradication itself, without further intervention, is likely to provide benefits to those native species that remain on the island. Second, some native species will naturally recolonize the island from neighbouring lands, and again no further management may be required although the process can be hastened by tools such as transferring fledgling seabirds to the island so that they imprint and return to nest (Gummer, 2003). Third, managers might return extirpated species that are unlikely to recolonize naturally. These first three options are increasingly being applied on islands where the key threats have been removed, for example, on Mana (Miskelly, 1998), Mangere (Atkinson, 2003), Korapuki (Towns, 2002) and the Marotere group (Towns, Parrish & Ngatiwai Trust Board, 2003) to note but four restoration plans for New Zealand islands. Fourth, managers might introduce taxonomically related or even functional surrogates for species that have become extinct (Atkinson, 1988; Donlan *et al*., 2005). Fifth, some islands can be treated as arks on which to maroon species under threat elsewhere, although neither they nor anything like them ever occurred on the island (Armstrong & McLean, 1995).

Most of the past motivation to transfer species to island refuges came from managers of threatened species who wanted to have more eggs in more baskets, the metaphor being apt as the managers appear to be mostly ornithologists (Steadman, 1997; Sherley & Tiraa, 1999). In essence, the focus of these managers was on threatened species, suitability of the source population and the process of translocation, and only secondarily on the receiving island (Craig & Veitch, 1990; Serena, 1995). Such translocations were particularly common in New Zealand, where many species are critically threatened on the main islands or exist as relict populations on offshore islands (Armstrong & Davidson, 2006). A 1998 database (McHalick, 1998) listed 415 such translocations involving three invertebrate, five lizard and 43 bird species, with many more since that time (R. Hay, pers. comm.) under standard protocols (Anon., 2002*a*).

However, in this paper we follow the more recent perspective and consider restoration scenarios not as a threatened species issue but as a means to return an island's biota to some previous complexity compromised by the presence of exotic pests whose removal is feasible. Whether this is ecosystem restoration or not depends on definition. Simberloff (1990) and Lawton (1997) have noted the impossibility of demonstrating ecosystem restoration in the sense of replicating some pristine state, even if such were known. However, Simberloff (1990) considered that managers could claim success if they reproduced a system whose structure and function could not be shown to be outside the bounds usually seen in other systems.

Thus, restoration does not have to be narrowly constrained. Even natural systems are changing over time and so are unlikely to return to some earlier state once disturbed (Sinclair & Byrom, 2006). Further, restoration involving related species with similar ecological function could have advantages in improving diversity, processes and stability, provided there are no predicted adverse consequences. The latter is a key consideration for planners of prerequisite pest eradication (Courchamp, Chapuis & Pascal, 2003; Hone, Bomford & Parkes, in press).

Characteristics of candidate islands

The ideal islands to restore are those where the removal of key threats is feasible, native biota was well known before the arrival of key threats, lost species or surrogates are present elsewhere, native communities are still largely intact, the degree of endemism is not so deep that surrogates can only be functional rather than taxonomic, or natural reintroduction is likely without human interference.

As examples of islands that do not meet these ideals, the extant biota of Guam before the arrival of brown tree snakes in the 1940s was well known, and the impact of the pest has been catastrophic, but with many of the lost species (or near relatives) being present on other islands in the Mariana islands or held in captivity. However, to date eradication of the snakes appears intractable (Rodda *et al*., 2002). Pests have been eradicated from Mana and Quail islands in New Zealand and some original species are being returned (Miskelly, 1998), but these islands were completely modified by farming; hence restoration requires construction of entire seral processes to create suitable habitats that eventually may or may not (Simberloff, 1990) restore the original ecosystems.

One island that potentially meets these characteristics is Lord Howe Island. It is one of the last places on earth to be discovered and settled on by humans. therefore the biological history of its native and exotic biota is well known, key pests have been or can be eradicated, and lost biota either will recolonize the island or can be replaced with related taxa. We use Lord Howe Island as a model to explore the management scenarios raised above.

Lord Howe Island

Lord Howe Island (1455 ha; 31°05′S, 159°01′E) and its 28 associated islets are remote from major land masses (*c*. 600 km from the east coast of Australia). It is an old island (the remnant of a large shield volcano that formed about seven million years ago), and geologically and topographically diverse (McDougall, Embleton & Stone, 1981). The climate is temperate, with mean temperatures of 25 °C in summer and 18 °C in winter. The annual rainfall is about 1650 mm in the lowlands but much higher in the southern mountains (875 m a.s.l.) and spread throughout the year (Anon., 2002*b*).

Polynesians apparently never discovered Lord Howe Island (Anderson, 2003), and it was not until 1778 that the British Navy found the island. Subsequently, it was regularly visited by the government and whaling ships, and was first settled in 1834. The island now has about 300 residents and up to 400 tourists at any time. Apart from the scenic beauty of the island, the marine and terrestrial wildlife are an important motivation for many visitors (Hutton, 2003). Seventy-five per cent of the island and all the associated islets were declared a Permanent Preserve and the whole island was listed as a UNESCO World Heritage Site in 1982. The surrounding seas, including the world's southernmost coral reef, were declared a Marine Park in 2000.

Native biota

Lord Howe Island has a diverse but disjunct native biota (e.g. it has none of the gymnosperms present in neighbouring lands) with a higher and deeper degree of endemism than the younger, less geologically complex islands, Norfolk and Raoul, at this latitude in the Pacific (Green, 1994; Sykes *et al*., 2000). Endemism at the generic level includes the palms (*Howea*, *Hedyscepe* and *Lepidorrhachis*), a woody composite *Lordhowea*, the tree *Negria*, the leech *Quantenobdella howensis*, three annelid genera (*Paraplutellus*, *Pericryptodrilus* and *Eastoniella)*, an isopod *Stigmops*, a hemipteran bug *Howeria* and a cricket *Howeta*. The native flora consists of 241 species, of which 44% are endemic (Green, 1994). The prehuman terrestrial avifauna of Lord Howe Island consisted of 13 endemic species or subspecies, and the island has two extant native terrestrial reptiles, a skink *Pseudemoia lichenigera* and a gecko *Christinus guentheri*, both also found on Norfolk Island (Hutton, 1991). Published lists of invertebrate taxa show that over 50% are of endemic species (e.g. Recher & Clark, 1974; Recher & Ponder, 1981), but descriptions of only a few groups have been published and the earlier records are incomplete.

The fossil record shows that natural extinctions or extirpations of native animals occurred long before any possible human influence. These include the large, terrestrial chelonian turtle *Meiolania platyceps* (Gaffney, 1981), white-faced storm petrels *Pelagodroma marina*, a penguin (probably *Eudyptula minor*) and a pigmy gadfly petrel (*Pterodroma* sp.) (van Tets *et al*., 1981). An endemic bat *Nyctophilus howensis* may have been present after human settlement (McKean, 1975).

However, the majority of extinctions and extirpations occurred after the island was discovered and settled by people. Two plants (*Solanum bauerianum* and *Sicyos australis*) are known to have been lost. Two terrestrial birds, *Porphyrio alba* and *Columba vitiensis godmanae*, were hunted to extinction by visiting sailors, and the parakeet *Cyanoramphus novaezelandiae subflavescens* was eradicated by 1869 because it damaged the islanders' crops. A large, flightless ground weevil *Hybomorphus melanosomus* may have become extinct before the arrival of ship rats (Olliff in Etheridge, 1889), but it was the arrival of ship rats in 1918 (Hutton, 1991) that caused the main wave of extinctions. These included five terrestrial birds: the vinous tinted thrush *Turdus poliocephalus vinitinctus*, the Lord Howe warbler *Gerygone insularis*, the Lord Howe fantail *Rhipidura cervina*, the robust silvereye *Zosterops strenua* and the Lord Howe starling *Aplonis fuscus hullianus*. The island subspecies of owl *Ninox novaezeelandiae undulata* persisted until the 1950s (Hutton, 1991).

Two invertebrate species no longer persist on the main island, but occur on offshore islets. The 12-cm-long phasmid *Dryococelus australis* vanished from the main island soon after the arrival of ship rats; however, 24 living animals were counted in 2001 on Ball's Pyramid (an islet 23 km from Lord Howe Island; Priddel *et al*., 2003). The cockroach *Panesthia lata* disappeared from the main island by the 1960s, but was found on Blackburn and Roach islands, and perhaps on other islets near Lord Howe Island (Rose, 2003). The earthworm *Pericryptodrilus nanus* is now restricted to sites on Mt Gower (Jamieson, 1977).

Of the remaining endemic biota, four land birds, two lizards, four invertebrates and five plant species are listed in either the Australian Commonwealth or the New South Wales threatened species legislation. A further nine seabirds are rare on the island but most of these species are common elsewhere (Hutton, 1991), and eight freshwater molluscs are classed as threatened under IUCN categories (Groombridge, 1993).

Exotic biota

A total of 230 exotic plant species is known from the island (Pickard, 1984; Anon., 2002*c*). Seventeen species of weeds are formally listed as 'noxious' on Lord Howe Island. The woody weeds cherry guava *Psidium cattleianum*, ochna *Ochna serrulata*, sweet pittosporum *Pittosporum undulatum* and bitou bush *Chrysanthemoides monilifera* are of most concern as they are spreading into the edges of the southern reserve from the settled area. A further 28 species represents potential problems (Anon., 2002*c*).

Twelve exotic vertebrates introduced with human assistance have formed wild or feral populations on the island. Barn owls *Tyto alba* and rabbits *Oryctolagus cuniculus* died out naturally (Etheridge, 1889; Hutton, 1991), while feral pigs *Sus scrofa* and feral cats *F. catus* were eradicated in the 1980s (Miller & Mullette, 1985). Of the remaining species (Table 1), feral goats were reduced to a few animals in a failed attempt at eradication (Parkes, Macdonald & Leaman, 2002). Rodents have been subjected to control strategies ranging from a bounty scheme and attempts at biocontrol with the introduction of Australian owls during the 1920s (Hindwood, 1940), to current use of warfarin baits in over 1000 bait stations largely to protect the islanders' palm seed industry (Billing, 2000). Eradication of the rodents is planned (Parkes *et al*., 2004).

In addition to these species, 10 birds are self-introduced and established. Of these, three European species (*Turdus merula*, *Turdus philomelos* and *Sturnus vulgaris*) can be classed as exotic while the rest are native to adjacent lands and arguably now part of the indigenous fauna of the island (Hutton, 1991).

Exotic invertebrates have been accidentally introduced to the island. Molluscs include six species of land snail, including the European snail *Helix aspersa*, which is common throughout the settlement and adjacent forested areas, and the leopard slug *Limax maximus*. At least 11 species of ants are thought to be introduced (I. Hutton, unpubl. data)

Table 1 Exotic vertebrates introduced by humans with current wild or feral populations on Lord Howe Island

Species	Date of arrival	Current status	References
House mouse *Mus musculus*	*c.* 1860	Widespread but particularly in the settlement area	Morton (1882)
Ship rat *Rattus rattus*	1918	Widespread	Billing (2000)
Feral goat *Capra hircus*	Early 1800s	Few left in 2004 after eradication attempt but may have died out	Parkes *et al.* (2002); I. Hutton, (pers. obs.)
Masked owl *Tyto novaehollandiae*	1918	Liberated as biocontrol for rats	Hutton (1991)
Peewee *Grallina cyanoleuca*	1924	Liberated but may also arrive naturally from Australia; widespread	Hutton (1991)
Eastern snake-necked turtle *Chelodona longicollis*	1960s	Pets liberated and still occasionally seen, but status unknown	I. Hutton (pers. obs.)
Rainbow skink *Lampropholis delicata*	*c.* 1995	Possibly arrived with cargo	Hutton (2003)
Bleating frog *Litoria dentata*	*c.* 1995	Possibly arrived with cargo	Hutton (2003)

although fortunately none are particularly invasive species. Three termite species that are potential pests are all probably introduced (Watson, 1989).

Restoring the native biota

There is a hierarchy of options that can be used in sequence or simultaneously to restore the native biota of islands, once the key threats are removed.

Recovery of extant species and habitats

The removal of feral pigs, feral goats and cats benefited many plants and animals that might otherwise have become threatened or extinct. Some species have recovered without further assistance. For example sooty terns *Sterna fuscata*, black-winged petrels *Pterodroma nigripennis* and red-tailed tropic birds *Phaethon rubricauda* have recolonized nesting areas and/or increased in numbers since the 1980s (Hutton, 1991).

Other species had reached such low numbers that extra management was required other than removal of their critical predators. The endemic woodhen *Gallirallus sylvestris* numbered only about 30 birds by the 1970s (Miller & Mullette, 1985). Removal of feral pigs and cats, plus the release of 93 captive-bred birds during the early 1980s allowed the population to increase from *c.* 30 birds in the 1970s to a population of between 250 and 300 birds in 2002 (NSW National Parks and Wildlife Service, 2002).

However, critical predators remain present for some extant species. All the small passerine birds, nesting seabirds, lizards, land snails and many other invertebrates would increase if rodents were eradicated. Similarly, rodents are not without impacts on plants, as their eradication on other islands has shown (Allen, Lee & Rance, 1994; Campbell & Atkinson, 2002); therefore removal of ship rats and mice from Lord Howe Island would undoubtedly change the abundance of seeds and seedlings with unknown flow-on effects. Some restoration of such species is possible even without pest eradication. As part of the recovery plan for the endemic snail *Placostylus bivaricosus,* a rodent- and bird-proof exclosure has been built and eight adult snails translocated into it to secure a breeding population (and learn something about the species' population dynamics) while the rodent eradication option is explored (Hutton, 2004).

Removal of feral goats from most (or perhaps all) of the island will have major effects on forest regeneration processes, for example, Parkes (2005), although this has not been formally monitored on Lord Howe Island. At a more local scale, habitat management, including weed and pest control, in representative and relict vegetation types is also required to protect some communities. For example, domestic cattle have been fenced out of relict swamp communities dominated by the tree *Lagunaria patersonia patersonia*, and the areas were planted with native species that were known to have been part of the original community (Auld & Hutton, 2004).

Natural recolonization of extirpated species

Some lost species, particularly seabirds, will naturally return to Lord Howe Island once the threats that originally eliminated them are removed. Black noddies *Anous minutus* and little shearwaters *Puffinus assimilis* have all been discovered breeding on the island (in 1989 and 1990, respectively) after cats were removed, the shearwaters after an absence of 150 years. The white swamp hen *Porphyrio alba* has been replaced naturally by its relative (and possibly conspecific) the purple swamp hen *Porphyrio porphyrio*.

Reintroduction of extirpated species

Other extirpated species will require more active intervention if they are to return to the island. Seabirds, such as the white-bellied storm petrel *Fregetta grallaria* and the Kermadec petrel *Pterodroma neglecta* that nested on the main island until at least 1914, could eventually recolonize the main island if rats were eradicated, although translocation of fledglings (Miskelly & Taylor, 2004) might be required to ensure (or hasten) this process.

The plant *S. australis* was lost from Lord Howe Island, but occurs elsewhere, for example, on Raoul Island and in

Table 2 Potential replacement taxa for extinct taxa on Lord Howe Island

Extinct taxa	Cause of extinction	Possible replacement species	From where?
Solanum bauerianum	Fruit and seed predation by rodents	*Solanum viride*	'viride' group widespread in Pacific and cultivated in Cook Islands
Columba vitiensis godmanae	Human hunting	*C. vitiensis godmanae* many sub-species	Many Pacific islands,? New Caledonia
Cyanoramphus novaezelandiae subflavescens	Controlled as pest + predation	*Cyanoramphus novaezelandiae cooki*	Norfolk Island
Turdus poliocephalus vinitinctus	Predation	*Turdus poliocephalus xanthopus*	New Caledonia, Fiji, Sunda?
Gerygone insularis	Predation	*Gerygone modesta*	Norfolk Island
Rhipidura fuliginosa cervina	Predation	*Rhipidura fuliginosa pelzilni*	Norfolk Island
Zosterops strenua	Predation	*Zosterops lateralis*	Norfolk Island, Australia
Aplonis fuscus hullianus	Predation	*Aplonis tabuensis*	Samoa
		A. metallica	Australia
Ninox novaezelandiae albaria	Competition?	*Ninox novaezelandiae undulata* hybrids	Norfolk Island

Australia, and could be reintroduced. The extirpated phasmid and cockroach could be reintroduced from the adjacent islets, via a captive breeding programme, if rodents are eradicated. *Solanum bauerianum* is extinct, but it is possible that viable seeds might be found in herbarium collections and the species returned.

Replacement of extinct taxa

Of the 11 species or subspecies of plants and animals known to have become extinct since human settlement, all but the lost ground weevil could be replaced with related taxa (Table 2).

We suggest a hierarchy of decisions on surrogate taxa based on the taxonomic relatedness of the candidates for reintroduction: the same species before subspecies before genera, with functional replacement being a further filter on candidates that are not the same species. In our opinion, taxa with functional equivalence but without taxonomic relatedness would not be acceptable candidates for reintroduction. In summary, for Lord Howe Island all the extirpated taxa could be replaced by definition, five extinct taxa could be replaced by subspecies, and four by congenerics.

Discussion

The ability to replace these extinct taxa does not mean it should be done; it would be wise to apply some rules before approving each candidate. The primary rule would be to at least do no harm with the reintroduction. There are two ways in which a reintroduction might cause harm – harm to the source population or harm to other species at the reintroduction site. The size and status of the source population would obviously have to be sufficient to 'harvest' enough individuals to form a founder population or, if not, to form the nucleus of a captive breeding population. Harm to other species at the reintroduction site might be direct if parasites or pathogens were inadvertently introduced with the reintroduced taxa, but this is manageable using standard quarantine procedures (Jackson, Morris & Boardman, 2000).

Reintroduced biota might also cause harm if they affect surviving resident species. Lord Howe Island had two species of *Zosterops* representing two colonization events by the putative ancestor *Zosterops lateralis*. The older species *Zosterops strenua* became extinct, but the more recent *Zosterops tephropleura* did not. The question is whether managers should consider reintroducing *Z. lateralis*, or even one of the endemic Norfolk Island species *Zosterops tenuirostris* or *Zosterops albogularis*, and risk competition with *Z. tephropleura*. *Zosterops* is known for interarchipelagal speciation (Diamond, 1977) and Norfolk Island has three sympatric species (the above two plus *Z. lateralis* since 1904); therefore, in this case an option might be to do nothing and let evolution take its course.

Managers also have to consider the order in which species might be reintroduced to improve the chance of success (Duncan & Forsyth, 2005) with minimal adverse consequences on extant species. They could consider the potential for competition (and predation) between the reintroduced species and extant native and exotic species, and between reintroduced species. For example, as a constraint among the Lord Howe candidate birds, the reestablishment of *T. poliocephalus* might be compromised by the presence of competition from the self-introduced exotics *T. merula* and *T. philomelos*. This competition might be overcome by introducing a large number of *T. poliocephalus* and/or some control to the exotic congenerics.

In contrast, the absence of an arboreal large frugivorous bird among the extant avifauna (native and exotic) might mean that a reintroduction of a subspecies of the pigeon *C. vitiensis* would succeed more easily, and reestablish the ecosystem services of fruit dispersal that the original bird is likely to have provided.

Finally, as Lawton (1997) has noted, conservation is as much a social science as a biological science, and there are social, aesthetic and legal issues that have to be considered. For island biodiversity managers, this is increasingly the case as they move their attention from uninhabited to inhabited islands (e.g. see most of the projects in the Pacific Invasives Initiative on www.issg.org/cii/PII/demo). On Lord Howe Island people killed parakeets as pests of their fruit crops; hence they may be reluctant to bring them back. The lost plant, *S. australis*, could easily be returned, but it is seen as a weed in other places and its spiny fruit capsule is a nuisance to people. Lord Howe Island is also a World Heritage Site and as such represents a case where management options will need to consider legal constraints. For example, it is interesting that the operational guidelines for assessing World Heritage Sites do not contain any clauses that specifically allow for active reintroduction of species within the general goals for *in situ* conservation (www.WHC-05/29.COM/INF.9A). Australian federal government legislation also imposes potential constraints on the prerequisite rodent eradication methods by insisting that no individuals of listed threatened species can be deliberately put at risk.

An extreme option for restoration management is to introduce exotic species as functional replacements for lost native species. This has been suggested where the lost natives are keystone or ecosystem engineer species and where no closely related species are extant (Atkinson, 1988; Donlan *et al.*, 2005). We can think of no reason to do this on Lord Howe Island and suspect it is politically unacceptable elsewhere.

Returning extirpated species or replacing extinct ones with relatives or even functional surrogates is currently largely practised on islands (Steadman & Martin, 2003). However, the lessons learnt from islands will be increasingly important on continents when the rates at which species' environmental envelops shift under climate change more quickly than species, particularly sedentary ones, can disperse (Sinclair & Byrom, 2006).

In conclusion, we think the trend towards a site-based management paradigm for islands will grow. This is being reinforced globally by the March 2006 adoption of an island biodiversity programme under the Convention on Biological Diversity, regionally as under the current partnership to manage invasive species in the Pacific Ocean (the Pacific Invasives Initiative) and nationally with current reviews by Britain and France of their island territories and the recent listing by the Australian Government of rodents as a key threatening process on Australian islands – with Lord Howe Island at the fore of their action list.

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