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REVIEW AND SYNTHESIS

A checklist for ecological management of landscapes for conservation

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Abstract

The management of landscapes for biological conservation and ecologically sustainable natural resource use are crucial global issues. Research for over two decades has resulted in a large literature, yet there is little consensus on the applicability or even the existence of general principles or broad considerations that could guide landscape conservation. We assess six major themes in the ecology and conservation of landscapes. We identify 13 important issues that need to be considered in developing approaches to landscape conservation. They include recognizing the importance of landscape mosaics (including the integration of terrestrial and aquatic areas), recognizing interactions between vegetation cover and vegetation configuration, using an appropriate landscape conceptual model, maintaining the capacity to recover from disturbance and managing landscapes in an adaptive framework. These considerations are influenced by landscape context, species assemblages and management goals and do not translate directly into on-the-ground management guidelines but they should be recognized by researchers and resource managers when developing guidelines for specific cases. Two crucial overarching issues are: (i) a clearly articulated vision for landscape conservation and (ii) quantifiable objectives that offer unambiguous signposts for measuring progress.

Keywords

Connectivity, ecosystem processes, land use change, landscape conservation, landscape models, resilience, thresholds.

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INTRODUCTION

Landscape ecology, conservation biology and restoration ecology aim to promote better management of natural resources including biodiversity. They have produced a large literature including many texts (e.g. Wiens & Moss 2005; Lindenmayer & Fischer 2006). While emerging methods such as meta-analysis (Lajeunesse & Forbes 2003) and systematic reviews (following leads from medicine; see Fazey *et al.* 2005) can identify some overarching patterns, many investigations have produced largely species-specific, landscape-specific or case-specific results. To guide better landscape conservation, can any general principles be derived from the enormous body of existing work? The need for them is now more urgent than ever because: (i) much ecological knowledge fails to be adopted on the ground (Fazey *et al.* 2006), (ii) it is impossible to study in detail all species in all landscapes and (iii) human landscape modification is accelerating, as are its potential interactions with other drivers such as climate change (Thomas *et al.* 2004).

In this study, we summarize insights relating to six broad themes in landscape ecology, conservation biology and restoration ecology. We briefly discuss points of agreement and important unresolved issues rather than present a comprehensive overview or attempt to resolve debates within those themes. We produce a conceptual model that emphasizes the interlinkages among the six themes. The model represents a significant advance in our understanding of the complex interactions occurring in landscapes and serves to guide future research and conservation. The interrelationships between themes are often overlooked but are critical, not-the-least because of the potential for cumulative effects of human modification of landscapes and emerging problems such as climate change. We concentrate on the ecological aspects of landscape conservation and have not explored socio-economic considerations, which are often of over-riding importance in influencing policy, planning and on-the-ground management (Haila & Dyke 2006).

Based on a synthesis of the six themes, together with discussions among the co-authors at a meeting in March 2006, we also present a checklist of considerations for the ecological management of landscapes for conservation. We are aware of the challenge of identifying considerations that are not so general as to be truisms that offer little substance. Conversely, because all ecological systems are unique, we do not provide specific prescriptions for on-the-ground implementation of these considerations: the composition and ecological processes of ecological systems are a function of their location, physical and chemical environment, spatial context and surroundings, history and current level and type of human use. Specific application will be context-dependent. Given the tension between truisms and specific prescriptions, our aim was to derive a set of general considerations to guide better landscape conservation regardless of the location or the type of system being managed.

LANDSCAPE THEMES

Although we discuss six broad themes separately, we acknowledge they are strongly interrelated and boundaries between them are somewhat artificial (Fig. 1). We have not touched on other important related areas such as landscape genetics, spatial statistics or issues associated with marine seascapes. Insights from these might well produce considerations additional to those generated in the second part of this paper.

Landscape classification

Landscape classification involves using a conceptual model to characterize a landscape, grouping landscape elements into categories and/or allocating entire landscapes into classes based on the amount and distribution of landscape attributes. This allows generalizations to be bounded (i.e. generalization X occurs within landscape type Y). Landscapes can be classified using: structural attributes, such as the amount and configuration of vegetation (e.g. Forman

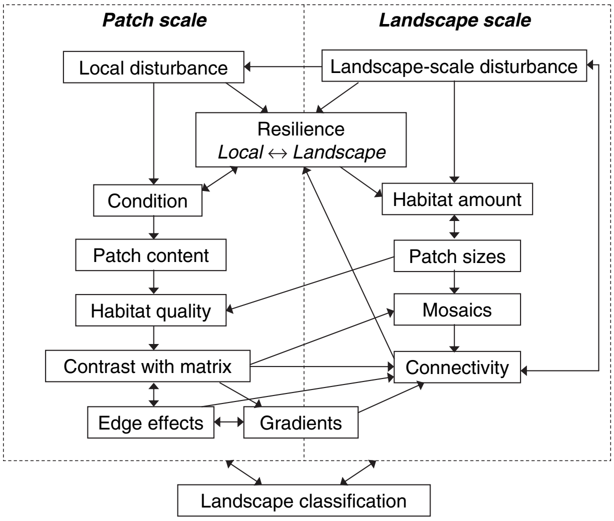

Figure 1 Conceptual model highlighting inter-relationships between key landscape themes discussed in the text. Arrows indicate likely primary relationships in most landscapes under most circumstances. Secondary relationship between themes are implied rather than shown explicitly.

1995); habitat for a particular species (e.g. Fischer *et al.* 2004) and functional attributes or landscape processes (e.g. Ludwig *et al.* 1997). These differences give rise to, for instance, the variegation model (McIntyre & Hobbs 1999) and gradient-based models (e.g. Manning *et al.* 2004). Despite many alternative models, many workers continue to use the island model or Forman's (1995) patch-corridor-matrix model to classify landscapes, particularly those subject to human modification (i.e. the majority of fragmentation studies; Haila 2002). Such simple models often portray landscapes in a binary form composed of 'habitat' and 'non-habitat' and therefore fail to consider many important aspects of landscapes.

Complexity, issues and interrelationships
Landscape classification is challenging because:

(1) Landscapes are dynamic and characterized by compositional (structural) attributes and process (functional) attributes, such as flows of energy, water and nutrients.
(2) Maps are the usual translation of a landscape into a classification and while they capture compositional attributes reasonably well, they have rarely been used to represent processes or flowpaths, particularly those that are continuous entities or gradients.
(3) There are many ways of perceiving the same landscape (Fig. 2). Organisms perceive landscapes differently (Manning *et al.* 2004) as do humans, including 'lumpers' who favour generality and 'splitters' who focus on complexity.
(4) Different problems and objectives may require different classifications, even in the same landscape. A classification to guide an organism-specific research programme may differ from one needed by a landscape manager.

The importance of classification and conceptual models is overlooked by many researchers and managers who seem unaware of interrelationships among themes such as edge effects, connectivity and patch sizes (Fig. 1). For example, edges are typically defined from a human perspective using a binary (habitat vs. non-habitat; original vegetation cover vs. cleared) model of cover. Edge definition becomes more challenging when edges are characterized from the perspective of an individual species (which can change seasonally or over short time periods) or when gradient or continuum landscape models are employed (Fischer *et al.* 2004). The way conceptual models are used can have marked influences on other themes such as what defines a patch, the size of that patch, within-patch content (e.g. vegetation condition) and [patch]area-species relationships (Fig. 1).

The spatial extent and pace of climate change poses additional challenges. New classifications and conceptual models may be needed, in particular to cope with likely (additive and/or cumulative) interactions between past and ongoing changes (such as human-derived vegetation loss) at the landscape and/or regional levels.

Habitat amount, amount of land cover, patch sizes and mosaics

Habitat loss is a major driver of species loss worldwide (Foley *et al.* 2005). Given this, it is crucial to determine how much habitat is needed to meet specific conservation objectives. First, we need to define habitat. The term is often used loosely and this has led to much confusion (Hall *et al.* 1997). Habitat is generally defined in two ways: (i) a species-specific entity – the environment and other conditions suitable for occupancy by a particular taxon or (ii) a particular land cover type (such as riparian vegetation), or sometimes, in urbanizing areas or regions recently developed for agriculture, simply the amount of native vegetation cover. These differences can be critical for conservation (Hall *et al.* 1997).

The area of a particular land cover type will rarely reflect the amount of suitable habitat for a given species. For example, a landscape might support a continuous area of native forest but a forest-dependent species may be absent because of the paucity of old growth that provides habitat for it (Lindenmayer & Franklin 2002). Habitat and land cover type is not synonymous is further as emphasized by aquatic taxa such as amphibians for which the nature of currents and flow patterns together with the attributes of riparian and upland vegetation are important. Similarly,

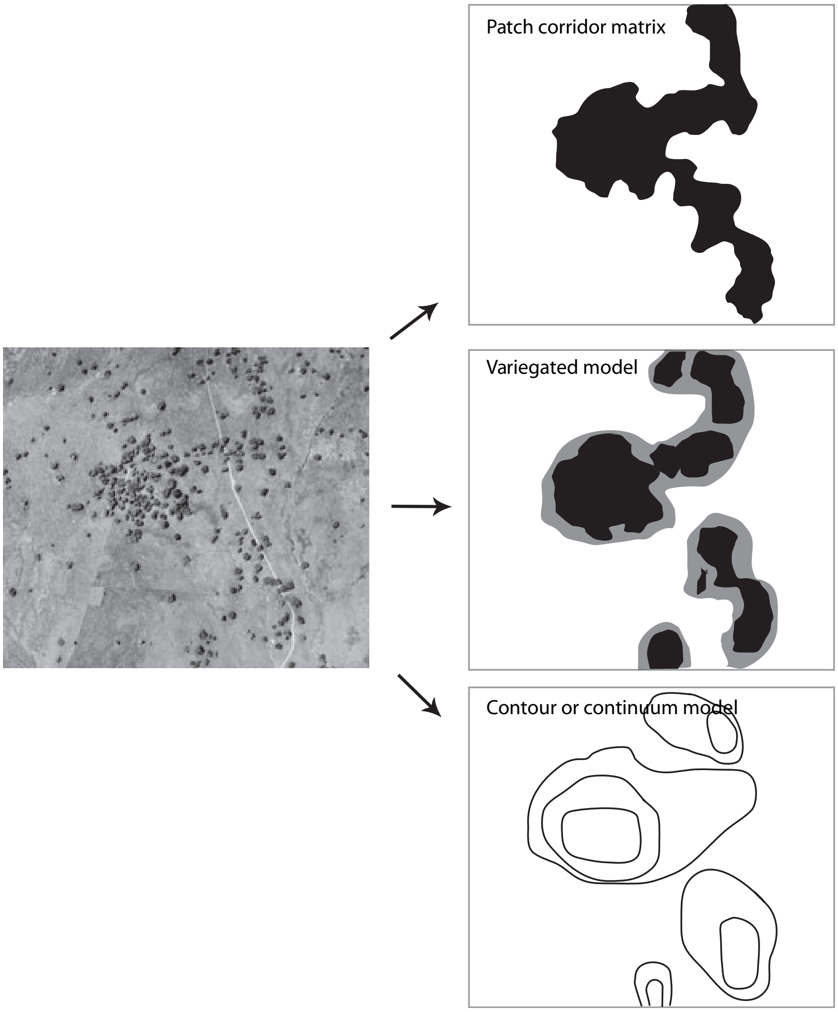

Figure 2 Classsification of the landscape in different ways.

habitat for some species such as those in European agricultural areas is strongly associated with extensively modified locations characterized by a prolonged human use. However, these species can be lost from such places if agricultural intensification occurs (Benton *et al.* 2003) or if cropping areas are abandoned (Schmitz *et al.* 2007).

The particular use of the term 'habitat', coupled with how a landscape is classified and mapped (see above) will determine what constitutes a 'patch' – a patch of habitat for a given species, or a patch of vegetation of a particular type. In both cases, larger patches have been considered critical. This is because of relationships between patch size and: (i) the size and extinction proneness of populations of individual species, (ii) species richness and (iii) many other factors (e.g. immigration rates, disturbance sizes and vegetation diversity). While large patches are important, many studies have shown that the ecological values of small- and medium-sized patches can be considerable (Turner 1996). In addition, patch size is relative; what constitutes a large patch of habitat for a species of beetle may be a small patch for a species of bird or mammal.

Complexity, issues and interrelationships

The species-specific concept of habitat can be complex because: (i) habitat is multi-scaled, (ii) the many different methods used to quantify habitat requirements can produce markedly different outcomes and (iii) the habitat requirements of a given taxon may vary between vegetation types, regions or different life stages of the same species. Similarly, while native vegetation cover may be a useful concept on continents such as the Americas and Australia where it often relates to pre-European vegetation, it is less relevant from a European perspective because many landscapes and vegetation types have a prolonged history of human modification and management. Historical benchmarks for native vegetation cover could relate to pre-human occupation, prior to forest utilization, pre-agriculture or before agricultural intensification.

A related problem then is that it may not always be straightforward to determine what constitutes a patch (Bunnell 1999) – a fact that has enormous implications for ecological and conservation theory; species–(patch)area relationships provide one of many examples. What defines a patch from a human perspective and implemented simply in a GIS might not be particularly meaningful for a particular taxon or species assemblage. In other cases, patch content (and hence often vegetation condition) can be critical in defining what constitutes a patch and hence helping to distinguish that patch from its surroundings (e.g. Forman 1995). This is a key consideration in many kinds of conceptual landscape models and classification systems (McIntyre & Hobbs 1999; Fig. 1). 'Patch' content and levels of contrast with surrounding areas can have a significant influence on biotic responses in landscapes. Two examples include the manifestation of edge effects (Harper *et al.* 2005) and the maintenance of connectivity (Franklin 1993) including the degree to which phenomena like fence effects (Wolff *et al.* 1997) occur.

Many studies have focused on individual patches or sites within patches, but patch size effects cannot be divorced from other pivotal issues such as the role of ensembles of patches or patch mosaics – a topic that remains poorly understood (Bennett *et al.* 2006). Mosaics of different patches (in different condition and characterized by different internal structure) are important as shown from research in fire dynamics (e.g. Parr & Andersen 2006) and native biota in agricultural landscapes (Schmitz *et al.* 2007). Patch sizes and vegetation mosaics are often closely associated with the total amount of habitat in landscapes – a factor governing the occurrence and abundance of many native species (Askins *et al.* 1987). Many past studies of patch content and connectivity may have failed to grasp the importance of the overall amount of habitat or land cover in landscapes. For example, connectivity is least likely to be disrupted when the amount of a particular kind of land cover is high (Hannon & Schmiegelow 2002; see below).

Thresholds may exist for the amounts of particular kinds of habitat or land cover types in a landscape. When these thresholds are breached, sudden changes in species abundance or ecosystem processes may occur, leading to changes in system state or 'regime shifts' (Folke *et al.* 2004). Hypothetically, thresholds are more likely to be crossed and regime shifts more likely to occur when levels of particular kinds of habitat or types of land cover are low (e.g. 10–30%; Radford *et al.* 2005). However, (i) it is difficult to identify critical change points or thresholds and to anticipate (and prevent) regime shifts before these occur (Groffman *et al.* 2006) and (ii) thresholds may not exist for some measures such as aggregate species richness because of contrasting responses of individual species. Nevertheless, the key point is to recognize the possibility of nonlinear responses to landscape modification and the existence of critical zones in which rapid change occurs.

Structure and condition

Relationships between structural complexity in vegetation and species richness are well documented. Many forms of human land use (e.g. livestock grazing and forestry) simplify vegetation structure and significantly alter vegetation condition (Foley *et al.* 2005). Assessing structure and 'condition' may be relatively straightforward for individual species if data on habitat requirements are available (Felton *et al.* 2003). Assessing vegetation structure and condition is more complex for multiple species, particularly because nearly all changes in vegetation condition benefit some species but not others. For example, highly disturbed vegetation in the early stages of succession following perturbation can be the primary habitat for some taxa including those of conservation concern, but late successional species can be absent from them for prolonged periods from these areas.

Complexity, issues and interrelationships

In the absence of knowledge on species' habitat requirements, reference conditions are sometimes used, for example, in assessing the deviation of a site from a benchmark that represents relatively 'natural' or unmodified examples of a comparable ecosystem (Parkes *et al.* 2003). Defining appropriate benchmarks can be difficult. Ecosystems are dynamic and may exist in multiple states, supporting different species combinations. In landscapes subject to natural disturbances such as wildfire, a single benchmark is inappropriate. Rather, attempts to define appropriate regimes of disturbance (*sensu* Gill 1975) and/or the quantification of the properties of mosaics may be needed (Bennett *et al.* 2006). It is also difficult to determine what is 'natural' in landscapes long influenced by humans, where naturalness may not even be an appropriate characteristic to consider. This, in turn, can lead to different human perspectives on what is appropriate vegetation structure and condition. This is allied with the concept of shifting baselines in which current perspectives on what is 'natural' may be poor facsimiles of what was natural for that same ecosystem, even relatively recently.

Scale issues are critical in assessing vegetation structure, degradation and condition. It is not always clear what spatial scale is appropriate to quantify vegetation condition; for example, the juxtaposition of dense and open areas that creates an appropriate mix of sheltering and foraging areas for a woodland bird will be a differently scaled mix from that required by wide-ranging grazing mammals.

There are many unresolved issues with the metrics available for assessing vegetation structure and for quantifying departure from benchmarks. Most are an amalgam of submetrics combined in some way to give a 'vegetation score' (e.g. Parkes *et al.* 2003). Problems have existed for several decades on how best to combine subscores (e.g. to add or multiply them) and how to substitute different vegetation subcomponents (e.g. van Horne & Wiens 1991). There are also tenuous links between metrics and viability of biota (McCarthy *et al.* 2004).

Although appropriate spatial and temporal quantification of vegetation structure, degradation and condition remains complex, they are critical elements of: (i) assessments of the conservation status of areas, (ii) development of targets for restoration, (iii) attempts to use natural disturbances as templates to guide human disturbance and (iv) our understanding of how future changes in climate may transform vegetation cover and composition.

Structure, degradation and condition are inextricably linked with other themes in this study such as disturbance, amount of habitat and patch content (Fig. 1). For example, it is not always clear what constitutes a patch within which to define 'condition' (Bunnell 1999) and hence the conceptual landscape model underpinning a landscape classification can be important. Vegetation condition is usually assessed at a site level which may be part of a patch or of a continuum. Thus, vegetation condition and hence patch content can influence levels of differentiation with surrounding areas with implications for estimates of the amount of habitat in a landscape, patch mosaics, edge effects and connectivity (Fig. 1).

Connectivity

Connectivity relates to the ability of species and ecological resources and processes to move through landscapes, not only in the terrestrial domain, but also in aquatic systems and between the two. Connectivity, and in particular the value of corridors, has been much debated. Some debates about connectivity stem from the term being too broadly conceived, rendering it difficult to use in practice and different interpretations of terms. Lindenmayer & Fischer (2007) suggested that some of the controversy might be avoided by making a careful distinction between: (i) habitat connectivity or the connectedness of habitat patches for a given taxon, (ii) landscape connectivity or the physical connectedness of patches of a particular land cover type as perceived by humans and (iii) ecological connectivity or connectedness of ecological processes at multiple spatial scales. Lindenmayer & Fischer (2007) further noted that although the three connectivity concepts are interrelated, they are not synonymous. In some circumstances, habitat connectivity and landscape connectivity will be similar (Levey *et al.* 2005). In others, habitat connectivity for a given species will be different from the human perspective of landscape connectivity.

Complexity, issues and interrelationships
Connectivity remains one of the most difficult areas of landscape conservation. Measuring connectivity is not straightforward and metrics used can be highly problematic (Tischendorf & Fahrig 2000a). Habitat connectivity and other forms of connectivity are hard to study because they are interrelated with the notoriously difficult area of dispersal biology (Keogh *et al.* 2007). Nevertheless, a better understanding of connectivity is urgently required given impending effects of rapid climate change on species distributions and the potential for shifts in species ranges to be blocked by human modification of landscapes.

The appropriate spatial scale for various connectivity concepts is another unresolved issue. Tischendorf & Fahrig (2000b) consider connectivity to be a landscape-scale concept, whereas Moilanen & Hanski (2001) argue that it is better understood as a patch-scale concept. Similarly, the spatial and temporal scales for what constitutes suitable habitat connectivity vary between taxa. Scale effects are also significant for ecological connectivity – seed dispersal (Levey *et al.* 2005) vs. hydrological flows (Lake 2000) provide an illustration.

Although most ecologists agree about the importance of various kinds of connectivity, disagreement arises when connectivity is equated simply with corridors or linear strips of a particular vegetation type that link patches of that vegetation type. Supply of corridors is just one of several approaches to providing connectivity for some species and ecological processes (Levey *et al.* 2005). The simplicity of the corridor concept and the relative ease with which corridors can be implemented in planning exercises can lead to a failure to consider the connectivity function of the surrounding areas (Hannon & Schmiegelow 2002). This emphasizes that the topic of connectivity cannot be readily divorced from others such as the amount of a particular land cover type in a landscape and the value of that cover as habitat for particular species (Fahrig 2003; Fig. 1).

The significance of edges

Empirical studies have shown that sharp boundaries between patches influence diverse biotic and abiotic processes (Ries *et al.* 2004; Harper *et al.* 2005). Edge effects refer to changes in biological and physical conditions that occur at a patch boundary and within adjacent patches. There are many types of edges and edge effects; for example, human/natural, primary/secondary and hard/soft. There is also much ecological variation in response to different kinds of edges – among taxa, between vegetation types and between regions. Although the magnitude of responses to particular edge effects may differ, often the nature of the effect (i.e. positive or negative) will not. Mechanistic approaches based on the strength of habitat associations and resource availability may help to clarify the nature and strength of edge effects and provide a foundation for improved predictive models – at least for biotic edge effects. Ries *et al.* (2004) and Harper *et al.* (2005) provide useful conceptual approaches in this regard.

Complexity, issues and interrelationships

Edge effects have received less attention than deserved despite their pervasive nature and potential for significant impacts. There are problems with the experimental design of many edge effects studies, although attempts to implement controls and obtain sufficient replicates are always challenging in landscape ecology. Variation in the field methods used in different investigations has made cross-study comparisons difficult (Murcia 1995). Moreover, there are few examinations of temporal variation in edge effects (Lindenmayer & Fischer 2006), and few studies of ecosystems other than forests. There have been remarkably few studies assessing relationships between extinction-proneness and edge sensitivity (but see Lehtinen *et al.* 2003).

Discussions of edge effects are intimately linked with other key themes in landscape ecology and conservation biology. An example is the relationship between edge effects and the amount and spatial configuration of particular vegetation types in a landscape (Bayne & Hobson 1997). Similarly, a particular classification of a landscape and the map generated from it will influence where and how edges are perceived to occur. Edges are usually considered from a human perspective and scale (Bunnell 1999), but edges and edge effects can exist at many scales (Laurance *et al.* 2001), and the way organisms perceive and respond to edges will often differ from humans. Hence, simple categorizations such as 'edge' or 'interior' species will often provide inadequate descriptors of complex responses. The assumption that edges and edge effects are important is also linked to the perpetuation of a patch-based conceptualization of landscapes. Patch-based classifications of complex landscapes may be artefacts of mapping. A large literature demonstrates that both biotic and abiotic variables change as continuous functions from the interior of one patch to the interior of the adjoining patch (Sisk *et al.* 2002). Gradient approaches that complement patch-based conceptualizations of landscapes may help foster the continued development of ideas about how landscape patterns, including edges, can influence ecological processes (Fischer *et al.* 2004; Fig. 1).

Disturbance, resilience and recovery

Disturbance shapes patches and landscapes (Fig. 1), influences biota, and accentuates the inherent complexity and dynamics of ecosystems and landscapes. Using natural disturbance regimes as a guide to manage human-induced disturbances such as logging and grazing has been proposed for many years. The underlying premise is that species are likely to be adapted to disturbance regimes with which they evolved, whereas they may be susceptible to novel disturbance. Hence, improved biodiversity conservation might be better achieved by using natural disturbance to guide human disturbance regimes.

Extreme natural disturbance events can have profound impacts on ecosystems (Lake 2000). They can be difficult to predict and manage. However, they can be anticipated (Scheffer *et al.* 2001) and help target management so that it maintains or builds the capacity of ecosystems to recover following disturbances. As an example, droughts are common in many areas, and organisms adapted to drought-prone areas have refugia where they can survive the dry period.

Complexity, issues and interrelationships

Many disturbance-related issues have yet to be resolved. Some paradigms such as the intermediate disturbance hypothesis have equivocal support as do others like 'pyrodiversity begets biodiversity' (Parr & Andersen 2006). Complexities arise because while single intensive and/or large-scale disturbances can have profound impacts (Turner *et al.* 2003), in many cases it is the disturbance regime (*sensu* Gill 1975) or the sequence of disturbances over time and the timing, intensity and spatial pattern of each perturbation in the regime that has the greatest impacts (Barlow & Peres 2006). It is hard to quantify the most appropriate disturbance regime/s for a given species, vegetation type or landscape because of the spatial and temporal variability in attributes such as intensity, frequency and timing (Gill 1975) and relationships with other key themes such as the development and importance of landscape mosaics (see above).

A further issue is that although the use of natural disturbance regimes to guide human-induced disturbances has considerable merit, it also has limitations. First, the concept is both difficult to test and actually remains largely untested in most forest ecosystems. Second, some very complex processes are extremely difficult to emulate (James & Norton 2002). Third, the needs of particular taxa and the conservation requirements for particular areas may not be met. Many landscapes have changed as a result of human disturbances such as vegetation clearance and river regulation and 'natural' disturbance regimes may no longer be appropriate or achievable. Human disturbance will never be a perfect analogue for natural disturbance, nor are human and natural disturbances independent. Rather, there may be magnified or cumulative effects resulting from both of them occurring in the same broad area. Salvage harvesting after natural disturbance is an example (Lindenmayer & Noss 2006).

A further complicating issue is that disturbances sometimes induce nonlinear threshold changes in ecological processes, species interactions and population sizes in which there is a sudden switch from one state to a markedly different one (Walker *et al.* 2004). Such thresholds are process-related, compared with the pattern-related thresholds in landscape structure discussed earlier (Homan *et al.* 2004). Crossing some thresholds may produce changes that are either irreversible or extremely difficult to reverse (Zhang *et al.* 2003). Consequently, understanding thresholds is critical. However, it is not clear how to identify thresholds before they occur (Groffman *et al.* 2006) and, in turn, ensure that management practices do not inadvertently drive ecosystems, species and ecological processes close to critical change points. Not all trajectories are characterized by critical breakpoints (Groffman *et al.* 2006), and so differentiating the kinds of species, landscapes, ecosystems and ecological processes prone to threshold responses from those that exhibit other kinds of responses is important.

One approach to dealing with complex and nonlinear dynamics is to apply different conservation strategies in different places and treat management practices as experiments with replication of management treatments and careful monitoring of responses. This can facilitate learning and better inform management practices that can then be altered on the basis of new knowledge and accompanied by further planned experimentation and monitoring. This procedure of active adaptive management (Walters & Holling 1990) is widely discussed but rarely implemented. Using natural disturbance regimes to guide adaptive management-by-experiment-and-monitoring also may help avoid crossing thresholds or critical change points. It might be possible to limit the risks of triggering negative nonlinear responses by managing for increased resilience. However, improving resilience of one ecosystem process may reduce resilience in another (Walker *et al.* 2004). The topic of resilience has been controversial because it is often unclear what is meant by resilience and resilience also can be difficult to quantify in the field. However, progress can be made when resilience is well-defined (Folke *et al.* 2004) and well-focused approaches are used to study it and then to maintain it (e.g. Fischer *et al.* 2007).

A CHECKLIST OF IMPORTANT ISSUES

From the many reviews and texts in landscape ecology, conservation biology and restoration ecology, coupled with perspectives in the themes discussed above, we present 13 important issues aimed at fostering the development of practical goals for landscape conservation. These considerations are not highly prescriptive. Rather, they form a checklist of factors to be considered by people managing landscapes for conservation. It may then be appropriate for them to be formulated as a set of hypotheses more specific to a particular set of circumstances.

While some of these considerations we have generated may seem trite to some researchers, there is evidence that they are often overlooked by both researchers and managers in developing landscape plans and hence that much existing ecological knowledge is not used (Fazey *et al.* 2006).

Setting goals

Develop long-term shared visions and quantifiable objectives

Much conservation is undertaken without consideration of goals or whether goals are achievable given ecological, social and economic constraints. Ecologists and resource managers have been poor at problem definition and objective setting (Peters 1991). Clear objectives need to be derived from a broad vision of what people want from landscapes in the future: What should they look like? What services do we want from them? Hence, we need better problem definition and priority setting because not all goals are equal. This is not a simple task because few if any areas of land or water have a single value. Even when conservation is the primary activity, different kinds of plans and actions will result from different objectives such as the maintenance of species diversity, the preservation of particular threatened species, the maintenance of ecological processes that generate diversity, the maintenance of ecosystem services (which can be extremely difficult to monitor). This is rarely acknowledged, either by researchers or managers (Possingham 2001). Different objectives will also arise depending on considerations such as land tenure and which management activity is deemed to be the most important one, and many kinds of objectives conflict (e.g. maximizing timber production vs. maintaining biodiversity; Lindenmayer & Franklin 2002). Because there often will be no single 'best' plan for a landscape, multiple scenarios need to be assessed (Peterson *et al.* 2003). In other cases, using science-based considerations and principles to set objectives and priorities may prove impossible in a political or social context – factors which can have profound impacts on landscape management (Bürgi & Schuler 2003). For example, using the size of wildfires to guide logging cutovers may produce large deforested areas that are socially and politically untenable in some jurisdictions (Lindenmayer & Franklin 2002).

Prioritization methods (Possingham 2001) are one way to assess the extent of trade-offs arising from different conservation objectives. However, it is not always straightforward to determine, for example, when the attempted recovery of an endangered species or landscape restoration should be abandoned. Nevertheless, we need to identify the best conservation options to achieve a particular goal and minimize the risk of unacceptable failure. To do this we must establish the relationships between conservation actions and the state of the system. This highlights the importance of active adaptive experimental management for landscape conservation (see below).

Spatial issues

Manage the entire mosaic, not just the pieces

Patch-based management is still the norm, but this approach ignores flows of biota, water and nutrients as well as interactions among elements of a mosaic. A single patch can be subjected to state-of-the-art conservation, but that management can fail if the surrounding landscape continues to degrade, with adverse impacts on the patch. Hence, patches need to be assessed and managed within the context of landscape mosaics and the entire landscape. A research challenge is to design robust surveys that generate high quality data on species inhabiting mosaics, emphasizing information on demographic performance (Mac Nally 2007). Because the dynamic temporal aspects of mosaics can be important (e.g. Thompson *et al.* 2007), another research challenge is to determine which mosaic is the most appropriate one to maintain including consideration of relationships between an existing mosaic and the mosaic that preceded it – sometimes termed the invisible mosaic (Parr & Andersen 2006). For managers, appropriate conservation strategies for landscape mosaics will vary depending on the overall conservation goal (Bennett *et al.* 2006). For example, where the goal was to maintain the diversity of a taxonomic or ecological group, this may be achieved by managing the diversity of certain elements in the mosaic. Where the goal was the conservation of a particular species with specific habitat requirements, this may best be achieved by managing the overall amount of habitat for that species.

Consider both the amount and configuration of habitat and particular land cover types

Related to 'Manage the entire mosaic, not just the pieces', the amount of habitat remaining in an area is often the most important factor determining persistence of biota in many (but certainly not all) landscapes. It also can influence ecological processes such as erosion rates and nutrient losses. Habitat configuration is often less important until levels become low (e.g. below 10–30%); threshold effects and regime shifts are also hypothesized to be more likely to occur under these conditions. Researchers need to develop better methods for testing for threshold and other kinds of responses, both for ecological processes (e.g. McIntyre *et al.* 2002) and individual species (Homan *et al.* 2004). In landscapes such as those in the Americas and Australia without prolonged history of European modification, it will be critical to consider both avoiding low levels of habitat and identifying 'safe' levels of management (Biggs & Rogers 2003) irrespective of whether dynamics are threshold, linear or some other kind of response. In other kinds of landscapes such as those with a long history of European agricultural management, recommendations for avoiding low levels of particular (original native) land cover types will be unattainable, but much biodiversity will be maintained through limiting agricultural intensification (Benton *et al.* 2003) or maintaining traditional grazing and other practices (Schmitz *et al.* 2007).

Identify disproportionately important species, processes and landscape elements

Some landscape elements may be disproportionately important because of their provision of key resources such as water or nutrients or for their spatial context in enhancing connectivity and gene flow. There may also be species of particular concern, either because of their relative scarcity due to landscape change or because of their disproportionate impact on an ecosystem (e.g. ecosystem engineers and keystone species). The importance of these entities is often only recognized when problems arise. Researchers need to develop approaches to better identify key landscape elements and species and assist with their proactive management (Hobbs *et al.* 2003).

Integrate aquatic and terrestrial environments

Terrestrial and aquatic elements of landscapes are closely interlinked, although management practices and institutional arrangements rarely reflect this interconnectedness (Grimm *et al.* 2003). Managers need to be better aware of relationships between, for example, patch and landscape-level land management activities such as restoration and plantation forestry and attributes of aquatic ecosystems such as streamflow (Jackson *et al.* 2005). Catchment or watershed-level management will usually be essential to better integrate the conservation of aquatic and terrestrial environments.

Use a landscape classification and conceptual models appropriate to objectives

Landscape classification is critical because it can significantly affect where and what conservation or other investments are made. This, together with interrelationships between landscape classification, landscape models and other themes (Fig. 1) means the selection of a landscape model for addressing a particular objective or problem needs much deeper thought than is widely recognized. There is no single 'best' approach to landscape classification. How humans perceive the landscape may not reflect how it is perceived by other species, and this is relevant to how we classify, map and conserve landscapes. For example, while the patch-matrix model of landscapes serves a useful purpose in portraying how species might respond to landscape change, for many taxa it may be simplistic, particularly in its binary assignment of landscape elements as either habitat or non-habitat. This is problematic when the surrounding landscape has some value as habitat for biota. Other models used in landscape classification may be more appropriate to guide conservation such as when improving the habitat value of surrounding areas for a particular species is an important goal. A way forward is to articulate *a priori* the goals and problems being addressed and the purpose of the classification. This will determine both the underlying conceptual model that is used and the resulting classification and its expression. In some cases, it may be useful to apply more than one landscape conceptual model and consider insights obtained in this way. This is rarely done (but see Ingham & Samways 1996), and more testing and cross-comparisons of conceptual models and landscape classifications are needed, particularly in terms of their implications for conservation and management.

Temporal issues

Maintain the capability of landscapes to recovery from disturbances
It is important to maintain the potential for a landscape to recover from disturbance. This includes maintaining processes and flows and the ability of the biota in a landscape to cope with extreme events (e.g. floods and droughts). Researchers need to develop a better understanding of how ecosystems recover after natural and human disturbances, for example, through maintaining the integrity of key refugia (e.g. Magoulick & Kobza 2003) and quantifying the extent to which biological legacies modify post-disturbance conditions and influence ecosystem recovery (Lindenmayer & Noss 2006). Managers need to better recognize that natural disturbances can be valuable for ecosystems and biodiversity and not limit their focus to single disturbance events but consider disturbance regimes (Gill 1975). Rather than allowing events to drive management responses, it may be better to anticipate extreme events and plan contingencies before they occur. For example, estimates of sustained timber yields in forest planning should account for the impacts of major natural disturbances such as wildfires and windstorms. This might be made more tractable by expanding the units for management beyond individual patches to mosaics, entire landscapes and broader regions (Spies *et al.* 2004).

Although increased recognition of the ecological roles of natural disturbances is important, researchers and managers also need to be aware of potential limitations of approaches based on using natural disturbances to guide human disturbances. For example: (i) human disturbance can never mimic natural disturbance regimes exactly, (ii) some very complex processes are extremely difficult to emulate and (iii) some management objectives will remain unachieved. Given these limitations, an objective should be to quantify differences between natural and human disturbance regimes and, in turn, to find ways of creating human disturbance regimes more similar (rather than identical) to naturally occurring ones. In addition, highly targeted actions (that go beyond following natural disturbance regimes) might be needed to meet particular management objectives such as the restoration of particular processes or the creation of specialized habitat attributes for an individual threatened species. Researchers and managers also must try to avoid unique combinations of disturbances, the potential for cumulative effects and the potential for novel disturbances.

Manage for change
Related to 'Maintain the capability of landscapes to recovery from disturbances', although conservation often aims at stasis and assumes an equilibrium state for natural systems, landscapes are dynamic and may become more so with future climate variability. Changes can be nonlinear and sometimes related to threshold phenomena. A deliberate effort to identify 'thresholds of potential concern' (Biggs & Rogers 2003) should be part of any landscape conservation strategy. Novel dynamics initiated by human intervention are often superimposed on natural dynamics in response to disturbance at varying scales. Failure to acknowledge the dynamic nature of systems will inevitably result in unexpected change and unachieved conservation goals. Thus, we should plan to accommodate successional dynamics, spatial and temporal mosaics, colonization and extinction processes, and likely range shifts associated with climate change. Developing this capacity is complicated by the institutional tendency to ignore potential problems until they become critical, only then instigating crisis management. There is therefore a need to develop a capacity to embrace preventative management (e.g. Hobbs *et al.* 2003).

Time lags between events and consequences are inevitable
This applies to attempts to restore damaged systems as well as to the adverse effects of human activities. For instance, the impacts of landscape restoration may not be seen in terms of biotic changes for many decades if the vegetation grows slowly and the impacts of human activities like pesticide use, may take a long time to become evident. Researchers need to develop approaches to better predict time lags and anticipate circumstances where they might be important. They also need to develop methods to reduce time lags (e.g. creative thinning of replanted forests to promote structural diversity of vegetation cover; Carey *et al.* 1999). Managers need to better understand that inappropriate actions now may take a prolonged period to manifest (extinction debts) and/or prolonged periods to reverse (e.g. recruitment of large slow growing trees).

Management approaches

Manage in an experimental framework
Because of contingency, lack of knowledge of biotic responses and complex system dynamics, there is always significant uncertainty associated with landscape management. Hence, it is crucial not to do the same thing everywhere so that we can limit the risk of making the same mistake everywhere. If we treat the variety of management options as adaptive management experiments (*sensu* Walters & Holling 1990), we can continuously improve ecosystem understanding. This involves careful consideration of experimental design and the implementation of monitoring programmes to ensure that the power of the results is maximized. Active adaptive management experiments also must pass the test of management relevance to be useful (Russell-Smith *et al.* 2003). True adaptive management landscape experiments are rare (Stankey *et al.* 2003) but need to be implemented far more widely.

Manage both species and ecosystems
Single-species and ecosystem conservation are not competing approaches. Rather, a range of conservation strategies will nearly always be required: some focused on individual species, others on suites of species and yet others on entire landscapes or ecosystems, and there will be interlinkages among all of these. Research and management may be effectively guided by strategically identifying key knowledge gaps, while maintaining the potential for complementarity between single-species and ecosystem conservation approaches. Related to 'Identify disproportionately important species, processes and landscape elements', focusing on disproportionately important species and ecological processes may have the greatest impact in terms of improved system understanding.

Manage at multiple scales
Related to 'Manage both species and ecosystems', there is no single 'right' or 'sufficient' scale for conservation and resource management. A single strategy adopted at a single spatial scale will meet only a limited number of goals. For example, it will provide suitable habitat for only a limited number of taxa. Multiple management scales are needed because there are multiple ecological scales, not only for different ecological processes and different species, but also for the same species. In addition, different processes at different spatial scales are inter-dependent (Wu 2007).

Allow for contingency
Broad considerations are contingent and must be considered in the context of conservation goals, landscape type and spatial and temporal scale. No single set of 'rules' applies everywhere. Instead there is a set of contingent (specific) principles that depend on context, conditions, species assemblages, processes and other factors. They will be most useful when coupled with a deep knowledge and understanding of a given landscape. There is an increasing number of examples where checklists and other approaches have facilitated the translation of broad considerations into useful on-ground management (e.g. Lindenmayer & Franklin 2002; Salt *et al.* 2004). Based on our knowledge of how particular landscapes work, we can at least make a start on developing more informed considerations which can translate into management guidelines. We can also begin to determine what options are best for a stated goal – i.e. when and where to do particular things (e.g. when are corridors important for habitat connectivity and when is managing the surrounding areas more likely to yield better results?).

WHERE TO FROM HERE?

Our objective was to gather a variety of perspectives on landscape ecology, conservation biology and restoration ecology and to mould them into a set of broad considerations that have some generality and that may provide a starting point for further discussion and development. These considerations cannot be transferred uncritically and directly into on-the-ground action. Rather, they provide a set of key issues to be considered by agencies and resource managers when developing practical plans and guidelines. Implementing these emerging guidelines must consider the local landscape, its biota and the goals and objectives of conservation. Interpreting them in the context of local examples is a valuable step in making them more accessible and relevant to managers, and this can be achieved best by conducting the relevant research in landscapes at a variety of appropriate spatial scales.

If we focus subsequent scientific endeavours on actual landscape conservation challenges, we may be able to make real progress in developing sound, scientifically based approaches to landscape management in general. This, in turn, can contribute positively to meeting the challenge of biodiversity conservation and ecologically sustainable resource use in the face of rapidly changing global, regional and local environments.

FUTURE RESEARCH

While much is already known, important knowledge gaps remain. Rather than produce a long list, below we touch on four areas for future work.

(1) The conceptual model illustrated in Fig. 1 emphasizes the interrelationships between key themes, but also highlights future challenges. First, how can we include

the complexity of gradients and other phenomena in landscape models and move beyond default use of traditional binary, patch-based models? Second, given that many processes associated with landscape modification are often confounded, how can we better identify those that give rise to emergent patterns? Conversely, given that many processes in landscapes are interrelated, are there ways that we can better understand their cumulative impacts (Cocklin *et al.* 1992)? Understanding cumulative impacts will be increasingly important as, for example, future changes in climate will be overlaid on already heavily modified landscapes (Thomas *et al.* 2004).

(2) Connectivity is a primary process influencing ecosystem function and the distribution, abundance and persistence of all biota. Yet the mantra of 'the more connectivity the better' is too simple as there are circumstances where this would have negative consequences (Whittaker 1998) because, for example, it may promote the spread of invasive taxa. We need better approaches to determine when, where and why more connectivity is desirable and when it is not.

(3) Large-scale disturbances such as fires and floods can be important drivers of ecosystem and landscape processes. We need to better understand the impacts of these events because they can produce ecological surprises (e.g. Turner *et al.* 2003) and because some kinds of major disturbances will increase in frequency, intensity or both as a consequence of climate change (Lenihan *et al.* 2003).

(4) How can the findings from the enormous body of knowledge from landscape ecology, conservation biology and restoration ecology be better translated into on-the-ground management of landscapes? Methods such as meta-analysis and systematic review are valuable, but much research has little bearing on practice; the knowledge transfer process itself requires deeper exploration. If more effective knowledge transfer can occur, it will be important to increase the number of scientifically based landscape planning and management examples that encompass true active adaptive management experiments. This will ensure that opportunities are taken to gain new knowledge about landscape management.

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