What Role Does Ecological Research Play in Managing Biodiversity in Protected Areas? Australia's Oldest National Park as a Case Study

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How we manage National Parks (protected areas or reserves) for their biodiversity is an issue of current debate. At the centre of this issue is the role of ecological research and its ability to guide reserve management. One may assume that ecological science has sufficient theory and empirical evidence to offer a prescription of how reserves should be managed. I use Royal National Park (Royal NP) as a case study to examine how ecological science should be used to inform biodiversity conservation. Ecological research relating to reserve management can be: i) of generic application to reserve management, ii) specific to the reserve in which it is conducted, and iii) conducted elsewhere but be of relevance due to the circumstances (e.g. species) of another reserve. I outline how such research can be used to inform management actions within Royal NP. I also highlight three big challenges for biodiversity management in Royal NP: i) habitat connectivity, ii) habitat degradation and iii) fire management. A key issue for local managers is finding a mechanism to enable their management to be informed by ecological research in their Park in an ongoing way and to be able to encourage further research. If resolved, Royal NP could provide a model to be used by other protected areas.

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INTRODUCTION

National Parks and Nature Reserves (protected areas) may be established for a variety of reasons such as to protect areas of visual beauty, to protect individual species, to protect geological values, or to protect cultural sites. However, the primary role that many now have is to protect and conserve biodiversity. Indeed, biodiversity values have been the driving force in new designations of protected areas in the last 15 years, and there has been much debate about whether the areas designated have been appropriately located with respect to sampling biodiversity (e.g. Pressey et al. 2002; Grantham et al. 2010). This has led to a focus on what is contained within the boundaries of protected areas (e.g. Pressey 1994; Kharouba and Kerr 2010) but little focus on how those areas are managed to retain their biodiversity once established.

The issue of how reserves are managed is a vexed one (Chapple et al. 2011). All reserves have competing interests for their management resources, and in many cases managing people in a reserve becomes the primary focus of reserve management. Fire management can also become an issue of immense importance that consumes a lot of time of reserve managers. But this leaves the question of how is biodiversity managed? Is management actively informed by ecological science or take place by benign neglect (*sensu* Soule et al. 1979), relying simply on protection within a reserve where human access or impacts may be controlled. One may assume that ecological science can offer a prescription for how to manage reserves, but this needs to be tested by examination of current reserve management.

One fundamental insight provided by ecological science is that reserve area is a primary determinant

of the persistence of species within reserves (e.g. Newmark 1995; Gurd et al. 2001). Furthermore, that the persistence of species will be greatly influenced by the combined area of habitats within and surrounding reserves (Wiersma et al. 2004). This highlights two key points. Firstly, that many reserves may not be fully isolated but may become so over time. Consequently, they can expect to lose species (Kitchener et al. 1980a; Newmark 1987). Secondly, every effort should be made to expand reserves or to provide connectivity with other reserves (e.g. Gurd et al. 2001). Thus, the equilibrium theory of island biogeography (MacArthur and Wilson 1967) can be used to guide reserve management at the largest spatial scale. But reserve management should be informed by other findings of ecological science.

Over the last decade there has been a focus on assessing the effectiveness of how protected areas are being managed (e.g. Hockings 2003; Hockings et al. 2009). However, these assessments are largely confined to the management processes themselves. Indeed, Hockings et al. (2004) stated that an assessment of the effectiveness of management should consider "design/planning issues, adequacy and appropriateness of management resources, systems and processes, and delivery of protected area objectives". Whilst this approach has obvious merit and is well suited to evaluation across large protected area networks and where large numbers of reserves are included (e.g. Hockings et al. 2009), it may fail to produce better outcomes in biodiversity conservation. Consequently, there is growing recognition that there must be a focus on measuring the ecological effectiveness or performance of reserves and a need for case studies that address the issue (Gaston et al. 2006, 2008). A key element to achieve ecological effectiveness is the extent to which ecological research is being used and encouraged to improve reserve management.

Within Australia there has been limited attention in the published literature given to the ecological effectiveness of reserves and the use of research findings to achieve ecological effectiveness. In this paper I use Royal National Park, Australia's oldest National Park, as a case study. My reasoning for this choice is that a reserve that has been established for a long period of time should have an established approach to managing biodiversity and there should be a record of the adequacy of that management. I ask two questions: how is biodiversity being managed within Royal National Park and what role does ecological research play? I focus on native vertebrate wildlife because this element of biodiversity should be well described and readily targeted by management.

BRIEF OVERVIEW OF ROYAL NATIONAL PARK

Royal National Park (hereafter Royal NP) is located 24 km south-west of the Sydney CBD. It is approximately 15,000 ha in area and defines the southern boundary of the Sydney metropolitan area. Its eastern boundary is the coastline, while its western boundary is the Princess Hwy, the F6 Freeway and associated urban development (Figs 1, 2). It is bounded to the north by urban development and Port Hacking. Its southern boundary is Garawarra State Conservation Area (SCA) (formerly a State Recreation Area) (900 ha) and south of that is the town of Helensburg. Immediately adjacent to Royal NP on the western side of the Princes Hwy is Heathcote NP (2250 ha). Royal NP was declared by legislation in 1879, while Heathcote NP was reserved in 1943 and Garawarra SCA in 1987 (NPWS 2000).

There are 347 species of vertebrate wildlife known to occur in or visit Royal NP, Heathcote NP and Garawarra SCA (DECCW 2011). Of these, 38 species are listed by the New South Wales *Threatened Species Conservation Act* 1995 and six are listed by the Australian *Environmental Protection & Assessment Act* 1999. Thus, these reserves and Royal NP in particular, have an important role to play in the conservation of vertebrate wildlife in New South Wales (NSW).

HOW ARE RESERVES FORMALLY MANAGED IN NEW SOUTH WALES?

To examine the management of biodiversity in Royal NP requires an understanding of the statutory requirements for management. National Parks and State Conservation Areas are managed in accordance with a Plan of Management as required by the *National Parks and Wildlife Act* 1974. This is a legal document that describes how these areas are to be managed and which prevents operations taking place that are not specified by the Plan (NPWS 2000).

The Plan of Management relating to Royal NP also includes Heathcote NP and Garawarra SCA (NPWS 2000). It describes the following general objectives for managing National Parks in NSW:

- "the protection and preservation of scenic and natural features;
- the conservation of wildlife and natural biodiversity;
- the maintenance of natural processes as far as is possible;

Figure 1. Urban development around Heathcote and Engadine separate Royal National Park from Heathcote National Park in the north-west.

Figure 2. Royal National Park is divided from Heathcote National Park for much of its western boundary by the Southern Freeway. The bridge over the freeway for Cawley Creek Rd (a management road) could be partially converted to a wildlife land-bridge.

- the preservation of Aboriginal sites and historic features;
- the provision of appropriate recreation opportunities; and
- the encouragement of scientific and educational enquiry into environmental features and processes, prehistoric and historic features and park use patterns".

The Plan of Management (NPWS 2000) also lists the following specific management objectives for Royal NP, Heathcote NP and Garawarra SCA, in relation to conserving biodiversity:

- "Royal National Park will be used as a primary venue within the southern Sydney Metropolitan area for the promotion of natural and cultural heritage conservation in NSW generally and for promoting the work of the Service.
- The protection and where necessary restoration of nature conservation values within Royal National Park, Heathcote National Park and Garawarra State Recreation Area as part of the system of parks and other protected lands of the Woronora Ramp within the Sydney Basin, with emphasis on the protection of biodiversity and maintenance of the ecological relationships between the reserves and adjacent natural lands.
- Garawarra State Recreation Area will be managed as an extension of Royal National Park for the protection of its nature conservation values."

Both the general and specific objectives make it clear that natural heritage conservation is fundamental to Royal NP while the specific objectives introduce the idea of the restoration of nature conservation values. The Plan of Management (NPWS 2000) describes the following policies in relation to the conservation of native animals:

- "Habitats will be protected to maintain the diversity of animal species.
- Research into the life history and habitat requirements of key species will continue to be encouraged.
- Habitats of species subject to international treaty agreements will be protected from disturbance."

A single action relating to native animals is described to satisfy these policies, namely: "fauna surveys will be carried out in the three areas, with priority on threatened or restricted species, including bats and herpetofauna."

The Plan of Management also describes the kind of use of the Park that is deemed appropriate. Research is one form of use and it is recognised that "The purpose of scientific study in the park is to improve the understanding of its natural and cultural heritage and the processes which affect them. Research will also establish the requirements for the management of particular species. Data and findings from research studies and surveys will be utilised in Park management." Examination of the Plans of Management for several other Parks in NSW (e.g. NPWS 1997, 2002a, 2003) reveals that, broadly speaking, these plans are generic with some local details. All of these plans place a strong reliance on encouraging research, particularly that relating to Park management, but the Royal plan is the only one that makes an explicit statement of an intention to use research findings to inform the management of the Park. It is also the only one that refers to the "restoration of nature conservation values".

TYPES OF ECOLOGICAL RESEARCH RELEVANT TO RESERVE MANAGEMENT

Ecological research relating to reserve management can fall into one of three categories: i) that of generic application to reserve management, ii) that which is specific to the reserve in which it is conducted, and iii) that conducted elsewhere but which is of relevance to another reserve due to the circumstances (e.g. species) of that reserve. I will review each of these categories.

Ecological research of generic application to reserve management

Ecological research can be very broad and cover a diversity of topics. I briefly review three topics here to make the point that reserve management can be guided by many areas of ecological research and can benefit from the many generalisations that arise from such research. That research does not need to be in the context of reserve management. The key point here is that the management of a specific reserve does not depend on only the research conducted within that reserve.

The Theory of Island Biogeography – The Theory of Island Biogeography postulates that the number of species on islands is in equilibrium between the rate of colonisation and extinction of species (MacArthur and Wilson 1967). For any given island these rates will be influenced by island area and distance to a

mainland. Extinction rates will be higher on small compared to large islands, while colonisation by new species will be more rapid on islands near as opposed to far from a mainland. Diamond (1975) subsequently recognised that the theory could be used to account for the number of species found in nature reserves and postulated some reserve design principles, including the notion of using corridors to connect reserves, which may enhance rates of colonisation and therefore minimise the loss of species. Although some authors highlight the limitations of the theory of island biogeography when applied to habitat fragmentation, there is agreement that the theory provides some important guiding principles such as the influence of fragment area and isolation on species richness (e.g. Laurance 2008). Thus, reserve managers should aim to limit habitat fragmentation within their reserves, as well as attempt to expand the area of their reserves and to connect their reserves to other reserves where feasible. A key realisation from the theory is that the reserve is unlikely to be in equilibrium and will lose species over time (e.g. Kitchener et al. 1980a,b; Soule et al. 1988). Combining reserves into larger assemblages by connecting corridors may be the most efficient means of preventing this loss (e.g. Gurd et al. 2001).

Fire ecology – fire management will be a key issue in most reserves. For Royal NP, 95% of the reserve was burnt by wildfire in January 1994 (Whelan et al. 1996; Andrew 2001) and ca. 60% of the reserve burnt again in 2001. The initial impact of such wildfires can be devastating for some wildlife (Whelan et al. 1996; Baker et al. 2010) but the actual longer term impact on populations is less well understood (e.g. Banks et al. 2011). Despite several decades of research on this topic in Australia there remain many gaps in knowledge (Driscoll et al. 2010). These gaps relate to the response of many species to fire, the influence of the spatio-temporal sequence of fire on species and how other biological factors (e.g. predation) interact with fire to determine ultimate population response. The greater glider (*Petauroides volans*) provides an example of this within Royal NP. Prior to the 1994 fire it was reasonably common in the tall forests at the southern end of the Park (Keast 1995; Andrew 2001). It was detected once immediately after the 1994 fire but was not seen again until March 2012 (Andrew 2001; Maloney 2007; DECCW 2011). It is possible it suffered a local extinction event following the 1994 fire. This provokes the question whether wildfire within Royal NP may trigger population collapses of other species.

Prescribed burning of the landscape may reduce the extent of wildfires but the ecological benefits that may be associated with fire mosaics are yet to be demonstrated, requiring more research to guide biodiversity management (Bradstock et al. 2005; Baker et al. 2010; Penman et al. 2011). However, a precautionary approach should be adopted to minimise population loss so a more active approach to fire management in Royal NP is required to prevent a repeat of the 1994 fire event (see below).

Road ecology – this topic is of particular relevance to reserve management because roads are often extensive within Parks. Roads may create partial or complete barriers to the movement of wildlife and produce high numbers of road-kill. Taylor and Goldingay (2010) recently reviewed this topic, highlighting gaps in knowledge as well as the current understanding about how road impacts may be mitigated. Several studies have been conducted on this topic in Royal NP (see below), which suggest that road-kill is a key management issue requiring attention. For other reserves, individual studies are not required to highlight road mortality as a management issue. Sufficient studies have been done at many locations to be able to conclude that roads through native habitats will produce road mortalities.

Ecological research of specific relevance to the reserve in which it is conducted

I conducted a literature search to identify papers published since 1995 that describe research in Royal NP on vertebrate wildlife. I searched *Scopus* and the *Web of Science* databases using keywords such as Royal National Park and the name of some of the key species found in the Park. I also checked the reference lists of any papers obtained. Although there are many unpublished theses that describe research conducted in Royal NP, these are more difficult to reliably search for and may have less influence on management because they are unpublished.

This search revealed 10 papers and two published agency reports. The reports described wildlife surveys conducted throughout Royal NP while the papers described studies on a small number of species; the broad-headed snake (*Hoplocephalus bungaroides*), eastern pygmy-possum (*Cercartetus nanus*), sooty owl (*Tyto tenebricosa*), swamp wallaby (*Wallabia bicolor*) and brown antechinus (*Antechinus stuartii*) (Table 1). These species-based studies can be organised into various broad management issues. Those on the endangered broad-headed snake deal with threatened species management as well as habitat degradation. Those that provide direct management recommendations include those that document road fatalities in Royal NP and those that describe impacts to the habitat of the broad-headed snake. To reduce

Table 1. Studies published since 1995 on vertebrate wildlife in Royal NP.

Management issue	Topic	Reference
Threatened species management	Broad-headed snake genetics	Sumner et al. (2010)
	Eastern pygmy-possum response to food availability	Tulloch and Dickman (2007)
	Sooty owl diet	Bilney et al. (2007)
	Sooty owl movements	Kavanagh and Jackson (1997)
	Broad-headed snake regional surveys	Shine et al. (1998)
Fire response	Eastern pygmy-possum habitat use	Tulloch and Dickman (2006)
	Fire ecology of small mammals	Whelan et al. (1996)
Road impacts	Swamp wallaby road kills	Ramp and Ben-Ami (2006)
	Wildlife road kills	Ramp et al. (2006)
Habitat degradation	Broad-headed snake regional habitat	Newell and Goldingay (2005)
	Broad-headed snake habitat degradation	Goldingay and Newell (2000)
	Broad-headed snake	Goldingay (1998)
Various issues	Vertebrate survey	DECCW (2011)
	Vertebrate survey	Andrew (2001)

road fatalities, it was suggested that speed reduction should occur at fatality hotspots, that exclusion fencing and underpasses should be trialed and there was a need to educate Park users (Ramp and Ben-Ami 2006; Ramp et al. 2006). None of these suggestions has been adopted and the recent wildlife survey of the Park (DECCW 2011) has highlighted that several threatened species, including the eastern pygmy-possum and the heath monitor (*Varanus rosenbergi*), may be severely impacted by road-kill. Studies on the loose rock habitat of the broad-headed snake have highlighted on-going degradation of this habitat by Park users, the need for habitat restoration, as well as the education of Park users and closure of walking tracks (Goldingay 1998; Goldingay and Newell 2000; Newell and Goldingay 2005). Minimal adoption of these recommendations has occurred; research into the education of Park users has been initiated (Hayes and Goldingay 2012) and some further research into habitat restoration has occurred (Goldingay and Hayes, unpublished). Exclusion fencing has been installed behind Heathcote Oval to restrict access by mountain bikes and to the habitat of the broad-headed snake.

Ecological research of specific relevance but conducted elsewhere

Research conducted in other reserves may be of direct relevance to management because it involves key species found in Royal NP or a specific issue of relevance to management in Royal NP. The key species may be threatened species or other species that have been identified as significant within Royal NP. This could include studies conducted at almost any location where these species occur but I illustrate this point by referring to a select number of studies. It is beyond the scope of this review to cover more than a few species.

Of the threatened species occurring in Royal NP, the broad-headed snake is one whose conservation has important implications for Park management. The studies conducted in Royal NP have established that rock habitat degradation is continuing and must be addressed (Goldingay 1998; Goldingay and Newell 2000). This species has been studied in detail in Morton NP, establishing many aspects of its ecology (Table 2). These studies are of direct relevance to understanding aspects of how the broad-headed snake should be managed in Royal NP. Regional surveys of the broad-headed snake and its rock habitat (Shine et al. 1998; Newell and Goldingay 2005) have demonstrated that rock habitat degradation is not restricted to Royal NP but occurs in all Parks examined. Indeed, a study conducted in Gibraltar Range NP in northern NSW (Goldingay and Newell 2006) found that rock habitat disturbance also occurs where the underlying geology is granite. The apparent ubiquity of this management issue for rock habitats suggests that Royal NP could provide an exemplar for other Parks of how it is addressed.

A number of studies have been conducted on three threatened species that are believed to be extinct

Table 2. Studies published since 1995 on selected vertebrate wildlife species and topics relevant to Royal NP

Management issue	Topic	Reference
Threatened species management	Eastern bristlebird genetics	Roberts et al. (2011)
	Population ecology of long-nosed potoroo	Norton et al. (2010a)
	Habitat of long-nosed potoroo	Norton et al. (2010b)
	Eastern pygmy-possum detection	Harris and Goldingay (2005)
	Broad-headed snake ecology	Webb and Shine (1997a,b, 1998)
	Broad-headed snake habitat restoration	Webb and Shine (2000)
	Broad-headed snake poaching	Webb et al. (2002)
	Broad-headed snake and climate change	Penman et al. (2010)
	Bristlebird translocations	Baker (2009)
	Bristlebird translocations	Bain and French (2009)
Road impacts	Mitigating road impacts on ground-dwelling wildlife	Taylor and Goldingay (2003)
	Mitigating road impacts on gliding mammals	Goldingay et al. (2011)
	Mitigating road impacts on arboreal mammals	Weston et al. (2011)
Fire response	Ground parrots and fire	Baker et al. (2010)
	Eastern bristlebird and fire	Baker (2000)
	Eastern bristlebird and fire	Baker (1997)
Habitat degradation	Rock habitat in Gibraltar Range NP	Goldingay and Newell 2006

within Royal NP: the eastern bristlebird (*Dasyornis brachypterus*); eastern ground parrot (*Pezoporus wallicus*); long-nosed potoroo (*Potorous tridactylus*) (Table 2). These studies have relevance if management decides to reintroduce these species (see below) because they were conducted at Barren Grounds Nature Reserve, the nearest location to Royal NP (ca. 60 km south-west) where established populations of these species still occur. These studies may also help to understand why these species were lost from Royal NP and may provide insight to prevent the loss of some other species. The studies of the eastern bristlebird and eastern ground parrot have addressed fire management which also has direct relevance to management in Royal NP.

Another key threatened species is the eastern pygmy-possum. Studies in Royal NP (Andrew 2001; Tulloch and Dickman 2006; Harris 2010; DECCW 2011) have revealed that this species is relatively abundant and that it should feature in deliberations of how biodiversity in Royal NP is managed. Insights from studies at Barren Grounds Nature Reserve (Harris and Goldingay 2005; Harris 2010) have relevance to this.

Road impacts on wildlife are now a major issue for wildlife management (Taylor and Goldingay 2010). The key elements of this topic, such as the likely impacts on species and how impacts should be mitigated, are relatively well known. Several studies have investigated the potential effectiveness of various kinds of impact mitigation (Table 2). The mitigation measures adopted in Royal NP will depend on their cost. Strategic road closures (e.g. seasonal night-time closure between McKell Ave and Bundeena Dr) may be one measure that has not been considered previously. Road impacts and how they are addressed are also of relevance to maintaining movement of wildlife between Heathcote and Royal NP across major roads (see below).

THREE BIG MANAGEMENT CHALLENGES FOR ROYAL NP

There are of course many management issues to be addressed to manage biodiversity in Royal NP. The three biggest issues that must be confronted without delay because they will take several years to resolve are: i) habitat connectivity, ii) habitat degradation and iii) fire management.

Royal NP exists as something of an island surrounded by boundaries that operate as filters to the movement of wildlife in and out. Although Heathcote NP extends along the western side of

Royal NP, the western boundary is the 4-lane wide Princes Hwy, which divides into the F6 Freeway (Fig. 2) about two-thirds of the way south along the western boundary. The Princes Hwy creates a break in habitat of at least 30 m width whilst the F6 Freeway (Southern Freeway) creates a break of at least 40 m. The Illawarra railway line follows the Princes Hwy and creates a break in habitat of at least 25 m. Where the highway splits from the freeway, the railway moves east of the highway but still creates a break in habitat of ca. 20 m along its length. These breaks in habitat will create barriers to the movement of some but not all species. Thus, it is likely that Royal NP is isolated for many small ground-dwelling species and arboreal mammal species.

The challenge here is to devise an effective management response. A recent approach to help breach road barriers is the installation of wildlife land-bridges (Bond and Jones 2008; Hayes and Goldingay 2009). These are very expensive structures (~$2 million), which is likely to prevent their installation when needed. However, there is an existing road-bridge linking between Royal NP and Heathcote NP that was built over the Southern Freeway to carry Cawley Creek Rd when the freeway was constructed (Fig. 2). This is a gated maintenance road that appears to receive little use and could be modified to make it more attractive for use by wildlife. Glide poles (Goldingay et al. 2011) and rope bridges (Weston et al. 2011) could be installed on the bridge to enable arboreal mammals to cross, or these could be installed elsewhere along the freeway. Some tree-dependent arboreal mammals can become genetically isolated when tree cover is lost (see Taylor et al. 2011). Approximately 3 km south of the Cawley Creek Rd bridge, the Princess Hwy passes under the Southern Freeway (Fig. 3). Although the highway forms something of a barrier (8-12-m wide at this point) the road underpass may provide some opportunity for species to cross under the 40-m wide freeway. This crossing point could be modified to be more attractive for wildlife to cross.

Royal NP contains a population of the broad-headed snake, Australia's most endangered snake. During the cooler months of the year this snake shelters under loose rocks in rocky habitat (Webb and Shine 1997a,b, 1998). This specialisation makes this species vulnerable to the loss in availability or quality of these shelter sites. Within Royal NP, damage to rock outcrops is on-going and is caused by hikers as well as reptile poachers (Goldingay and Newell 2000; Newell and Goldingay 2005). The impacts of this disturbance are not confined to the broad-headed snake because many species are associated with rocks in rock outcrops (Newell and Goldingay 2005; Goldingay and Newell 2006). This form of

Figure 3. The location where the Princess Hwy passes under the Southern Freeway could be enhanced to facilitate occasional movement by wildlife.

habitat degradation needs to be addressed by Park management to reduce its impact.

Wildfires burnt >50% of Royal NP in each of 1968/69, 1988/89, 1994 and 2001 (NPWS 2002b). The 1994 fire in particular, burnt 95% of the Park and was of high intensity (Whelan et al. 1996). In most cases wildfire is not likely to lead to the loss of species. However, the ability for wildlife populations to persist following a wildfire will depend on their ability to survive the passage of the fire, the availability of unburnt habitat, the ability of the post-fire environment to sustain the population and the availability of a source of recruits to the burnt landscape (Whelan et al. 1996; Bain et al. 2008; Bradstock 2008; Lindenmayer et al. 2008; Taylor and Goldingay 2009; Baker et al. 2010; Banks et al. 2010). Because Royal NP is something of a habitat island for some species (see above), a wildfire that burns a majority of the Park may have a severe impact on the populations of some species. For example, the 1994 fire appears to have triggered a collapse of the population of the greater glider in Royal NP (see Andrew 2001; Maloney 2007). Thus, a precautionary approach to managing biodiversity in the context of fire is to manage the Park to minimise the probability of extensive wildfires. Although the notion of a mosaic of fire ages being favourable to wildlife has been questioned (Bradstock et al. 2005), the goal for Royal NP should be to prevent extensive wildfire and to ensure the availability of unburnt refuges to enable recolonisation when fires occur.

The fire management plan for Royal NP (NPWS 2002b) includes among its strategies "determining and implementing appropriate fire regimes to maintain biodiversity to prevent species or communities becoming extinct and to protect specific natural assets; assessing environmental impacts prior to undertaking fire management works; and monitoring vegetation regeneration following fire events". The main performance indicator that relates to this is: "There is no significant decline of species' populations (common or endangered) due to inappropriate fire regimes, suppression activities or other fire management works, during the planning period". A fire management strategy was produced in 2009 (DECC 2009). This identifies fire management zones and fire thresholds of the vegetation (whether mapped areas should be protected from or allowed to burn) and provides operational guidelines. It also documents the locations of records of threatened species and lists actions to be avoided for these locations (e.g. avoid burning around nest trees).

Research within Royal NP is needed to address the above strategies and the specified performance indicator in the fire management plan. A focus must be placed on vertebrate wildlife to understand how they respond to wildfire. A small number of species should be selected and research commenced before another wildfire occurs. The species I see as most relevant here are three threatened species, the eastern pygmy-possum, broad-headed snake and red-crowned toadlet (*Pseudophryne australis*), and the non-listed rockwarbler (*Origma solitaria*). This covers all vertebrate classes and focuses on Sydney basin endemics. The eastern pygmy-possum is not restricted to the Sydney basin but its population in Royal NP is one of the most significant in NSW (Bowen and Goldingay 2000; Harris 2010). Comprehensive surveys in Royal NP that target this species, with an emphasis on methods of detection, have already occurred (Tulloch and Dickman 2006; Harris 2010; Rueegger 2011), enabling future studies of fire response. Likewise the broad-headed snake has been studied over many years in Royal NP (Goldingay 1998; Goldingay and Newell 2000, unpubl. data; Hayes 2010), with a large number of survey sites established that could be resurveyed in the context of a fire. The red-crowned toadlet and the rockwarbler have not been the subject of specific studies in Royal NP but are widespread (DECCW 2011) and surveys could be readily established.

THE LOCAL EXTINCTION OF SPECIES WITHIN ROYAL NP

Although not considered a management challenge requiring immediate attention, the loss of species from Royal NP does require consideration. Indeed, a specific management objective for Royal NP, Heathcote NP and Garawarra SCA is the "protection and where necessary restoration of nature conservation values" (NPWS 2000). This could be taken to mean that management must consider restoring species that suffer local extinction.

So what consideration should be given to a documented local extinction in a reserve such as Royal NP? Should these losses be accepted and conservation efforts focussed only on remaining species? Or should there be an attempt to reverse these losses, as a part of "necessary restoration". One perspective is that restoration may provide new insight that can guide future management of other vulnerable species in NSW. Trying to understand why those species have become locally extinct in itself may provide fundamental insight for future management of biodiversity within Royal NP and other reserves.

Table 3. Species recorded in Royal NP and which are now extinct and presumed extinct. This list is taken from DECCW (2011) and using information in Baker (1997) and Andrew (2001).

Status	Species	Last record
Extinct on mainland	Eastern quoll (*Dasyurus viverrinus*)	Date not available
Locally extinct	Eastern bristlebird (*Dasyornis brachypterus*)	1880
	Eastern ground parrot (*Pezoporus wallicus*)	1923
	Bushstone curlew (*Burhinus grallarius*)	1938
	Regent bowerbird (*Sericulus chrysocephalus*)	1920s
	Parma wallaby (Macropus parma)	1920s
	Long-nosed potoroo (*Potorous tridactylus*)	1970s
Presumed extinct	Green and golden bell frog (*Litoria aurea*)	1980
	Stuttering frog (*Mixophyes balbus*)	1994
	Dusky antechinus (*Antechinus swainsonii*)	1974
	Red-necked pademelon (*Thylogale thetis*)	1980s
	Spotted-tailed quoll (*Dasyurus maculata*)	1970s
	Platypus (*Ornithorhynchus anatinus*)	1970s
	Water rat (*Hydromys chrysogaster*)	1964

A comprehensive inventory and survey of vertebrate wildlife in Royal NP (and adjoining reserves) is described by DECCW (2011). This study has sifted through the various species records and produced a list of species that have become or are presumed to be locally extinct (Table 3). I will focus on two species: the green and golden bell frog (*Litoria aurea*) and the ground parrot. Each is still present within the region and extensive areas of suitable habitat remain in Royal NP. I believe there is value in attempting reintroductions of some species and treating these as part of an adaptive management process in which such intervention is used as a learning exercise that provides management insight that can benefit future management of those species (see Goldingay 2008).

Green and golden bell frog

This species was known from Jibbon and Marley Lagoons in Royal NP but has not been detected since 1980 (White and Pyke 1996; DECCW 2011). It is still present on the Kurnell Peninsula (White and Pyke 2008), approximately 6 km away. It has undergone a major contraction in geographic range since the 1970s and is still in decline (White and Pyke 2008a; Goldingay and Lewis 1999). The primary causes implicated in its decline are habitat loss, introduced fish (gambusia) and chytrid fungus (Goldingay 2008). Jibbon (Fig. 4) and Marley Lagoons still offer largely undisturbed breeding habitats that appear to be unaffected by gambusia (Goldingay pers. obs.). The continuing loss of populations suggests that re-introduction to locations such as Royal NP should be included in any long-term recovery plan for the green and golden bell frog. Re-establishment within a National Park has merit because few populations of this species occur within such protected areas (White and Pyke 2008a). Furthermore, bell frog populations immediately south in the Illawarra are far from secure (Goldingay and Lewis 1999; Goldingay 2008). The green and golden bell frog has been the subject of four attempted translocations but all have failed (Daly et al. 2008; Pyke et al. 2008; Stockwell et al. 2008; White and Pyke 2008b). Many lessons were learnt from the failure of these earlier translocations. The population at Kurnell could provide a source of tadpoles for translocation. The persistence of the Kurnell population may suggest that either the waterbodies are sufficiently saline to reduce the virulence of the chytrid fungus or that individuals within this population show some natural immunity.

Eastern ground parrot

The last confirmed record within Royal NP was in 1923, though an unconfirmed record exists from 1996 (DECCW 2011). Heathland, the habitat of this species, occupies >20% of Royal NP (DECCW 2011) so there are extensive areas of apparently suitable habitat. The nearest population of the ground parrot occurs at Barren Grounds Nature Reserve and the adjacent Budderoo NP (Baker et al. 2010), approximately 60 km away, though there are single recent records from the nearby Woronora Special Area and at Malabar (DECCW 2011). The next

Figure 4. Jibbon Lagoon offers undisturbed habitat for various species. This is a former location of the green and golden bell frog.

population north occurs on the NSW central coast. This species is of regional conservation significance and due to the extensive heathland areas within Royal NP, should feature in deliberations of managing vertebrate wildlife within the Park. This will require extensive surveys to determine whether the ground parrot does occur within Royal NP. If these are unable to detect the species from a concerted survey effort then a program of reintroduction should be devised.

THE NEAR EXTINCTION OF THE GREATER GLIDER

The greater glider is a large (900-1700 g), gliding folivorous marsupial, which is widely distributed in eastern Australia, from north Queensland to western Victoria. Its presence in Royal was well documented prior to the wildfire in 1994 (Andrew 2001; Malony 2007). A single observation of this species was made approximately one month after the fire but until 20 March 2012 none were seen, including 12 surveys of 1.5 h duration along 1 km sections of Lady Wakehurst and Lady Carrington Drives during 2003-2006 (Andrew 2001; Maloney 2007). I conducted a 2-h spotlight survey on 20 December 2011 along sections of Lady Carrington Drive and McKell Ave but detected no greater gliders. However, on 20 and 30 March 2012, a single greater glider was observed near the southern end of Lady Carrington Drive (Andrew et al. 2012).

Whether this represents a rare long-distance dispersal event (see Taylor et al. 2007) or dispersal from a previously unsurveyed location within Royal is unknown. There are locations within 15 km of Royal NP where the greater glider still occurs (Maloney 2007) but recolonisation from such locations requires dispersal across major roads, which is predicted to be difficult for this species (see Taylor and Goldingay 2009). The isolation of Royal NP makes recolonisation extremely difficult once it has disappeared. This may be why 18 years elapsed between observations at Lady Carrington Drive.

Ongoing surveys will be required to determine whether the greater glider becomes re-established within the forest surrounding Lady Carrington Drive, rather than this representing an unsuccessful dispersal event. Its reappearance should not be taken for granted. The presence of the powerful owl within Royal may hamper recolonisation. This owl can prey heavily on greater gliders and even cause a local decline when the greater glider is a primary prey item (Kavanagh 1988). It is now recognised that the greater glider is susceptible to decline, though the causes are not always clear (Kavanagh 1988; Lindenmayer et al. 2011). Its decline after wildfire has been observed (Lindenmayer et al. 2011). Population viability analysis predicts the vulnerability of isolated populations of this species to wildfire (Taylor and Goldingay 2009). Ongoing study of the greater glider can provide some valuable lessons about the management and conservation of other species within Royal.

DISCUSSION

The management of protected areas is a complex undertaking (Chapple et al. 2011). Within Australia this management is likely to be primarily focussed on Park visitors, fire, exotic species and native biodiversity. My focus here is on how biodiversity can be maintained and conserved. It is fundamental that ecological research must inform how biodiversity is managed within any protected area. Although local research will be central to this there is now a large body of research findings that can inform biodiversity management within any protected area. This information needs to be synthesised, periodically updated and integrated into local management. The challenge to local managers is finding a mechanism that can achieve this (e.g. Burbidge et al. 2011). The current plans of management for National Parks and Nature Reserves in NSW are too generic, which consequently requires local managers to perhaps independently, identify more specific priorities and actions. One solution may be the establishment of a biodiversity management committee that includes research ecologists among its members, and that this committee formulate the specific plan for the local reserve. Royal NP could serve as a model for how this would work and how it might be applied in other reserves.

Undertaking local ecological research will be needed to manage local biodiversity. How can this be financed or encouraged? This may be done by identifying projects and allocating small research grants to attract students. Plans of management already state that a prospectus of preferred research projects will be prepared (e.g. NPWS 2000, 2002a). These should be made available on the web site for each reserve. Providing facilities such as local accommodation can also help to offset research costs. This has been helpful within Royal NP where accommodation within the Park has often been provided to researchers. Other forms of assistance will facilitate research projects and make them attractive to researchers. Royal NP has benefited in attracting researchers by being located close to universities in Sydney and Wollongong. Other Parks more distant from universities may struggle to attract researchers. However, providing research grants and establishing links with research ecologists may allow some progress to be made. It may also be feasible to involve volunteers (e.g. Andrew 2001), such as recent graduates or community members experienced in ecological studies to assist with or in some cases to independently conduct projects.

The findings of local ecological research need to be linked back to the biodiversity management committee. Students often move onto other activities once a research project is completed. Reports or theses need to be provided and stored by the local managers. The biodiversity management committee needs to decide how that new knowledge may be used. Royal NP has occasionally hosted seminar days for the presentation of local research. This should continue with a commitment that it would be a regular event (e.g. annual) as a forum for the communication of local research findings, and with summaries available through the Park web site.

Management within protected areas should be adaptive (e.g. Burbidge et al. 2011; Chappell et al. 2011) but one aspect of this that is often overlooked is that it should be informed by small-scale field experiments. Management actions are often applied over large spatial scales (e.g. pest species control) without full appreciation of the cost implications if an action is unsuccessful or if it has adverse unintended consequences (e.g. decline of non-target species). Small-scale field experiments should be employed to understand and refine particular management actions (e.g. Goldingay and Newell 2000). Such experiments should cover a sufficient period of time to be adequately evaluated before being scaled up.

Much of the wildlife research in Royal NP (and elsewhere) is focused on threatened species (e.g. Tulloch and Dickman 2006; Bilney et al. 2007; Baker et al. 2010; Norton et al. 2010a). This is appropriate because the knowledge gaps associated with these species are often the most pressing and some funding is made available for recovery actions for these species. Royal NP can make a significant contribution to the conservation of many listed threatened species, so it is appropriate that ecological research and management in the Park continue to have a focus on them. What also needs to be recognised is that Royal NP could be developed as a model of how ecological research can be used to inform the effective management of biodiversity within a protected area.

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