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Adaptive risk management for certifiably sustainable forestry

B.A. Wintle [a,*], D.B. Lindenmayer [b]

[a] Commonwealth Environment Research Facility (AEDA), School of Botany, The University of Melbourne, Parkville, Victoria 3010, Australia
[b] Commonwealth Environment Research Facility (AEDA), Fenner School of Environment and Society, The Australian National University, Canberra, ACT 0200, Australia

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ABSTRACT

The past decade has seen a global surge in forest management certification, with over 200 million hectares of the world's forest now certified as sustainably harvested. Because forests are some of the most species-rich environments on earth and more than 90% of the world's forests occur outside formal protected area systems, forest management certification will be one of the pervasive influences on global biodiversity for the foreseeable future. We find that current forest certification schemes are largely deficient because they fail to demand: (i) measurable management objectives for biodiversity, (ii) formal risk assessment of competing management options that integrate impacts on biodiversity, (iii) monitoring that directly addresses management performance requirements and a clear plan for how monitoring information will be used to make better management decisions, and (iv) ongoing research targeted toward practices that enhance biodiversity in managed landscapes. We argue that the credibility of certification schemes hinges on their ability to dictate scientifically defensible management systems for biodiversity conservation. We present a framework for adaptive risk management (ARM) of biodiversity that is both responsibly proactive and diligently reactive and recommend its incorporation in all certification schemes. We highlight the need for substantial government and agency investment in fostering ARM.

1. Introduction

Forests are among the most species-rich environments on earth and the way they are managed has a substantial impact on global biodiversity loss (Millennium Ecosystem Assessment, 2005). Much of the focus on conserving forest biodiversity has centered on setting aside large reserves (Soulé and Sanjayan, 1998; Mittermeier et al., 2005) and wilderness areas (Donlan et al., 2005). Reserves undoubtedly play a key role (Mittermeier et al., 2005), but it is increasingly clear that off-reserve conservation is critical (Lindenmayer et al., 2006), especially as most of the world's biota is presently not in reserves or wilderness areas (Daily, 2001). Approximately 92% of the world's forests (and associated biota) occur in unreserved areas used for the production of wood, paper and other forest products (Lindenmayer and Franklin, 2002).

Biodiversity conservation is now widely acknowledged around the world as a fundamental part of ecologically sustainable forest management (Hunter, 1999; Lindenmayer et al., 2006). Policy documents note that the conservation of biodiversity requires "conserving species throughout their known ranges", maintaining the "evolutionary potential" of populations, and maintaining species interactions and "ecological processes" (e.g. Commonwealth of Australia, 1992, 1996; Haynes et al., 2006). Workable interpretations of these policy statements must be developed through cooperation between managers, the community, and ecologists to provide specific goals and performance measures as a basis for forest management.

Market-based instruments such as certification are rapidly gaining popularity as effective motivators for improved forest management. Certification schemes have developed in the fishing industry (Marine Stewardship and Council, 2002) and some areas of agriculture (USDA, 2000). As of mid-2005, more than 214 million ha of forest worldwide had been certified under various standards with more than 50% of European forests and 30% of North American forests managed under certification schemes (UNECE/FAO, 2005). The area of forest certified under the Forest Stewardship Council (FSC) has increased approximately linearly since 1998 (Fig. 1) and the total area of forest certified under the Pan European Forest Certification Scheme alone is now greater than 200 million hectares. Forest certification is considered a potentially important measure to counter the current ecological problems being created by globalization of the wood products industry (Viana et al., 1996;

* Corresponding author. Tel.: +61 3 83443306.
E-mail address: brendanw@unimelb.edu.au (B.A. Wintle).

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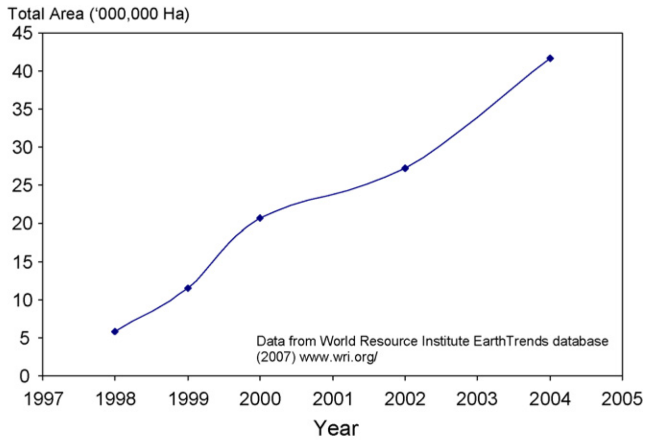

Fig. 1. Rate of growth in forest areas certified under the Forest Stewardship Council certification scheme since 1998.

Gullison, 2003). Thus, it is likely that forest management, practiced according to certification standards, will be one of, if not the major influence on forest biodiversity the foreseeable future. Other competing influences on forest biodiversity include forest conversion in the tropics, development in third world economies, and climate change.

Under forest certification schemes, standards of conduct are prescribed for forest operations. Some certification schemes defer to existing institutional arrangements in the jurisdiction under which the forest is managed, such as codes of practice and forest management plans. Successful certification rests largely on the existence and adherence to such processes (AFS, 2007). Other schemes are more prescriptive about what constitutes sustainable forest management (FSC, 1996). Common to all certification processes are periodic, third party assessments of adherence to the certification standard. The overall goal in certification is the adoption of standards that will ensure forest management is environmentally sensitive, socially aware, and economically viable (Upton and Base, 1996).

The focus of conservation biologists on reserve design as the pre-eminent tool for biodiversity conservation has meant that significantly less effort has been allocated to the development of ecologically sustainable management practices in forests outside reserves (Lindenmayer and Franklin, 2002). A convincing working definition is yet to be developed of what ecologically sustainable forest management actually means in terms of off-reserve forest management, making demonstration of sustainability difficult (Lindenmayer and Franklin, 2003). Noss (1993) concludes that sustainable forestry is a "multifaceted and relative concept". A more realistic approach to demonstrating sustainability may be to define it in terms of well measurable local and regional management goals, and attempt to demonstrate progress toward those goals (Lindenmayer and Franklin, 2003). Such an approach would be consistent with the principles of adaptive risk management outlined below.

We believe that six key factors underpin the failure to demonstrate ecologically sustainable forest management. These are:

1. A failure to clearly specify biodiversity management objectives and constraints in terms of measurable attributes at the management, landscape and regional level. This hinders transparent evaluation of management performance through monitoring and renders managers largely unaccountable for their management performance (Bunnell et al., 2003). Managers have largely failed to set measurable performance thresholds for biodiversity or to specify remedial actions that would be conducted if thresholds are breached.
2. Management options (e.g., silvicultural systems) are typically uniform throughout a forest type (e.g. wet schlerophyll eucalypt forest in Australia is almost always clear-felled Lutze et al., 1999), with no attempt to undertake management experiments to test competing theories about best practice and competing social preferences.
3. A failure to formalize competing views about the impacts of forest management (or relative impacts of competing management options) as transparent models. This makes it difficult for outside observers to identify the expected outcomes of management and how those expectations were determined.
4. A failure to embrace prospective biodiversity risk analysis (but see FEMAT, 1993). We could find no published peer-reviewed examples of biodiversity risk analyses being used to support the assertion that forest management practices are sustainable. However, there have been several cases where risk assessments demonstrate the opposite (Burnham et al., 1996; Noon and Blakesley, 2006).
5. A failure to design and implement monitoring (*sensu* Nichols and Williams, 2006) to assess the performance of management strategies for biodiversity conservation. There is commonly a mismatch between the amount of money required to implement successful monitoring and the amount of money managers and policy makers are prepared to invest in monitoring. A reluctance to set measurable biodiversity management objectives and thresholds (Point #1 above) also makes designing effective monitoring strategies very difficult.
6. A failure to take a systematic approach to setting research priorities based on the uncertainties that most impact on the quality of management decisions. Many of the uncertainties that substantially undermine the decision-making are not being resolved and many research projects are addressing questions that have only a minor influence on decision-making.

If forest management were not subject to uncertainty, then the major challenge facing managers would be to set goals that were agreeable to stakeholders. If agreeable goals could be set, implementation of management would proceed without controversy. However, because uncertainty is pervasive, we argue that a serious commitment to adaptive management (*sensu* Walters, 1986), linked to a systematic risk assessment protocol is necessary to provide a sound basis on which to assert 'ecologically sustainable forest management'. The expression "adaptive management" can be found in standards documents (e.g. FSCC, 2005; AFS, 2007) although the exact meaning seems to vary from standard to standard and definitions are largely absent. The context in which the expression "adaptive management" is commonly used in existing standards indicates a pervasive misconception that any decision to change a management action in light of an observed (usually unexpected) change in the state of a system is, by definition adaptive management. While a semantic argument in favor of this position may be defended, it ignores the large body of work that has developed the theory of adaptive management to a high degree of sophistication. Adaptive management provides a coherent approach to decision-making under uncertainty and a philosophy for learning (Nichols and Williams, 2006). However, this is only the case when it is properly implemented as a whole package from goal-setting and system modeling to monitoring and model-updating (e.g. Johnson et al., 1997). Despite frequent claims to the contrary, forest management relies more on trial-and-error management (sometimes augmented by the results of definitive experiments) than formal adaptive management (*sensu* Walters, 1986; Johnson et al., 1997; Nichols and Williams, 2006, see below). In the remainder of this paper, we outline the key ingredients of an adaptive forest management strategy that would better meet the aims of ecologically sustainable forest management. We argue that scientifically defensible certification schemes should embrace true adaptive management as an overarching framework and philosophy for management and as a minimum standard for certification.

2. Adaptive risk management

Formal approaches to adaptive management (Walters, 1986; Walters and Holling, 1990) integrate information from research, monitoring and management to test and improve management practices. Experimentation is central to understanding the system under management, enabling learning from both successes and mistakes under a systematic, replicated experimental design (Taylor et al., 1998). Adaptive management is not management by 'trial and error' (Linkov et al., 2006). This is because trial-and-error management: (1) is not underpinned by a formal model (or models) for the system being managed, (2) does not formally identify and select between competing management options using competing system models, (3) does not involve a plan for learning, and (4) is usually not replicated and statistically rigorous.

Adaptive management is not a new concept (Walters, 1986), but successful applications are rare in natural resource management (Stankey et al., 2003, 2005). Several barriers have been identified, including difficulties in modeling ecosystem responses to management, risk avoidance, lack of institutional flexibility, the cost of monitoring, and a lack of community involvement (Stankey et al., 2003).

To date, there has been no attempt (that we could find) to reconcile the adaptive management literature with the equally prolific literature on formal risk analysis methods (Burgman, 2005). Risk analysis may be defined as "the consideration of the sources of risk, their consequences and the likelihood that those consequences may occur" (AS/NZS 4360–1999). Risk assessment has become an integral part of conservation science, providing a basis for comparing the value of alternative management options (Akçakaya et al., 2004; Wintle et al., 2005), prioritizing conservation effort between species (IUCN, 2001), and setting research priorities (Lindenmayer and Possingham, 1996). Surprisingly, references to formal risk assessment methods and literature are largely absent in the adaptive management literature.

The integration of formal risk analysis methods with adaptive management will help overcome some of the major impediments to successful adaptive management, including dealing with risk-averse stakeholders (Gray, 2000; Stankey et al., 2003). It will improve approaches to characterizing uncertainty about management outcomes and developing robust management strategies. By integrating risk assessment and adaptive management, we envisage a forest management system that is both responsibly proactive and diligently reactive. Given this, we argue that certifiably sustainable forest management systems must be underpinned by adaptive management principles and formal risk assessment methods (Fig. 2). In the following sections, we detail key components of an adaptive risk management (ARM) system needed to underpin ecologically sustainable forest management and, in turn, underpin credible forest certification schemes.

2.1. Statement of goals, constraints and performance measures

The first step in the development of an adaptive management program is to clearly define management goals and constraints as well as measures by which management performance may be assessed (Possingham, 2001). Without clearly stated goals and performance measures, assertions of sustainability are essentially baseless. Appropriately constructed statements of goals and constraints convert broad (but often opaque) policy objectives such as "maintain species throughout their range" into operational and measurable goals. A possible example would be:

> "achieve at least a 7% internal rate of return on investment in timber management within the region, subject to the constraint of maintaining (with at least 90% confidence) priority species in populations no less than 80% of their estimated population size within the management region for the next 100 years".

This statement is characterized by measurable performance criteria (in units of dollars and population size) and both an explicit spatial context (management region) and an explicit temporal context (100 years). It also explicitly states acceptable levels of uncertainty (>90% confidence). The goals are social preferences that must be elicited throughout the management planning process via community engagement. Clear statements of goals make trade-offs explicit; here, some loss of population size may be tolerated for some gain in net economic benefit. Management performance can then be assessed against goals and constraints.

We reinforce the key points that:

- Goals and constraints must be measurable and clearly define the spatial and temporal scale.
- Required confidence (tolerable uncertainty) is explicitly specified.
- Specification of goals and constraints is a social process and should not be defined by technicians and management professionals alone.

Performance thresholds are often implicit in clearly stated management goals. For example, in the hypothetical management goals defined above, a biodiversity performance threshold is identifiable; the manager must ensure, with 90% confidence, that populations of forest-dependent species would not fall below 80% of the current estimated population size. Setting a threshold has limited value unless there is an identified action if that threshold is breached. In our example, one such action might include the cessation of logging until it can be proven (with sufficient confidence) that the population in question has recovered to the required level.

The inherent unpredictability of natural systems means that unforeseen population declines may occur that were not predicted by rigorous risk assessment. This should not reflect badly on a manager. Rather, a manager should be judged by how quickly the decline was detected (i.e. how robust was their monitoring strategy) and the speed of implementation of remedial actions.

2.2. Specification of management options

Specification of management options is partly a social and partly a scientific process. Management options are usually generated by opinions of stakeholders and scientists about the best means to achieve management objectives. The need for multiple management options arises from uncertainty about the outcomes of particular management options. For example, a manager may predict that the implementation of clearfell harvesting with scattered tree retention will maintain sufficient habitat for large forest owls while ensuring the minimum acceptable economic return. Alternative opinions about the best harvesting strategy to achieve sufficient returns while maintaining

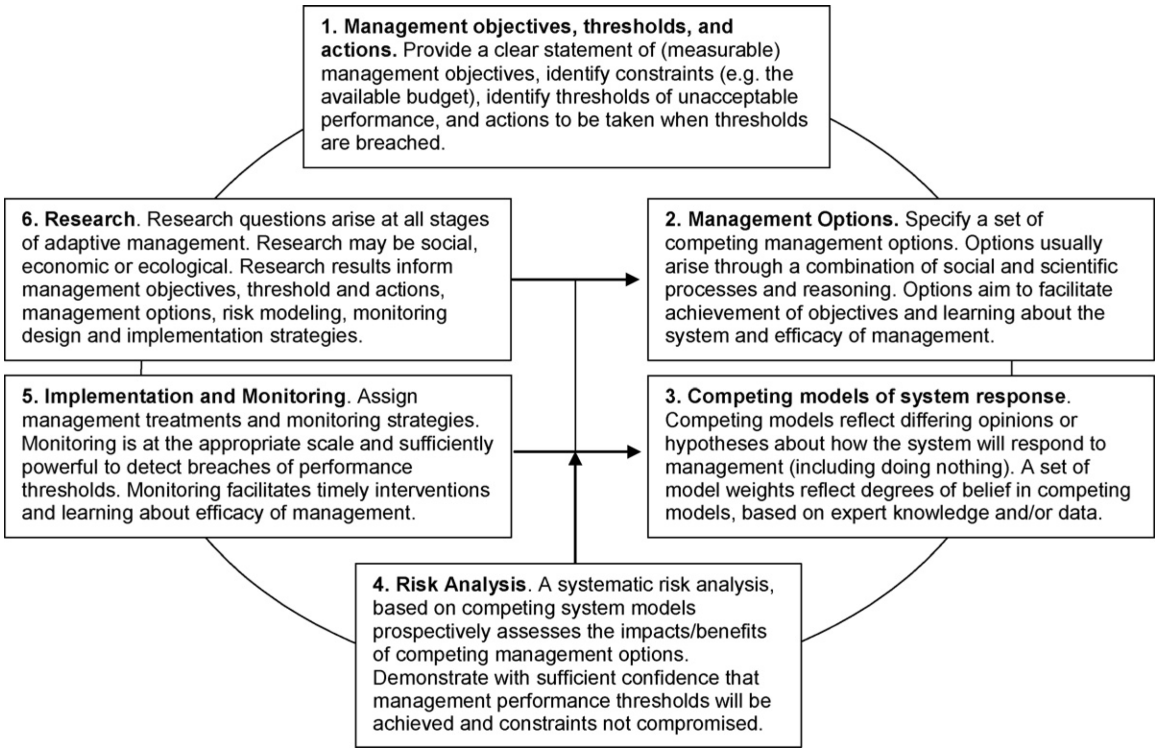

Fig. 2. An adaptive risk management model for sustainable forest management. The model integrates the steps in adaptive management with formal risk assessment protocols. We argue that no forest management should be certified as being ecologically sustainable without demonstrating full integration of the six steps of adaptive risk management for biodiversity.

owls in the landscape may be held by other scientists or stakeholders. An adaptive management strategy would explore the plausible strategies proposed by scientists and stakeholders. The extent to which investment would be distributed between options will depend on the benefits predicted to arise from each management option under assumptions about how the system will respond to management.

2.3. System modeling and model credibility

There is usually substantial uncertainty about how a system will respond to management intervention, or indeed, the ecological processes that mediate that response. It is common for different experts to support qualitatively different models of ecological processes. Qualitatively different forest management models usually imply different views about how species and environmental processes interact with human and natural disturbances. When suitably qualified experts support qualitatively different models, there is substantial uncertainty about the best approach for achieving desired management outcomes. When such uncertainty exists (and is acknowledged), there is value in implementing management options that will facilitate learning about the relative merits of competing models, and ultimately, the best long-term strategies for achieving management outcomes. In some instances, data and expert opinion may favor some models over others. When this is the case, formal methods for weighting competing models may be utilized (Burnham and Anderson, 1998; Wintle et al., 2003). Competing model weights may be used to assist in the allocation of effort between competing management options. If there is no substantial evidence in favor of any one model, then uninformative (equal) model weights may be appropriate until further evidence arises. When new ideas or hypotheses are proposed that previously have not been considered, they should be formalized as a new competing model and added to the model set. There is no requirement that the set of competing models remain the same over time.

In developing an adaptive management strategy for Mallard duck harvesting, Johnson et al. (1997) describe a process for annually updating beliefs about the plausibility of competing models, such that the plausibility of a model given the newly observed data represents a weighted average of current and previous evidence for and against it. Debate about appropriate harvest quotas for Mallards focused on whether population growth would compensate for harvest mortality, and whether reproductive success was strongly or weakly linked to habitat availability. Competing views were summarized as four models of population response (Table 1, USFWS, 1999). Model probabilities were updated with duck population monitoring data over the years 1995–1999 (Table 1). Prior to the collection of monitoring data in 1995, all models shared equal prior probability of 0.25. As monitoring data were collected and compared against the predictions of the four competing models, it became apparent that the compensatory mortality hypothesis was not supported by the data. The data provided support for strong density dependence. It is worth noting that such a quick resolution of competing models would not be expected for most ecological questions around forest-dependent species. This is because of the long time periods over which landscape level impacts are likely to manifest. Nonetheless, the principle provides a basis for a coherent learning strategy that can be applied over any time period, assuming institutions are prepared to invest in learning on that scale.

2.4. Risk assessment

Prospective assessment of the impacts of forest management on biodiversity is a central element of ecologically sustainable forest management. For example, if risk assessment indicates that a forest management plan was likely to commit a particular species

Table 1
Trends in probabilities of competing hypotheses of Mallard population dynamics taken from USFWS (1999) (model probabilities have been rounded to two decimal places)

Model (defined above)	Year				
	1995	1996	1997	1998	1999
1 (am, sdd)	0.25	0.65	0.53	0.61	0.61
2 (am, wdd)	0.25	0.35	0.46	0.39	0.38
3 (cm, sdd)	0.25	0.00	0.00	0.00	0.00
4 (cm, wdd)	0.25	0.00	0.00	0.00	0.00

The four models represent competing views about the relationship between harvest and Mallard population dynamics (1) additive mortality, strongly density dependent recruitment; (2) additive mortality, weakly density dependent recruitment; (3) compensatory mortality, strongly density dependent recruitment; (4) compensatory mortality, weakly density dependent recruitment (USFWS, 1999).

to extinction over a significant area, then it is unlikely that the plan would be considered 'ecologically sustainable' by most stakeholders. The performance measures used to determine the acceptability (or otherwise) of management options under risk assessment must be directly linked to the level of aspiration embedded in the management objectives and performance measures that underpin the adaptive management strategy (see previous section).

We suspect that formal and systematic assessments of the risks faced by forest dependent species have been absent from the vast majority of management plans (but see FEMAT, 1993). Most planning is based on the assumption that the impacts of harvested units are minor (compared with the scale at which biodiversity varies) and that cumulative impacts of a series of cut blocks in a landscape will manifest more slowly than ecosystem recovery. These assumptions are erroneous in some cases (Franklin and Forman, 1987). The onus of proof is on forest management agencies to demonstrate the ecological sustainability of management practices in terms of species persistence and other defined objectives. Given that threatened species legislation in many jurisdictions tends to require the protection and maintenance of viable populations of listed species (e.g. EU Habitat Directive, 2006), it seems logical that detailed risk assessments that predict impacts and benefits of management options on species persistence will be the minimally acceptable demonstration of due-diligence.

Past attempts at prospective assessments of biodiversity impacts have been, at best, ad hoc, often without reference to clearly stated objectives, performance measures, and competing system models, and often at a scale much finer than the scale at which management performance might reasonably be measured. Recent developments in risk assessment techniques (Akçakaya et al., 2004; Wintle et al., 2005) provide managers with powerful and readily accessible tools for assessing the biodiversity impacts of proposed forest management practices.

In a recent study of the impacts of timber harvesting and plantation conversion on the Tasmanian Wedge-tailed Eagle (*Aquila audax fleayi*), Fox et al. (2004) utilized dynamic landscape metapopulation modeling techniques (DLMP: Akçakaya et al., 2004; Wintle et al., 2005) to assess how competing management options impact on future expected population size of the eagle. The process of developing DLMP models may be broadly described in four steps (Wintle et al., 2005): (1) building a habitat model, (2) developing a model of population dynamics, (3) linking these models in a metapopulation model, and (4) building a forest-dynamics model and linking it to the metapopulation model to evaluate management options. Fox et al. (2004) summarized the eagle DLMP results using the expected minimum population size

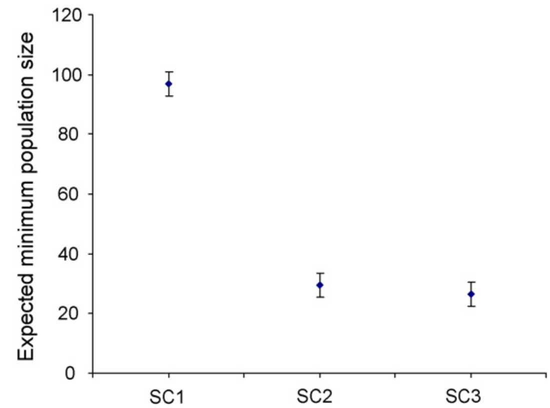

Fig. 3. Expected minimum wedge-tailed eagle population sizes (EMPs) over a 160-year time horizon under three management scenarios (SC1 = no logging or plantation conversion, SC2 = only native forestry logging with natural regeneration, SC3 = native forestry with natural regeneration and approximately 30% of total forest area converted to plantation). EMP may be interpreted as there being a 50% chance of the population falling below the stated level at some time over the next 160 years.

(EMP) metric that represented the average (across multiple simulations of a stochastic population model) minimum population size for the simulation period (in this case 160 years). The results of the DLMP risk assessment process indicated that all anthropogenic disturbance scenarios generated an EMP less than half that of the no-logging scenarios, but that there were no appreciable differences between native harvest-only and conversion scenarios for this species (Fig. 3). This was thought to be because the primary limiting resource for the species was the availability of nesting habitat that occurs only in old, relatively undisturbed forest on sites with large trees, and that these conditions were approximately equally compromised by native forest harvesting and plantation conversion.

Methods such as DLMP provide an explicit framework for modelling the deterministic and stochastic impacts of timber harvesting and natural disturbance on populations of individual species at a scale relevant to management objectives. However, such methods could not be reasonably applied to the whole biota and a defensible subset of species would usually be chosen. For instance, it would be appropriate to select species that:

(i) exhibit dependency on forest attributes affected by forest management (e.g., cavity trees, downed wood, late successional taxa), and
(ii) are potentially adversely affected by fragmentation of old growth forests.

DLMP models provide a short temporal scale of reliability and should be updated regularly to reflect changes in habitat availability and new information obtained by targeted research and monitoring (Lindenmayer and McCarthy, 2006; see below).

2.5. Implementation and monitoring

Monitoring has a quality control and performance evaluation function in the adaptive management process (Walters, 1986). The existence of a monitoring system is a key requirement for certification under existing standards (e.g. AFS, 2007). Monitoring often fails to positively influence management because the link between monitoring results and management decisions is unclear, the questions being addressed are poorly defined, and the monitoring design is inadequate for discerning relevant changes (Roberts, 1991; Macdonald and Smart, 1993; Possingham, 2001).

A major impediment to successful monitoring is the often held attitude that monitoring is a waste of resources, peripheral to management objectives, and at worst, an excuse for inaction (Possingham, 2001). Monitoring programs are often the last budget items to receive approval and the first ones to be cut if funding shortfalls arise (Lindenmayer and Franklin, 2002). Institutional impediments to establishing and maintaining long-term funding and logistical support for monitoring remain a major challenge. However, without a commitment to monitoring, it is impossible to measure management performance and assert ecologically sustainable forest management.

Apart from some notable exceptions (e.g. Haynes et al., 2006; Spies and Martin, 2006), there are few examples of monitoring designs powerful enough to detect pre-specified changes of interest in performance measures, at appropriate spatial and temporal scales (Thompson et al., 1998; Franklin et al., 1999). Monitoring is plagued by the problem of low statistical power and the high probability of failing to detect and act on important declines in biodiversity before it is too late. A major problem is that monitoring has been seen as a trend detection problem and that changes to management are conditional on the rejection of the null hypothesis of no decline or change (usually at some strenuous type 1 error aspiration such as 0.05).

Nichols and Williams (2006) describe an alternative approach to monitoring within an adaptive management framework that does not require null hypotheses rejection and is less reliant on arbitrary statistical conventions. Their approach is similar to the multi-model inference approach of Burnham and Anderson (1998) and utilizes Bayesian updating to iteratively assign credibility to competing models (or hypotheses) as new data becomes available. Bayesian updating can be achieved with readily available software and well-documented methods (Johnson et al., 1997; Wintle et al., 2003). Such an approach can also be used to update model parameters that indicate degree to which management actions influence (or impact upon) the indicators of interest (Duncan and Wintle, 2008). The role of monitoring is to iteratively update and improve such models so that more and more reliable predictions of management effectiveness can be made, resulting in better management decisions.

Successful application of such a decision strategy requires a commitment to monitoring the performance of competing management actions and flexibility to alter management actions in light of the evidence gained from monitoring. It does not require the completion of an experiment or the discovery of a statistically significant trend before a change to management can be instituted; rather it identifies the best decision to be taken now, based on what is believed about the state of the system. This approach is well suited for managing systems in which changes take a long time to become apparent and definitive experiments are not possible in reasonable timeframes.

A formal approach to adaptive management helps clarify the role of monitoring, highlighting the importance of good monitoring design, and decreasing instances of wasteful monitoring. The British Columbian FSC standard (FSCC) requires "measurable management objectives and indicators by which their achievement can be assessed" and reinforces the need for a "clear link between the monitoring plan and the management plan". These are two important elements of an adaptive management strategy. However, without properly specified models that predict the outcomes of management actions it is unclear how the monitoring data will be used to update knowledge about the system response to management. When any key element of the adaptive management system is missing, the system will break down, even if the rest of the elements are well defined. This issue would be resolved if standards were explicitly couched within the adaptive risk management paradigm.

Thinking about monitoring as a model updating exercise reduces the need to worry about whether the monitoring strategy will have sufficient statistical power to reject a false null hypothesis of, say no change in a given period. However, it does not diminish the need for careful sampling design and appropriate statistical analyses of monitoring data. A detailed review of statistical monitoring best-practice is beyond the scope of this paper (see Thompson et al., 1998; Nichols and Williams, 2006), but a good monitoring strategy can generally be characterized by:

- A clear link between monitoring and clearly stated management objectives.
- Clearly defined performance measures (e.g., population size of forest dependent species).
- Planned responses to findings; there is no point in monitoring if there is no intention to change management in light of findings.
- A sampling design that adequately reflects the precision (confidence) requirements implied by the stated management objectives.
- A spatial extent and resolution that is congruous with the stated management objectives.
- Monitoring of a small number of things well rather than many things poorly.
- The targeting of taxa for which detailed risk assessments are also undertaken (e.g. Haynes et al., 2006; Lindenmayer and McCarthy, 2006).

2.6. Research

Many important gaps remain in the information required to underpin sustainable forest management. Given the limited resources for conservation management, there is a need to make strategic decisions about the research most appropriate to inform sustainable forest management. It is impossible to study every species, ecological process and ecological pattern. Determining research priorities for conservation management is a non-trivial task. In an adaptive management system, research may be prioritized by the knowledge requirements identified in, and the modeling phase of, the adaptive management cycle as well as in response to un-explained patterns observed during monitoring. When building models that links performance measures to management options the knowledge gaps that impact most on predictions (and therefore management decisions) become apparent. Questions generated during the system-modeling phase of adaptive management serve as suitable research priorities. The ability to have such priorities funded may depend on the extent to which management agencies are prepared to underwrite such research and how public research funding bodies prioritize 'applied' research. As long as prioritization of research questions is tightly linked to the adaptive management process, research output will be of use to managers and the uptake of research will be improved.

3. Linking the pieces

Much has been written about adaptive management and some of its elements—objective setting, model formulation, monitoring and evaluation. All steps of adaptive management (Fig. 2) are tractable with currently available knowledge and technology. However, forest management has largely failed to link these components to provide convincing examples of successful adaptive management (Stankey et al., 2003). Adaptive management is mentioned in existing certification standards. However, it is far from being central to attainment of certification. It is not enough to simply require that managers will monitor and 'adapt' to new information as it arises. We argue that standard-setting bodies must go further toward instituting adaptive management, such that a requirement for certification is to demonstrate that management is conducted within an ARM framework that includes all of the elements we have described here.

An inability to translate broad policy aspirations (e.g., "ensure the persistence of forest dependent species throughout their range" Commonwealth of Australia, 1992) into measurable performance targets may be the largest impediment to the institutionalizing adaptive management. We encourage those setting standards for forest management to require clear statements of management goals, in terms of measurable performance targets. Until management is based on measurable outcomes, forest managers will not be in a position to demonstrate ecologically sustainable forest management and certification schemes may be failing to adequately conserve forest biodiversity.

4. Dealing with uncertainty

Application of an adaptive risk management framework requires the specification of models to describe and predict the influence of management on key performance measures. Substantial uncertainty and a lack of data (e.g. population estimates, demographic parameters, disturbances responses, environmental stochasticity) are cited as reasons not to develop such models. It is sometimes feared that application of formal decision frameworks may serve to clarify the extent of uncertainty, leading to policy inertia. However, in the absence of a formal decision model, decisions will, nonetheless, be made on the basis of *someone's* (usually a manager's) internal conceptual model of the system (expert opinion). We argue that it is better that the model is written down and made explicit, so that it can be tested against other people's opinions and data; where relevant data exists. Writing down a model is a good way of improving internal consistency; something that cannot be guaranteed in even the most experienced expert (Burgman, 2005). Model building requires all assumptions to be stated and key uncertainties to be identified. Model building and sensitivity analysis enables identification of the *important* uncertainties that, if resolved through monitoring, will contribute most to improved decision-making. Separating the uncertainties that are important from those which are not is a crucial benefit of structured, model-based decision analysis. The advantage of adaptive management is that it provides a framework for resolving key uncertainties without having to cease management or wait for a definitive experimental result. Because we can never hope to completely resolve uncertainty, we recommend adaptive management as a coherent strategy for acting in the face of it.

One of the most important parts of the objective setting phase of adaptive risk management framework is the identification of tolerable levels of risk (e.g. no more than a 5% chance of 10% decline in 50 years). If stakeholders are not prepared to accept any risk (i.e. a requirement of 0% chance of a failure to achieve performance thresholds), then management cannot proceed. The value of an inclusive structured decision framework is that the constraints that stakeholders impose on management are written down for everyone to see and judge as either reasonable or unreasonable. A major impediment to sound decision-making is the inability of political institutions to accept that most management is conducted under severe uncertainty. Adaptive management forces an explicit statement of uncertainty that may not always be politically palatable (Davis et al., 2001). Strategies for convincing policy makers and the public of the value in admitting uncertainty should be a high research priority (Lindenmayer and Franklin, 2003).

5. Institutional support for adaptive risk management

ARM is a framework. While we have given some simple examples here, ARM itself does not prescribe particular objectives, actions, methods of system model development and risk assessment, or best practice monitoring strategies. Individual applications of ARM necessitate choices about all of these things to be made by managers. Development of a full ARM system is a big investment. ARM places technical demands on forest managers, agencies and companies. Elicitation of measurable management goals, system modeling, and monitoring design and analysis requires social, ecological and statistical expertise that is not always readily available to managers. Many certificate holders with limited access to ecological modeling or statistical expertise will struggle to develop aspects of the adaptive risk management framework to an adequate level. Similarly, certificate holders may have difficulty in providing appropriate forums for eliciting social preferences, management objectives, performance measures and acceptable risk thresholds. This highlights the need for coordination between certifiers, agencies and companies to facilitate ARM across the range of certificate holders. Strong agency commitment is required to support elicitation of social preferences, objectives, tolerable risks and other technical matters such as biodiversity risk assessment and regular analysis of monitoring results. To date, such commitments have not been forthcoming. Government agencies have focused more heavily on development of broad-scale indicators of sustainable forest management (Commonwealth of Australia, 1998) that are largely irrelevant at the landscape scale. Issues of scale also arise when considering the aggregate influence of several relatively small cutblock accumulated over a landscape (Franklin and Forman, 1987). Individual certificate holders operating in accordance with a standard on their own patch does not ensure good outcomes for biodiversity at a landscape or catchment level. More emphasis on coordination at a landscape level is required to ensure good biodiversity outcomes. This again will require substantial State and Federal agency commitment to foster and facilitate ARM.

6. Managing indirect impacts on biodiversity

Much of the debate about the impacts of forest management is focused on the identification and management of direct risks posed to species and ecosystems by forest management activities such as habitat loss or alteration. Indirect impacts of forest management on biodiversity may include such problems as increased mortality of fauna species due to 'bush-meat' harvests (Redford, 1992; Bennett, 2000) or the gradual loss of key tree species through inadequate post-logging regeneration (Felton et al., 2007).

The adaptive risk management system proposed here provides an appropriate framework for dealing with both direct and indirect impacts of forest management on biodiversity. The primary challenge in dealing with indirect impacts is the identification of potentially threatened species and communities and the mechanisms by which they are threatened. A genuine adaptive management system explicitly accommodates new threats and opportunities into the management cycle as they arise or become apparent.

7. Certification as an instrument of biodiversity conservation

Certification schemes largely acknowledge the primacy of legislation. The Australian Forestry Standard sets State and Federal requirements as the base level of performance. Rametsteiner and Simula (2003) found that certification standards are ''at least equal to legal requirements and often include elements that set actually higher standards''. Because certification bodies do not represent the larger community, it would be inappropriate for certification to supersede or somehow diminish the importance of regulation in protecting biodiversity. One implication of this is that if the laws in a country do not set a good base level of management, then the importance of a good standard is increased and the detailed wording of a standard must be scrutinized to avoid loop-holes. However, even in countries with good biodiversity regulation, certification has advantages over legislation and regulation in that it can require managers to adopt standardized management systems such as adaptive risk management that provide a more meaningful commitment to sustainability than simply adhering to legislation. In return, managers should be rewarded with a market advantage over non-certificate holders.

Forest certification schemes will drive the standard of forest management for the foreseeable future. Current certification schemes fall short of achieving goals of adequate off-reserve forest biodiversity conservation because they do not adequately define and require adaptive risk management. Most forest managers are not currently in a position to substantiate the assertion they are managing forests (and forest biodiversity) in an ecologically sustainable way. The credibility of certification schemes will hinge on a demonstrable commitment to adaptive risk management.

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