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PROFILE

Integrating Science into Management of Ecosystems in the Greater Blue Mountains

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Abstract Effective management of large protected conservation areas is challenged by political, institutional and environmental complexity and inconsistency. Knowledge generation and its uptake into management are crucial to address these challenges. We reflect on practice at the interface between science and management of the Greater Blue Mountains World Heritage Area (GBMWHA), which covers approximately 1 million hectares west of Sydney, Australia. Multiple government agencies and other stakeholders are involved in its management, and decision-making is confounded by numerous plans of management and competing values and goals, reflecting the different objectives and responsibilities of stakeholders. To highlight the complexities of the decision-making process for this large area, we draw on the outcomes of a recent collaborative research project and focus on fire regimes and wild-dog control as examples of how existing knowledge is integrated into management. The collaborative research project achieved the objectives of collating and synthesizing biological data for the region; however, transfer of the project's outcomes to management has proved problematic. Reasons attributed to this include lack of clearly defined management objectives to guide research directions and uptake, and scientific information not being made more understandable and accessible. A key role of a local bridging organisation (e.g., the Blue Mountains World Heritage Institute) in linking science and management is ensuring that research results with management significance can be effectively transmitted to agencies and that outcomes are explained for nonspecialists as well as more widely distributed. We conclude that improved links between science, policy, and management within an adaptive learning-by-doing framework for the GBMWHA would assist the usefulness and uptake of future research.

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Introduction

Prevention of biodiversity loss is commonly addressed by setting aside protected areas (Bruner and others 2001; Rodrigues and others 2004; Pressey and others 2007). Although this satisfies basic conservation requirements and political ends, active management of these areas is important for effective conservation (Margules and Pressey 2000; Pressey 2004; Deguise and Kerr 2006; Pressey and others 2007).

Management of large protected areas is confounded by ecological, institutional, and political complexities and inconsistencies (Walters and Holling 1990; Brunner and others 2005; Clark 2008; Parr and others 2009). These include arbitrary jurisdictional boundaries, competing values and obligations, ecological knowledge gaps, lack of consistent and adequate funding and resources, and failure to link successfully with on-ground research and monitoring. Protected-area management includes a range of management approaches, including "leave it alone," ad hoc management (e.g., subject to funding and resources), conventional top-down management (including the "fences and fines" approach), and, more recently, an adaptive-management approach.

Conventional Management

Conventional management of protected areas uses top-down policies of control and exclusion under the assumption that ecosystem functioning is static and predictable (Gunderson 1999). In some situations, there are simple technical environmental problems that can be successfully addressed using a top-down "command and control" management style in conjunction with sound science (Brunner and others 2005). However, this approach is unsuitable for managing ecological systems undergoing rapid and unpredictable changes and where knowledge gaps and uncertainty are significant (Holling and Meffe 1996). This includes the management of large protected areas, such as the Greater Yellowstone Ecosystem (reviewed by Clark 2008) or Kakadu National Park in Australia (see Parr and others 2009). These areas have complex socioeconomic contexts and numerous stakeholders with different and often conflicting values, views, obligations, and objectives. In such contexts, top-down "command and control" approaches are inflexible and unlikely to be effective (Cortner 2000; Brunner and others 2005; Clark 2008).

Conventional management has been variously described as fragmented, disciplinary, legislative, and departmental (Berry and others 1998; Cortner 2000; Connor and Dovers 2004; Brunner and others 2005; Clark 2008). In relation to management of large protected conservation areas, it is often poorly defined and ad hoc due to political requirements, environmental uncertainties, and insufficient knowledge of ecosystem dynamics. Management flexibility and effectiveness can be hampered by governance that involves several government agencies, disparate knowledge bases, and conflicting values. Policy is a process: Policies can be described as principles that underline actions, including management, and involve people's values, politics, decisions, governance, science, and other forms of knowledge. Conventional management commonly treats policy as fixed and is slow to accommodate unpredictable drivers of ecosystem change (such as fire, pests, and climate change) and new knowledge (Walters and Holling 1990). The complexity and uncertainty confronting environmental and natural resource policy and management have prompted calls for alternative approaches.

Adaptive Management

Adaptive management, as proposed by Holling (1978), is the systematic procurement of reliable knowledge to improve management during its application and is sometimes simplified to "learning by doing" (Walters 1986; Walters and Holling 1990). Essentially, adaptive management builds understanding (i.e., learning) by using management to test different alternatives and gain knowledge about ecosystem response to intervention and then iteratively refining management actions (Reever Morghan and others 2006). Management occurs within an experimental framework where success, or otherwise, of actions can be determined (Walters and Holling 1990). Using this approach, science should effectively inform policies (Ascher 2004).

An adaptive-management approach is fundamentally different from the conventional approach and embraces the key principles of holistic and integrated science, meaningful public involvement, collaborative decision-making, and flexible and adaptable policy and institutions (Cortner 2000; Brunner and others 2005). An adaptive governance setting is essential for adaptive management (Gunderson and Light 2006), where scientific and other types of knowledge are integrated into policies through open decision-making structures (Brunner and others 2005).

Knowledge generation and uptake are keys to adaptive management. Although conservation management should be guided by ecological science (Ascher 2004), there are inevitable system uncertainties (Walters 1986). Allen and Gunderson (2011) noted that elements most appropriate for adaptive management are scientific uncertainty, competing hypotheses that are finite and testable, and leadership (e.g., scientists, bridging organizations, and managers). Even with the establishment of a sound scientific knowledge base, there is a need for structured learning processes to improve management and for negotiation of goals and values that transcend tenure boundaries. This also involves tradeoffs among competing goals and ongoing monitoring and assessment of management actions.

Hockings and others (2009) noted that park management agencies in Australia have been slow to move toward an adaptive-management approach. This can be partly attributed to the characteristics of bureaucratic and scientific management systems, the cost and difficulty of establishing effective monitoring to decrease uncertainty (Parkes and others 2006), and insufficient capacity and training of managers who are expected to perform the adaptive management (Stankey 2003; Reever Morghan and others 2006). Allan and Curtis (2005) noted that despite the "rhetorical abundance" of adaptive management, the lack of implementation can only be addressed by fundamentally changing natural resource-management culture and existing institutional frameworks to accommodate new ways of learning, new ways of sharing information, and new ways of incorporating learning into planning.

This article presents a case study on the effectiveness of a collaborative project (see Ramp and Chapple 2010) in the Greater Blue Mountains World Heritage Area (GBMWHA) that aimed to bridge science and management and to facilitate adaptive management. The authors of this article participated as researchers in collaboration with the management agencies. This article focuses on knowledge generation and uptake and negotiation of goals and values that transcend tenure boundaries. We review two specific management issues (fire regimes and wild dogs) and detail the management goals, values, policy, legislation, and trends in knowledge and management. This description of management and policy trends is then considered in terms of generating improvements for the future.

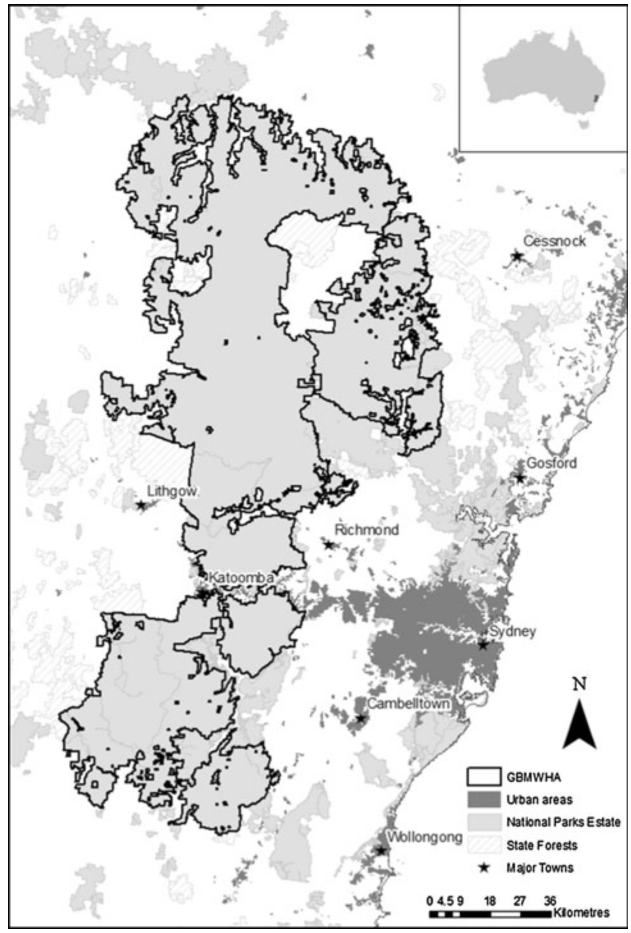

Fig. 1 Map showing jurisdictions and management boundaries

The GBMWHA

Geographical and Biophysical Context

Eight national parks (Blue Mountains, Wollemi, Kanangra-Boyd, Nattai, Yengo, Gardens of Stone, Thirlmere Lakes, and Jenolan Caves Karst Reserve) were integrated in 2000 to form the GBMWHA, which is the largest integrated system of protected areas (approximately 1 million hectares) in the state of New South Wales (Fig. 1). The region was awarded World Heritage status based on the following two natural heritage selection criteria: (1) outstanding examples of ongoing ecological and biological processes significant during the evolution of Australia's highly diverse ecosystems and communities of plants and animals, particularly eucalypt-dominated ecosystems; and (2) significant natural habitats for in situ conservation of biological diversity, including those containing threatened species of outstanding universal value, in particular the eucalypts (woody sclerophyllous plants from three genera in the family Myrtaceae) and eucalypt-dominated communities (World Heritage Committee 2001). Fourteen percent of all eucalypt taxa (for which there are >850 species) occur within the GBMWHA, which is also outstanding for its expression of the structural and ecological diversity of the eucalypts associated with its wide range of habitats (GBMWHA Strategic Plan 2009). The site provides significant representation of Australia's biodiversity with substantial numbers of rare or threatened species, including endemic and evolutionary relict species, such as the Wollemi pine (*Wollemia nobilis*) (GBMWHA Strategic Plan 2009).

The GBMWHA begins 60 km inland of Sydney, Australia's largest city, and encompasses some of the central portions of the Great Dividing Range (Fig. 1). The area abuts urban development to the east and agri-industry to the west. The northern section of the area is geographically split from the south by a corridor of townships (population 80,000), including local government and privately owned land. The GBMWHA is the primary catchment for Sydney's drinking water supply and is also an important tourist destination for residents and visitors, which is supported by increasing levels of urban development and road networks.

Institutional Context

The Australian government and several state government agencies are responsible for different elements of the GBMWHA. Under the World Heritage convention, the Australian government is responsible to the United Nations Educational, Scientific and Cultural Organisation (UNESCO), for protecting and monitoring the World Heritage values. Day-to-day management is primarily the responsibility of a state agency, the New South Wales (NSW) Department of Environment, Climate Change and Water (DECCW). The Blue Mountains City Council (BMCC) manages the local government area that bisects the GBMWHA. Other state government agencies involved in management include the NSW Rural Fire Service (RFS), the NSW Department of Industry and Investment (DII), and the Hawkesbury-Nepean Catchment Management Authority (HNCMA). Livestock Health and Pests Authorities (LHPA) assist with pest animal management in the GBMWHA and on adjoining private lands. The Blue Mountains World Heritage Institute (BMWHI) was established in 2004 as an independent organisation that works with these management agencies to broker and facilitate research and community engagement in support of conservation and management of the GBMWHA. In this way, BMWHI is essentially a "bridging" (Allen and others 2011) or "boundary" (Cash and others 2002; Michaels 2009) organisation that facilitates the generation and uptake of knowledge and perspectives into the policy and management process for the World Heritage Area.

Knowledge Generation and Uptake in the GBMWHA

The first comprehensive project initiated by BMWHI that sought to build links between science and management for the GBMWHA was a 3-year (2007–2010) collaborative research project called Managing for Ecosystem Change in the GBMWHA (see Ramp and Chapple 2010). This government-funded Australian Research Council project formed a valuable point of reflection on science integration at the management interface, and all authors of this article were part of the research team in partnership with government management agencies (DECCW, BMCC, HNCMA, and DII). Below we outline key research goals and outcomes and the challenges that arose.

Table 1 Project objectives for the Managing Ecosystem Change project

1. Past and current ecosystem condition
Construct a GIS database and collate all available biodiversity information for the World Heritage Area
Develop species distribution models for Myrtaceae and Fabaceae species, identifying hotspots and climate impacts
Develop species distribution models for terrestrial fauna, identifying assemblages and climate impacts
2. Reserve effectiveness
Quantify the distribution of surrogate species and assess representation and efficiency of surrogates
Incorporate economics into surrogate modelling
Explore the effectiveness of the current reserve boundary by comparing a historical perspective on the establishment of the reserve with the current status of biodiversity within the GBMWHA
Identify the efficacy of existing conservation planning units and highlight potential land acquisitions
3. Responses to drivers of changēimpact and spatial extent
Map the spatial extent of drivers of change
Assess dispersal ability of plant species in response to climate change
Measure resource overlap and interactions between native and introduced apex predators
Model invasion potential of weeds
Assess resilience of upland swamps to climate change
Assess surrogate species responses to climate change and fire regimes
4. Modelling ecosystem condition and drivers of change
Model threat distributions and their impacts on chosen surrogates
5. Adaptive management
Inform a monitoring strategy for the GBMWHA within an adaptive-management framework

The project focused on climate change, fire, and pest animals, and the overall aim was to build the knowledge base to inform management about these drivers of ecosystem change, including modelling future projections and the efficacy of potential management strategies. The objectives are shown in Table 1. The key objective was the development of computer models that could project future ecosystem changes. This involved collating all available ecosystem data for the region and compiling it into a geographic information system (GIS). Large-scale spatial models could then be built to present the distribution of biodiversity across the World Heritage Area, based on the use of surrogate species and ecosystems, along with the spatial impacts of drivers of change. Project components included ecosystem modelling, analysis of reserve design, ecological representation, and distribution of invasive weeds and threatened communities.

Table 2 lists key outcomes for the objectives with the issues and opportunities that arose. Key project outcomes

Table 2 Achievement of objectives for the Managing Ecosystem Change project

Objectives[a]	Key outcomes	Issues in knowledge uptake	Future opportunities
1. Past and current ecosystem condition	Database constructed and information collated	Database not accessible; agencies lack computer hardware and technical skill; essentially a specialist tool	Capacity developed can be used in on-going research projects to further develop the GIS and models
	Modelling capacity developed to project future scenarios (e.g., climate change variables) for the region	Lack of funding prevented ground-truthing of models and assessing impact of varying detection probability; resultant potential inaccuracy and thus uncertainty of results inhibits uptake by managers	Agency staff must be trained in use of the models; data and programs must be modified to allow greater Internet access by agencies
	Flora and fauna distribution models developed for all species within the plant families Myrtaceae and Fabaceae and all terrestrial mammals (except bats) (700 species in total)		Follow-up research needed to ground-truth models and assess impact of varying detection probability
2. Reserve effectiveness	Quantified capacity of GBMWHA to represent diversity and endemism in the Myrtaceae family	A framework for knowledge uptake is absent; required to enable transfer of tools and information to the agencies	Common species used as surrogates for monitoring closely related rare species
	Created spatially explicit models of distribution, abundance, and hotspots of terrestrial mammals	Pathways for integrating findings into decision frameworks and policy required	Facilitate transfer of tool to agencies along with capacity building of agency staff (potential role for BMWHI)
	Identified optimal monitoring techniques for fauna to inform monitoring effort	Hardware for manipulating findings held by the university, not by the agencies, and agencies lack skill base to apply it	
	Assemblages of mammal species identified to quantify conservation objectives; predictions used to prioritise land acquisition		
	Incorporated spatial proximity as a cost-function in land acquisition to use both biodiversity values and management costs in assessment of representation efficiency		
3. Responses to drivers of change	Examined efficacy of monitoring survey methods for establishing robust habitat suitability maps for terrestrial mammal species across NSW	Need framework for knowledge uptake	Develop framework for knowledge uptake
	Examined the dispersal capacity of plants to facilitate range shifts under climate change	Tools required to enable managers and communities to use and explore research findings	Modelling capacity for lantana can be used to model other invasive weeds
	Quantified risk to endangered ecological communities in experiencing climate conditions outside those currently experienced		Outcome can facilitate monitoring of fire and wild dogs (decreasing cost)
	Measured resource overlap (diet) and interactions (activity and distribution) between introduced and native apex predators (including various mammal species, powerful owl and lace monitor)		
	Examined invasive potential of surrogate weed (Lantana camara) under climate change		

Table 2 continued

Objectives[a]	Key outcomes	Issues in knowledge uptake	Future opportunities
4. Modelling ecosystem condition and drivers of change	Assessed potential response to changes in climate and fire regimes from surrogates (Myrtaceae; Fabaceae; terrestrial mammals)	Need framework for knowledge uptake	Develop framework for knowledge uptake
5. Adaptive management	Developed capacity for adaptive management through the previously described objectives	More explicit progress on developing an adaptive-management framework was not achieved primarily due to lack of funds to support time of researchers (especially BMWHI) in engaging with this process	Significant foundations for adaptive management developed through this project, e.g., use of models for a risk-based approach to management of the GBMWHA Develop hierarchy of objectives for the GBMWHA and a monitoring strategy based on development of TPCs

[a] See Table 1

included predictive models for 700 species, including all species in the plant families Myrtaceae, an important outcome given that the eucalypts in this family were a key reason for World Heritage listing of the area.

An issue arose midway through the 3-year project when a meeting was held between researchers and managers at which the researchers sought to present what the science and the models were telling us and how they might inform a monitoring strategy. A communication breakdown was apparent. The early (assumed) understanding by researchers and agency staff of the project aim and objectives, which were defined at the outset of the project, was insufficient to guide the research for its application to management. There were no clearly defined management objectives to guide research directions and subsequent uptake of outcomes. There was a lack of clarity as to what the project could deliver to partners that was directly useful to management. There was an expectation by agency staff that the researchers should take leadership in this, but the researchers expected the managers to articulate what the management questions were that they wanted research to inform. Management agencies expressed uncertainty in how the project's outcomes, in particular in the utility of the GIS, would be useful (Table 2).

The case studies (in later text) describe current legislation and management for wild dogs and fire regimes, and the challenges presented. These two case studies were chosen due to the complexity of social, ecological, political, and economic factors they presented to land managers. Wild dogs and fire are both widespread and recurrent processes with apparent, measurable, and controllable impacts, and there is considerable corresponding pressure from communities to manage them. With both case studies there has been conscious recent effort to introduce adaptive-management principles. We describe research and management for wild dogs and fire regimes in terms of (1) values, policy objectives, and legislation and (2) trends in knowledge and management. Based on these descriptions, the Analysis and Discussion section discusses how adaptive their management is and what improvements could be made, especially in terms of problem definition, management objectives, and uptake of research into management of fire and wild dogs.

Case Study: Wild Dogs

The term "wild dogs," as defined by Fleming and others (2001), includes the native dingo (*Canis lupus dingo*), feral domestic dogs (*C. l. familiaris*), and their hybrids. Distinctions between these are often unclear, with some dingoes in the GBMWHA region being assessed as pure although displaying traits representative of hybridisation with domestic dogs (Purcell 2010a, b, c). Wild dogs predate on livestock (Newsome and others 1983a, b; Robertshaw and Harden 1985, 1986; Corbett and Newsome 1987) and thus management of dingoes conflicts with livestock producers on landholdings adjacent to the GBMWHA.

Values, Policy Objectives, and Legislation

Wild-dog management is primarily based on the often-conflicting values of biodiversity protection and livestock protection. Reflecting these values, cross-agency goals for managing wild dogs in the GBMWHA include protecting biodiversity through maintenance of dingoes as apex predator in ecosystems along with decreasing impacts on native species and surrounding agricultural production (see Table 3). Conflicting goals exist across tenures, and optimal management for agriculture (economic imperative) is often not optimal management for conservation and vice versa.

Table 3 lists the management plans for wild dogs and responsibilities of agencies under various legislative acts. The two key legislative requirements, including additional Australian Government and NSW legislative acts for wild dog control in NSW, are protection of rural lands and protection of native ecosystems. Management of wild dogs presents a legislative dilemma demanding innovation in management (Macdonald 2006). Wild dogs include dingoes that are protected in parts of the GBMWHA (scheduling of the NPW Act 1974), and all land managers in NSW are required to control them under the Rural Lands Protection Act (1998). All domestic dogs (*C. l. familiaris*) are specifically excluded from protection within the GBMWHA (scheduling of the NPW Act 1974), and this causes difficulties in identifying between dingoes, hybrids and feral dogs, with consequent uncertainty in decision-making by managers in the GBMWHA.

Trends in Knowledge and Management

Wild-dog management in the GBMWHA follows traditional species-based management in which culling (e.g., use of poison, shooting, and trapping) is undertaken to limit their abundance at the boundary of the protected area (Blue Mountains Region Pest Management Strategy 2007–2011). Since the 1990s, pest management (including wild dogs) across Australia has tried to focus more on pest damage rather than control of pest numbers per se (Caughley and Sinclair 1994; Fleming and others 2001), yet implementing control focused on decreasing impacts is hampered by knowledge gaps (Hone 2007). Decisions to cull wild dogs are largely made in response to demands from livestock owners after sheep losses assumed to be due to dog predation. The effectiveness of wild-dog management in the GBMWHA for achieving mitigation of livestock predation on adjacent lands is assumed rather than being evidence based. Similarly, the effect of management on biodiversity is unknown. There are to date no measurable objectives for wild-dog control, preventing the testing of explicit management objectives other than the effectiveness of wild-dog eradication.

Wild dogs in the GBMWHA are controlled independently of other species (introduced and native) (Blue Mountains Region Pest Management Strategy 2007–2011; wild-dog management plans) and without measuring ecosystem responses to control, including concomitant responses of foxes, feral cats, and prey.

The legislative dilemma relating to wild dogs as outlined previously has prompted wild-dog management planning that follows adaptive-management principles and includes conservation and control objectives (Fleming and Harden 2003a, b). Some of these wild-dog management programs have decreased livestock predation (Fleming and others 2006); however, others in Queensland have exacerbated predation (Allen and Gonzalez 1998; Allen 2000). Most wild-dog plans for the GBMWHA require the government agency DECCW to address both dingo conservation and livestock loss mitigation, and little progress has been achieved in cooperative strategic planning of wild-dog management. Stakeholders have pushed for change, but implementation is slow and is attributed to inadequacy of consultation among stakeholders, insufficient capacity of stakeholders, and inequity of stakeholder groups in planning processes (Fleming and others 2006).

Adaptive-management planning for wild dogs in NSW is often subjective (Purcell and others in press), although it is being informed by research investigating trophic interactions (Visser and others 2009; Purcell 2010a, b; Purcell and others in press) and behavioural and genetic studies (Paplinska 2010; Purcell 2010a, b, c). Because carnivorous predators, dingoes, and other wild dogs may be top-down trophic regulators (Glen and others 2007), thus maintaining biological stability, which is a similar outcome to that achieved for Gray wolves in America (Mech 1970). Dingoes have been identified as a keystone species for biodiversity conservation in Australia (Johnson and others 2007; Glen and others 2007; Claridge and Hunt 2008; Dickman and others 2009; Johnson and VanDerWal 2009; Ritchie and Johnson 2009; Purcell 2010b; Wallach and others 2010). Allen and others (2011) recently challenged that the methods used in some of these studies did not allow conclusions on regulation of introduced mesopredators by dingoes, and no experimental studies on function have been undertaken in wetter eastern environments, such as the GBMWHA. However, the current policy on conserving dingoes in core areas of the southern GBMWHA (Table 3) is consistent with the possibility of important functional roles of dingoes there. This question requires experimentation to better inform management planning.

Table 3 Legislative and policy basis for wild-dog management in NSW

Institution	Legislation	Management plan	Goals	Response variable[a]	Values[a]
NSW DECCW	NPW Act 1974 Threatened Species Conservation (TSC) Act 1995; Rural Lands Protection (RLP) Act 1998	Pest management strategy for each of 3 regions Wild-dog policy	To decrease adverse impacts of pests on native flora and fauna and to decrease nos. of pests to protect agricultural production	No. and impact of wild dogs; nos. of wild-dog attacks on livestock	Biodiversity protection; top-predator function; agricultural production; neighbour relations
Sydney Catchment Authority	Sydney Water Catchment Management Act 1998	Warragamba Special Area Pest Management Plan	Maximise protection of water quality and ecosystem integrity	Water quantity and quality	Water protection
NSW Department of Primary Industries (DPI)	Rural Lands Protection (RLP) Act 1998; Game and Feral Animal Control Act 2002	State Wild Dog Management Plan (in preparation)	To ensure risks posed by vertebrate pests to the economy, environment, and community are excluded, eradicated, or effectively managed	No. and impact of wild dogs; nos. of wild-dog attacks on livestock; community and agricultural producer satisfaction	Competitive, productive, safe, healthy, and biosecure primary industries; stakeholder capacity building
NSW Livestock Health and Pest Authorities	RLP Act 1998; Game and Feral Animal Control Act 2002	LHPA Strategic Directions 2006–2011	To be the accepted first contact for all wild-dog issues and to provide pest-animal services to all stakeholders	Agricultural producer satisfaction based on no. of wild dog attacks on livestock	Agricultural production; neighbour relations; wildlife protection
Game Council NSW (statutory authority of the NSW Parliament)	Game and Feral Animal Control Act 2002	N/A	To help decrease the impacts of introduced pest and feral animals on natural and agricultural environments	No. and impact of pests on nature and agriculture	Recreation; Conservation hunting

[a] Derived from authors' assessment, not from statutory documents

Case Study: Management of Fire Regimes

Fire is a major ecological process in the highly flammable eucalypt forests that dominate the landscape of the Greater Blue Mountains (Hammill and Bradstock 2006, 2009; Bradstock and others 2010). The occurrence of major wildfires and predicted changes to fire behaviour due to climate change (Bradstock and others 2008, 2009; Bradstock 2010) pose a considerable challenge to management agencies, which currently allocate substantial resources to controlling the spread of fire and consequent fire regimes (i.e., frequency and intensity).

Values, Policy Objectives, and Legislation

Fire-management goals for the GBMWHA (see Table 4) address the three primary values of protection of human life and livelihood, conservation of biodiversity, and maintenance of water quality (Bradstock and Gill 2001; Bradstock and others 2008). These goals are often regarded as being incompatible. With a considerable urban–bushland interface in the GBMWHA, protection of human life and property is the key driver of fire management. The goals of protecting human life and property and water quality in the GBMWHA are generally met successfully (see Chapple and Booth 2007). The region is prone to large wildfires that impact the ability of water catchments to maintain production of quality drinking water (Wallbrink and others 2004; White and others 2006). As a consequence, preventative measures, such as prescribed burning to decrease fuel, are undertaken to decrease the likelihood of large wildfires, along with various kinds of suppression to limit the spread of fires after ignitions (Gill 2009). Effectiveness of present fire regimes for protecting biodiversity is uncertain (Driscoll and others 2010), primarily due to a lack of field studies on a wide range of taxa (with the exception of vascular plants and some higher vertebrates).

Table 4 lists the different emphasis placed on protection of each of the primary values, and the key acts legislating for fire management that reflect these values. The DECCW is required to decrease the threat of fire to native plants and animals (National Parks and Wildlife Act 1974 and the Threatened Species and Conservation Act 1995). Goals of fire control agencies for the protection of human life and property (Rural Fires Act 1997) can sometimes appear to conflict with management for conservation (e.g., see Chapple and Booth 2007). Multiple fire-planning processes exist across agencies (Table 4), with management plans (RFS risk management plans and DECCW reserve management strategies) that are neither well integrated or cross-referenced (see Chapple and Booth 2007).

Trends in Knowledge and Management

With limited resources for fire management, agencies must prioritize where to expend effort (Penman and others in press). Fire-management activities in the GBMWHA include the following: (1) prescribed burns and hazard decrease to decrease fuel loads to minimise the risk of wildfire that threatens human life and property; (2) extinguishment of ignitions (e.g., from lightning or arson) and suppression of resulting fires; and (3) prioritization of fire regimes for maintenance of biodiversity using a "thresholds of potential concern" (TPC) approach (outlined later in text).

An adaptive-management approach to fire management for biodiversity conservation has been applied in the GBMWHA. There is limited knowledge and understanding of indigenous fire regimes used in the region in the past (Black and others 2007). Fire histories from mapped boundaries (circa 30 to 40 years of reliable data) and fire-severity information based on remote sensing have recently been consolidated in GIS format. This has allowed for new insights into how local fire regimes are influenced by environmental and management factors (Bradstock and others 2008, 2009, 2010; Hammill and Bradstock 2006, 2009; Price and Bradstock 2010). This information provides a basis for the development and assessment of TPCs to indicate the optimal fire recurrence interval for different vegetation types (Bradstock and Kenny 2003). Such approaches attempt to capitalise on available relevant knowledge on plant responses to achieve a measurable conservation goal (e.g., minimization of extinction probability at landscape scales [Bradstock and Kenny 2003]). This approach has been adopted in the last decade in fire-management strategies for the GBMWHA and other conservation reserves in NSW. It includes formal linkages for assessment of spatially explicit fire regime information in relation to TPCs, thus allowing identification of areas in the landscape where either too little or too much fire may be occurring, as well as development and targeting of operational management responses where appropriate.

Process-based simulation models, such as FIRESCAPE (Bradstock and others 2008), integrate landscape-scale information and provide a capacity for experimentation by varying fire behaviour, fuel, and weather. Such models can explore relations between prescribed burning strategies, spatial patterning, and management objectives. Current research in the GBMWHA is using FIRESCAPE to investigate strategies to decrease the risk posed by wildfires to people, property, biodiversity, and catchments (Bradstock and others 2008). The results of modelling indicate that current fire regimes fall within the desirable domain of specified TPCs, but there is scope for alteration of fire regimes through increased rates of prescribed fire to address other ecological management issues, such as slope

Table 4 Legislative and policy basis for bushfire management in NSW

Institution	Legislation	Management plan	Goals	Response variables[a]	Primary values[a]
NSW RFS	Rural Fires Act 1997	District Bushfire Management Committee (BFMC) risk-management plans	Protection of life, property, and environment within the community Protection, maintenance, and, wherever possible, enhancement of natural and cultural values of the area through management of appropriate fire regimes	Frequency and intensity of fire at the urban–bushland interface	Human and asset protection
NSW DECC	Rural Fires Act 1997; NPW Act 1974; TSC Act 1995	Fire-management strategies for each of 8 reserves	Protect persons and property in or adjacent to the reserve from bush fires affecting the reserve Manage fire regimes to protect water quality and natural biodiversity of the reserve and avoid the extinction of any species Minimise risk of arson in the reserve Minimise spread of unplanned fires within, from, or into the reserve Protect the reserve's Aboriginal sites, historic places, and culturally significant features from damage by bush fires Minimise effect of bushfire management and control operations on local economy	Distribution of fire across landscape	Biodiversity protection; agricultural protection; neighbour relations
Sydney Catchment Authority (SCA)—fire is jointly managed with DECC	Sydney Water Catchment Management Act 1998	Special Areas Fire Management Operations Plan; Water-Quality Risk Management Framework	Maximise protection of water quality and ecosystem integrity	Water quantity and quality	Water protection
Blue Mountains City Council (BMCC)	Crown Lands Act 1989; Local Government Act 1993; TSC Act 1995	BM Bushfire Risk Management Plan	Protection of life, property, and environment within the community Protection, maintenance, and, wherever possible, enhancement of natural and cultural values of the area through management of appropriate fire regimes	Frequency and intensity of fire at urban–bushland interface	Human and asset protection

[a] Derived from authors' assessment, not from statutory documents

stability and catchment integrity, without pushing fire regimes substantially beyond the range specified by the TPCs. Satisfactory tradeoffs among ecological management goals [i.e., water and biodiversity (Table 4)] for the managed use of fire are therefore feasible within the dominant forest types of the GBMWHA.

The effects of climate change on temperature and rainfall are predicted to favour an increase in the frequency, intensity, and size of bush fires (Hennessy and others 2005; Williams and others 2009). Projected increases in the severity of fire weather and any resultant increase in area burned are unlikely to be counteracted by plausible levels of prescribed burning (Bradstock and others 2008, 2009).

Analysis and Discussion

The Managing Ecosystem Change project highlighted barriers to effective integration of science into management and demonstrated a disjunction between what information is or can be provided and what information the users may actually want or need. The problematic uptake of outcomes by managers typify the observation by Margules and Pressey (2000) that it is often not lack of ecological science, but rather inadequate linking between the scientific and policy-making and management communities, that hampers effective decision-making. In this study, effective collaboration and information flow between science and management were found to depend on the following:

- *Shared comprehensive problem definition*. Clark and others (2009) described the importance of problem orientation that defines what participants are seeking (goals), what stands in the way (problems), and the alternative options for action. Project participants shared the common goal of filling knowledge gaps to inform management of drivers of ecosystem change (climate change, fire, and pests). Project objectives were defined as measures to address these gaps. However, not addressed was what stands in the way of achieving the goal. In hindsight, problems in relation to this project that were not defined include lack of feedback about management interventions and lack of a framework for integrating science into management of the threats.
- Similar issues of problem definition can be seen in relation to the case studies on fire and wild dogs, where the considerable effort expended on management is underpinned by competing values, significant uncertainty, and gaps in knowledge, and action is often based on political pressure independent of knowledge. Negotiation of goals and values across tenures can be expected to meet with more success if all stakeholders agreed on goals that address the range of values. Achieving biodiversity outcomes in conjunction with agricultural/livestock and asset/property protection is challenging and complex as shown for both wild dog and fire management. Legislation polarises the competing values inherent in wild-dog and fire management, with each legislative act prioritising either biodiversity or livestock/property protection. Competing goals and legislative requirements (or perceptions of these) of different stakeholders inhibit dialogue. Economic and political imperatives to safeguard property generally predominate over biodiversity imperatives, with control efforts often instigated by agricultural and/or political demands (English and Chapple 2002, Chapple and Booth 2007).
- *Clearly defined management objectives to guide research directions and uptake*. A key issue that arose as the project progressed was lack of clearly defined management objectives to guide research and its uptake. The absence of these objectives resulted in the researchers being uncertain how to steer the research to meet management needs. This same issue applies to issue of wild dogs in the GBMWHA, where there are no measurable objectives, and failure to meet broad pest-management goals is often related to inadequate definition of the problem and failure to set measurable objectives (Braysher 1993; English and Chapple 2002). The effectiveness of wild dog control to protect biodiversity (including dingo conservation) and livestock in the GBMWHA also is not measured, which is essential in evaluating any lethal control (Caughley and Sinclair 1994). Because there is a reported cultural shift within the agencies, with a concomitant shift in perceptions of dingoes and the functional roles they may play in GBMWHA ecosystems (Purcell 2010b), the requirement for better information is becoming more pressing so that measurable goals can be set. Information is needed on trophic interactions (see Glen and others 2007; Claridge and Hunt 2008; Ritchie and Johnson 2009; Visser and others 2009), impacts of wild dogs on biodiversity (see Robertshaw and Harden 1986), and production values (see Thomson 1984; Fleming and Korn 1989). More active engagement of wild-dog researchers with managers, along with development of clearer management objectives, is necessary before new knowledge can be expected to influence on-ground management (Fleming and others 2006).
- *The role of scientists and their information being transparent and understood by all stakeholders and scientific information made more understandable and accessible*. Resource managers involved in the project expressed concern due to the lack of utility of research outcomes and of the database in particular (see Table 2). Many investigators have discussed the challenge of science being biased, inaccurate, inadequate, conflicting, and poorly focused (see Walters and Holling 1990; Cortner 2000; Brunner and others 2005), which can result in resource managers taking uncertainty as a pretext for inaction, selecting suitable scientific opinion, or ignoring research findings (Ascher 2004). In addition, Ascher (2004) noted the equal obligation of scientists to communicate scientific uncertainty so information is not discredited or inaction justified. This project exemplifies some of these issues (see Table 2), notably habitat-suitability models (objective 1) and large-scale predictions of mammal distributions (objective 2).
- *An adaptive framework for integrating research into management*. The researchers were confronted by the need to establish a process or framework for integrating science with the wider context of policy, values, politics, and governance. This article demonstrates that although building the knowledge base is essential, it is equally important that a framework for knowledge uptake (e.g., research outcomes) is developed that can track and assess results of management actions in the GBMWHA. For example, knowledge of the interactive impacts of fire regimes and natural resource use on biodiversity and ecosystem function is necessary (Morton and others 2009), yet knowledge of fire

behaviour and impacts has not always translated into improved management (Bradstock and others 2002; Keith and others 2002; Cary and others 2003). The adaptive fire-management framework developed for the GBMWHA provides an illustration of how this problem can be overcome. The interplay between fire management and science engendered by implementation of this approach has stimulated much new local research in the GBMWHA as well as expansion of relevant management databases and planning capacity.

Each of the four steps in the research management process identified previously highlight the important role that a bridging organization, such as the BMWHI, can fulfill to help ensure that the capacity developed by research can be better used by managers. It is hoped that the lessons learned in this project can result in BMWHI being better able to achieve success in this role in future.

Moving to an Adaptive Approach

The fire and wild-dog case studies demonstrated the failure of conventional management and present the need for an approach that is more adaptive. Both fire and wild-dog management have generally been based on a "command and control" approach, which is predicated on the notion that along with fire (or dog) control, there is system control (Bradstock 2008). During the 20th century, variants of the "command and control" approach, ranging from fire exclusion to broad-scale controlled burning, have dominated differing eras of organised fire management in Australia (Bradstock 2008). Wild-dog management continues to follow a more conventional approach, whereas fire management in the GBMWHA has advanced considerably in the last decade through applying an adaptive approach. Climate change heightens the need for fire-related research to address knowledge gaps and for the adaptive-management approach to realise its full potential through better integration of research and monitoring into management. The interactions between management options and future effects of climate on fire regimes will determine future responses of biodiversity and ecosystem function.

An adaptive-management approach is particularly valuable for issues, such as fire and wild dogs, where there are multiple objectives and tradeoffs. Multiple objectives in fire management pose the problem of designing tradeoffs that minimise adverse effects on biodiversity (Driscoll and others 2010). The implementation of adaptive systems based on risk-based approaches (e.g., risk of extinction, risk of property loss) that involve tradeoffs opens up new possibilities for exploration of tradeoffs among objectives and decision analysis based on evaluation of cost-effectiveness (Driscoll and others 2010; Penman and others in press). New approaches may face opposition from government agencies who have a stake in the status quo (Cortner 2000). Elements of this new approach have taken hold for fire management in the GBMWHA, allowing potential for further development of such solutions. Convincing managers of the value of adaptive management is often difficult (see Ascher and Healy 1990; Berry and others 1998), yet the elements of a social (institutional) system that explain lack of responsiveness or adaptability to environmental signals must be confronted (see Gunderson and Holling 2002).

Further research to quantify tradeoffs between human-asset protection and biodiversity conservation for management of fire at the urban–bushland interface is an important key challenge that can better align fire policy and practices with multiple objectives (Gill and Stephens 2009; Driscoll and others 2010). The simulation studies for parts of the GBMWHA (Bradstock and others 2008) provide an example of an approach that explicitly addresses key elements of the problem. In a similar vein, research is needed to quantify tradeoffs between managing wild dogs for biodiversity or livestock protection and to quantify the biodiversity outcome of culling.

Wild-dog management has recently been following some adaptive-management principles, including recent engagement of agency personnel with an iterative research process to gain new knowledge about the ecosystem role of wild dogs (Purcell 2010b). However, strategic planning for wild-dog management in the GBMWHA remains rudimentary. Foundations for adaptive management of wild dogs include a good knowledge base as well as potentially useful strategic management frameworks (see Braysher 1993; Fleming and others 2006), legislative instruments promoting collaborative management, and cooperative management plans and guidelines (Fleming and others 2001; Fleming and Harden 2003a, b) to assist stakeholders in adaptive-management planning. Yet there is much to be learnt and much stakeholder knowledge to be included in the adaptive management of wild dogs in the GBMWHA. Scientists and managers appear to share a general acceptance of the failings and a willingness to pursue wild-dog management within an adaptive framework.

A significant barrier to adaptive management of the GBMWHA, as elsewhere, is lack of resources and funding. Monitoring is generally time-consuming and expensive, and the results are often uncertain. Consequently, monitoring is difficult to fund on an ongoing basis.

Although the World Heritage Area was established on the basis of its natural heritage values, management decisions must constantly address the imperative and statutory responsibilities to protect these values. A decision-making framework based on clearly defined management objectives and monitoring of responses to management actions can provide a way for management to maintain an ongoing emphasis on biodiversity conservation. This framework can also help integrate conflicting objectives, such as linking high-level goals across different aspects of management (e.g., fire and pest animals, biodiversity values and goals, and sociopolitical goals) with on-ground monitoring that feeds back to management.

Successful implementation of an adaptive-management framework for Kruger National Park in South Africa (see du Toit and others 2003) is based on a hierarchy of management objectives, stemming from an overarching vision and branching out into specific on-ground measurable management objectives for each ecosystem component (e.g., biodiversity, water). The success of this process in Kruger is partly due to the capacity for scientific research within the park, directed at specific management questions, rather than being idiosyncratic (Parr and others 2009), as well as its single jurisdictional agency and an adequate funding base. In NSW, the government management agency DECCW is planning to make "the institutionalisation of adaptive management more robust and permanent" (Stathis and Jacobson 2009 [p. 305]), and strategic adaptive management is currently being trialed for the Macquarie Marshes Nature Reserve (Kingsford and others 2011).

Conclusions

More science and greater certainty are important to help overcome management conflicts and lack of conservation effectiveness; however, as shown here, uptake of science by management and adaptation to new knowledge pose enduring challenges. A bridging organization, such as the BMWHI, at the science–management interface was key to the establishment of the broad-scale research project described in this article. However, although some of the project's key objectives were achieved, delivery of project outcomes to managers proved problematic. Effective collaboration and information flow between science and management were found to depend on the following: (1) shared comprehensive problem definition; (2) clearly defined management objectives to guide research directions and uptake; (3) the role of scientists and their information being transparent and understood by all stakeholders and scientific information made more understandable and accessible; and (4) an adaptive "learning by doing" framework for integrating research into management. A useful role of BMWHI would be to focus more on how research results with management significance can be effectively transmitted to agencies, including ensuring outcomes are explained for nonspecialists as well as more widely distributed.

Adaptive management of fire and wild dogs is appropriate and achievable in the GBMWHA. Considerable progress in this regard has been made with fire management. However, management of fire and wild dogs in the GBMWHA are both characterized by arbitrary jurisdictional boundaries, competing values and obligations by a wide range of stakeholders, diverse operational approaches, knowledge gaps, and narrow and conflicting legislation. These characteristics limit the ability to achieve management objectives, and it is argued that the four steps identified previously are key elements in overcoming this limitation.

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