Landscape Ecology

Six principles for managing forests as ecologically sustainable ecosystems

--Manuscript Draft--

Manuscript Number:	LAND-11-3000R1
Full Title:	Six principles for managing forests as ecologically sustainable ecosystems
Article Type:	SI: Musacchio Special
Keywords:	Ecologically sustainable landscape management; landscape management principles; commodity production landscapes; conservation management; land sparing.
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Abstract:	<p>Managing a landscape for its natural resources while attempting to ensure an ecologically sustainable future is a truly complex and challenging task. We present six general principles for sustainable forest landscape management derived from insights in an array of natural and commodity production ecosystems in south-eastern Australia but which are likely to have broad applicability to many forested ecosystems worldwide. These principles are: (1) Landscape management problems are typically underpinned by human-use drivers that over-commit natural resources and undermine the ecosystem services which support the replenishment of those resources. (2) Not all parts of a landscape are equal in their contribution to species persistence and ecological processes. Special steps are needed to secure the ecological integrity of these disproportionately important areas. (3) Managing connectivity is critical, but it is essential to determine what kind of connectivity is desirable, and for what species and processes. (4) Land use practices can produce spatial and temporal cumulative effects with negative impacts on biodiversity and ecological processes. (5) Land use decisions on the land sparing-land sharing spectrum are highly scale and context dependent. (6) Our understanding of landscape-scale processes is shaped by our conceptual model of the landscape. It is therefore important to check if a given mental model is appropriate for a given landscape and the species or ecological processes of concern. These six principles should not be applied uncritically. Rather, it is best to treat them as a checklist of considerations that will help guide our thinking about landscape change, so that we can orient toward more ecologically sustainable landscape management.</p>
Response to Reviewers:	<p>Professor David Lindenmayer Fenner School of Environment and Society The Australian National University Canberra ACT 0200 12 January 2011</p> <p>Re: Major revisions to LAND-11-3000 Six Principles for managing forests as ecological sustainable systems</p> <p>Dear Professor Laura Musacchio, Thankyou for the referees comments on our paper. We have used the suggestions of</p>

the Editor and the referees to guide an extensive revision of our paper. We believe that these changes have considerably improved the manuscript. In the remainder of this letter we outline the extensive revisions we have made to the paper. We appreciate the comments of the Editor and the referees and have taken the liberty of thanking them in the Acknowledgements section of the revised paper. We hope that the revised paper is now suitable for publication in Landscape Ecology and look forward to hearing from you in the near future.

Yours sincerely

David Lindenmayer and Saul Cunningham

Comments by the Editor

I have received three reviews for David Lindenmayer and Saul Cunningham's manuscript and ready to make a recommendation to you. Two reviewers recommended minor revisions while the other recommended major revisions. From these recommendations, I recommend that this manuscript will need moderate revisions. The reviewers made positive comments about certain aspects of this manuscript such as the usefulness of the contribution, its approach to unifying theory, and reputation of the researchers. Sometimes this combination creates higher than normal expectations in the reviewers' minds, and this idea turns out to be the case for this manuscript. Given this situation, I make a series of recommendations for revision based on a combination of suggestions from the three reviewers:

Editor's comments

1. Add more references to adequately previous contributions to the key principles and vocabulary.

Author's response

We have added more citations to the paper as requested. These better connect to the literature. Conversely, we also have removed excessive citations of work by the first author.

Editor's comments

2. Some definitions of vocabulary need improved precision.

Author's response

We have attempted to do this as a key part of the revision. Notably, we have removed the original Table 1 and moved definitions into the text where appropriate and deleted other terms where they were unnecessary.

Editor's comments

3. The figures and tables need some polishing, especially figure 1 and table 1.

Author's response

We have deleted both Figure 1 and Table 1 as they seemed superfluous to the main text. Instead, we have developed an entirely new Figure 1 which shows the inter-connections between the 6 key principles that underpin the paper. This creates a nice sense of flow and interconnection between principles as well as provides a vehicle to integrate the key topics that are the focus of the paper. This also demanded that the key principles be re-ordered to equate with the ways that they are best inter-related.

Editor's comments

4. Create a stronger connection of the six principles to actual research application and findings.

Author's response

We have worked hard to connect the principles to research application. Our new conceptual model also provides a valuable vehicle for demonstrating how the principles are inter-connected.

Editor's comments

5. A more synthetic approach to the principles would be helpful. Another round of polishing would help strengthen this aspect.

Author's response

We have indeed undertaken a major attempt at synthesis with the revised paper – especially given the very negative comments of Reviewer #2. Importantly, we have developed a new conceptual model that highlights new ways in which the general principles are inter-related.

Editor's comments

6. Line-by-line revisions as suggested by the reviewers, especially #2 and #3.

Author's response

We have used these suggestions to guide the revisions of the paper.

Editor's comments

Overall this manuscript will make a very good contribution to the special issue about "Key Concepts and Research Priorities for Landscape Sustainability" and look forward to receiving a revised copy.

Author's response

We thank the Editor for her supportive comments and we hope that our considerable attempts to significantly improve the paper meet expectations for the Special Issue of Landscape Ecology.

Comments by the Reviewer #1

Reviewer #1 comments

Reviewer #1: Review: LAND-11-3000 Six Principles for managing forests as ecological sustainable systems

General Comments: This perspective-type manuscript provides six meaningful and insightful principles for the ecologically sustainable management of forest landscapes. It draws on the extensive research experience of the lead author in the production forests of Southeast Australia. The principles are sufficiently broad that they can be applied in other production landscapes in Australia and elsewhere. They are logically structured and synthesise/articulate much of our current understanding of how excessive human land use pressures can force landscape into an unsustainable state. However, most have their origins in existing ecological literature (e.g. Principle #5. Landscape connectivity is critical) and this needs to be recognised and adequately referenced beyond the author's own work.

Author's response

This is a fair point from Reviewer #1. We have therefore undertaken an extensive process of greater and broader referencing of key topics throughout the text.

Reviewer #1 comments

Concerns:

Table 1 clarifies the concepts used in the manuscript. However, the claim of a "new vocabulary" is excessive as many of these terms have been used elsewhere in the landscape ecological literature in a similar form. For example, environmental accounting has been around for a long time and landscape accounting is just a branch of this (e.g. see work by Roy Haines-Young). This work needs to be recognised and adequately referenced. Similarly, how different is the concept of over-committed landscape to ecological threshold that may be linked to the amount of vegetation or some other indicator. Table 1 needs another column that identifies measures that can be used to by landscape managers to quantify these terms.

Author's response

We have decided to delete Table 1 – and added text, definitions and citations to the text where appropriate. Claims about new vocabulary have been removed as they were, on reflection, excessive.

Reviewer #1 comments

Figure 1 is a bit of a spaghetti-diagram and would benefit from improved graphics.

Author's response

We have now decided to remove Figure 1 as we feel that it did not add much to the main points of the paper. As outlined above, we have constructed a new and far more synthetic conceptual diagram for our paper.

Reviewer #1 comments

Checklist: The term checklist conveys ticking boxes. There must be a better term that represents the evaluation of key considerations underpinning landscape sustainability.

Author's response

We understand the concerns of Referee #1 but the term Checklist has been used very widely and also used in an operational sense. It is important as it conveys a sense of

entities/issues that landscape managers need to consider in making decisions about landscape management and conservation.

Comments by the Reviewer #2

Reviewer #2 comments

Reviewer #2: Review of Lindenmayer and Cunningham Landscape Ecology 1 Nov 2011 #11-3000

The authors lay out six principles for managing forests as sustainable systems in response to a paper charge for a special issue of LE. The charge addresses specific issues to be addressed.

The first author has published a number of papers over recent years in this area of research. I was frankly expecting something more from them, based on the volume of previous work, and the fairly specific charge for the special issue. In general, I found the six principles did not really bring much that is new, and the sections of each under operationalization are mostly general, somewhat academic, restating. I expect operationalize to be much more applied, more synthetic insight from the original work. I was looking for greater insight for application from their body of work. I don't see much original thought or effort to do this.

Author's response

We are saddened by the fact that Reviewer #2 was so negative about our paper. We were writing closely to the brief that was given to us. It is important to recognize that some of the key principles that we have proposed are obvious and well recognized – sometimes so well understood that they are overlooked by landscape managers and researchers. Other principles in our paper are less obvious and still subject to debate (such as the land sparing-land sharing debate; see Fischer et al., 2011 vs Phalan et al., 2011 in Science). Therefore, our paper is a mixture of well established and more contentious principles. We now state this at the end of the Introduction section of the paper. Nevertheless, given the caustic criticism of Reviewer #2, we have thought more expansively about the content of our paper and tried to add more original thought to the revised manuscript.

Reviewer #2 comments

I think the principles have weaknesses; again, I expect more based on the previous body of work. This is an opportunity for a real synthetic essay, from someone who, at least, has certainly written a large volume to base it on.

Author's response

As outlined above and where appropriate, we have tried to present a more synthetic and innovative approach to the revised manuscript.

Reviewer #2 comments

For example, the first principle is a tautological statement. In part there is a reliance on jargon, sometimes newly minted, sometimes not. Here it is over-committed landscapes, which even warrants its own definition in the glossary. But the entire principle doesn't seem like anything new, insightful, or newly synthetic. Lines 68-69: "For example, water is often over-committed so that flows for environmental purposes are limited". Really? This seems like a key point for intro environmental studies.

Author's response

We have re-worded this principle to remove the apparent tautology. Nevertheless, we are confident that the underlying principle is not tautological – it's a reality of landscapes and seascapes the world over. Yet this often fails to be realised by vast numbers of policy makers and politicians – it still happens – as evidenced here in Australia with the massive problems in Murray Darling Basin and widespread landscape degradation. We have however, made some substantial editorial changes to the text to better highlight the key problems associated with over-committing resources as part of landscape management.

Reviewer #2 comments

Principle #2 links cumulative effects with "negative feedbacks" implying "negative" means "bad". But negative feedbacks are an element of ecosystem processes, implying a direction, not a value. This seems like sloppy thinking and at worst misleading.

Author's response

We can see how Principle #2 might be mis-interpreted and we have reworked some of

the text to make our meaning clearer. The term negative feedback has been removed from the revised manuscript.

Reviewer #2 comments

I find the term "landscape trap" another recent term from another of the authors work, describes ecosystem or landscape states that we have been aware of for some time, but not under this term. Certainly this describes many (most?) human-dominated landscapes if compared with some earlier state, and accompanying disturbance regime.

Author's response

In writing up the landscape trap paper earlier this year, one of us (DBL) spent over 6 months checking the literature on regime shifts, thresholds and other kinds of traps. The landscape trap concept is very different from has been recognized previously. We now make this case more strongly in the revised manuscript.

Reviewer #2 comments

Principle #3. The concept of "land sparing-land sharing" has also been around for a long time, as they acknowledge at least since Seymour and Hunter 1999. As they also acknowledge there has been a long literature of controversy around it. This principle restates this, under a new term. But what else is new here?

Author's response

Both Cunningham and Lindenmayer were editors on a recent book on Land Use Intensification (to be published in mid 2012). It was clear from that exercise that there are new perspectives on land sparing and sharing such as those of scale and off-site and on-site impact. These new perspectives are now more strongly emphasized in the revised paper. As an example, it somehow does not even dawn on the proponents of the current debates on land sparing versus land sharing (which is focused on agricultural land) that there is a long history of the same debates in the forest management literature. Similarly, the issues of scale also do not seem to be explored in many of the debates; problems like the impossibility of further intensifying production in some landscapes also have escaped the thinking on land sparing-land sharing.

Reviewer #2 comments

In #4, quite a few examples, perhaps too many, draw on ag research, as well as a fair number elsewhere; maybe too many.

Author's response

We have re-examined the number of examples in Principle #4 and reworked the text as suggested by Reviewer #2. We have now reduced the number of examples from agricultural areas.

Reviewer #2 comments

The rest of the principles too, sound like bullets from an intro to LE lecture. They encompass brief synopses of the literature.

Author's response

Reviewer #2 is correct in stating that some of the principles are akin to brief synopses of the literature. But we re-iterate that many of the principles we have made in the paper are very often overlooked by landscape managers and policy makers. If they were well known and fully embraced and applied, then the planet would not be facing so many of the major problems that it currently is! Notably, we have now indicated in the Introduction that some principles are well established whereas other remain under debate and are far from settled.

Reviewer #2 comments

The summary I am afraid is also terribly weak. It lacks substance.

Author's response

The summary has been rewritten. It is much shortened and much of the material it formerly contained was moved back into the main text to support the research components of the principles – albeit in a heavily rewritten and modified form.

Reviewer #2 comments

I don't feel the charge for the essay is met at all. Surely, these authors can do much better than this. This is a general problem with invited papers, whether in a journal or

edited book, or invited talks. It is too easy for scientists to do, and the bar is very low. This means we have much too many of these volumes, and little of value. We would never allow our students such an easy out. I realize this is a quite negative review, and at one level I regret that. I try not to do so, and to be constructive. But to be honest, I tried to do it twice, and found the more oblique version did not convey my annoyance. Please give us something more pithy and useful.

Author's response

Again, we are saddened by the fact that Reviewer #2 was so unhappy about our paper. We have tried to extensively revise and strengthen the paper in a way that captures more synthesis and innovation. This includes drawing a new conceptual model that draws together the 6 key principles in a coherent and logical way.

Comments by the Reviewer #3

Reviewer #3 comments

Reviewer #3: This study clearly condenses the dynamical interactions among ecological and socio-economic landscape components, scaling from baseline levels (processes) to levels that are related to the decision making process in landscape planning. Unlike other works dealing with sustainable management, this study proposes a unifying theory to address the integrated landscape management, and aims to introduce new concepts that guide this increasingly important discipline. I therefore recommend this work to be published in Landscape Ecology. I have minor comments and observations that could be addressed by the authors:

Author's response

We thank Reviewer #3 for her/his supportive comments.

Reviewer #3 comments

L28-L32. I do not see clearly why the ideas presented in the Fig. 1 highlight the need to establish general principles.

Author's response

As outlined above, we have now deleted Figure 1.

Reviewer #3 comments

I think it would be interesting to include a conceptual diagram showing how the six principles considered in this study can be applied on sustainable planning of a local landscape, as showed in Fig 1. This recommendation arises from the fact that the principles, and the concepts underlying such principles, are functionally and operationally linked with each other. For example, the choice a landscape model (i.e. land sparing-land sharing) is dependent on the interactions among: the level on which the landscape is over-committed, the need to reduce the incidence of feedbacks between human and natural disturbances, the desired levels of connectivity and the landscape conceptual model used.

Author's response

This was a very astute point and we have included a new conceptual model in the revised paper as a way of trying to better connect the principles to landscape management.

Reviewer #3 comments

L30. "This highlights the need?": repeated use of the word "this". Try starting with the concept to which you are referring.

Author's response

We have revised the sentence as requested and indicated that "This" relates to complexity. .

Reviewer #3 comments

L36-L46. The authors say their principles are derived from two sources, its own research and previous publications on forest management and landscape of their own authorship. Perhaps the authors should have cited the work of other researchers who have contributed to the knowledge of sustainable management in other regions. Incorporating these experiences could ensure that the proposed principles are truly "general" and, therefore, they apply to any wooded landscape.

Author's response

This was a good point and we have expanded the citations in the paper to better reflect the work of others. In addition, we have deleted many of the Lindenmayer et al.

references as the over-citation of these in the original version of the paper was over the top.

Reviewer #3 comments

L66-L68 and Table 1. I have a concern about the definition of "Over-committed landscape". According to the authors, "if a resource is overcommitted, then the key ecosystem services which support replenishment of that resource are undermined". I think the overexploitation of a resource does not necessarily imply that the processes responsible for the renewal of this resource should be affected. For example, if water from a spring is over-exploited, this should not affect ecosystem processes that contribute to the production of clean water. In this case, the removal of trees in the basin would have a greater impact on water production.

Author's response

We have re-crafted the text to move away from the tautology that concerned Reviewer #2. We have also tempered the text on altered ecological processes.

Reviewer #3 comments

L91-L94. In practice, developing a "Landscape accounting? is very complex task. Quantifying resource availability could not be problematic, but determining the "safe? level of natural resource use for conserving biodiversity is an analysis that involves many information and modelling effort. In this sense, such concept would be better understood if it is partitioned.

Author's response

We agree that landscape accounting could be a very complex task. There is a long history of traditional resource accounting but not the kind of accounting that we are proposing here. We have now revised the text to make it clearer what we had in mind with landscape accounting and which might prevent resource over-commitment.

Reviewer #3 comments

L106-110. I have a concern with the use of the term "negative feedback". I understand that a feedback between the land use intensification and a natural disturbance should have a synergistic negative impact to the extent that the feedback loop is "positive". Negative feedback should stabilize, and so, dissolve these interactive effects. Moreover, a positive feedback has the potential to move the system from a stable equilibrium point to another stable equilibrium point, as in the case of "landscape traps".

Author's response

This was, again, an astute point and we have modified the text to make our key point clearer on the issues of feedbacks and traps. We have removed the term feedback from the revised manuscript as it could easily have been mis-understood and was confusing as originally presented.

Reviewer #3 comments

L131-134. Consider that at larger spatio-temporal scales there could be a feedback among global warming, land use change and forest fires.

Author's response

This is a good point, especially for tropical ecosystems. We have added this nuance and some supporting references on this.

Reviewer #3 comments

L213-217. Small landscape elements in a land-sparing landscape, such as fencerows or riparian corridors, could provide connectivity for some species with limited mobility.

Author's response

This is a good point and we have added some text and a reference in support of this point.

Reviewer #3 comments

L229-231. For the land-sparing model the most important problem could be conserving few large forest remnants (providing core habitat) vs conserving several small stands (i.e., the SLOSS dilemma).

Author's response

Again, this is a good point and we have added some text on this issue.

Reviewer #3 comments

L258. It would be advisable to mention that some areas can function as source habitats for native species.

Author's response

Again, this is a good point and we have added some text and a reference to underscore this.

Reviewer #3 comments

L292-296. The difference between habitat connectivity and landscape connectivity appears to be analogous to the distinction between functional and structural connectivity.

Author's response

We disagree that the two sets of terms are analogous. Habitat connectivity is very much a species-level issue whereas functional connectivity can include ecological functions like the movement of water or nutrients through a system.

Reviewer #3 comments

L306. Consider that the connectivity for an organism can also change depending on their life history or season, being foraging movements (e.g., occurring at the home range scale) clearly different from dispersal or migration (occurring on longer distances or at the population level).

Author's response

This is a good point and we have added some text to capture this useful suggestion.

Reviewer #3 comments

L318-325. The contrast between the production and non-production patches could be regulated from a land sparing-land sharing model.

Author's response

This is true and we have added some text to reflect this thought.

In summary, we have made a large number of changes to our paper which we believe have considerably improved the manuscript. We thank the reviewers and the editor for their useful comments. We hope that the paper will now be suitable for publication in Landscape Ecology and look forward to hearing from you in the near future.

Yours Sincerely,

David Lindenmayer and Saul Cunningham

Revision #5 – January 2012

Landscape Ecology

Six principles for managing forests as ecologically sustainable ecosystems

David B. Lindenmayer · Saul A. Cunningham

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Date of MS draft: January 12, 2012

Word count (including text, references and caption): 7290 words

Running Head: Landscape management principles

Abstract

Managing a landscape for its natural resources while attempting to ensure an ecologically sustainable future is a truly complex and challenging task. We present six general principles for sustainable forest landscape management derived from insights in an array of natural and commodity production ecosystems in south-eastern Australia but which are likely to have broad applicability to many forested ecosystems worldwide. These principles are: **(1)** Landscape management problems are typically underpinned by human-use drivers that over-commit natural resources and undermine the ecosystem services which support the replenishment of those resources. **(2)** Not all parts of a landscape are equal in their contribution to species persistence and ecological processes. Special steps are needed to secure the ecological integrity of these disproportionately important areas. **(3)** Managing connectivity is critical, but it is essential to determine what kind of connectivity is desirable, and for what species and processes. **(4)** Land use practices can produce spatial and temporal cumulative effects with negative impacts on biodiversity and ecological processes. **(5)** Land use decisions on the land sparing–land sharing spectrum are highly scale and context dependent. **(6)** Our understanding of landscape-scale processes is shaped by our conceptual model of the landscape. It is therefore important to check if a given mental model is appropriate for a given landscape and the species or ecological processes of concern. These six principles should not be applied uncritically. Rather, it is best to treat them as a checklist of considerations that will help guide our thinking about landscape change, so that we can orient toward more ecologically sustainable landscape management.

Keywords: Ecologically sustainable landscape management, landscape management principles, commodity production landscapes, conservation management, land sparing

Introduction

25 The sustainable management of landscapes is a complex, multi-faceted task. Many individual case studies detail the layers of complexity, highlighting interacting factors at multiple spatial and temporal scales, which can influence the resources being managed and the landscape level outcomes. Such complexity highlights the need not only for place-based models (Kates et al. 2000) but to go beyond “the uniqueness of place” (Beven 2000) to integrate sustainability science (*sensu* Bettencourt and Kaur 2011) into landscape ecology (Wu 2006; Musacchio 2009).

In this paper, we outline six general principles for the sustainable management of forest landscapes. We have derived them from two primary sources. First, experiences from conducting four large-scale, long-term landscape management investigations in south-eastern Australia (Lindenmayer 2009a,b; Lindenmayer et al. 2008b, 2011a;). Second, shared knowledge generated from writing sets of principles for forest management (Lindenmayer and Franklin 2002), landscape design (Lindenmayer and Hobbs 2007), commodity production landscapes (Fischer et al. 2006), and conservation biology (Lindenmayer and Hunter 2010). Four principles relate to the biology of systems, particularly drivers of threatening processes and their expression in landscapes. Two principles relate to the way humans interpret evidence for change and select options as part of making environmental decisions (Figure 1). We provide a short discussion of each of these six principles, including some of the issues and nuances associated with their conceptualization. We also outline some perspectives on operationalizing these principles. Some of our general principles have been established for a long time and will be obvious to many researchers, but, this has not prevented them from sometimes being overlooked by policy makers and resource managers (e.g. see Harris 1998; Smith et al. 2010). We state them here because they are important, not because they are novel. Conversely, other principles are less well established,

and significant debate remains around them (e.g. compare Phalan et al. 2011 and Fischer et al. 2011), but we believe they understanding them will help guide better landscape management.

50 **Figure 1. Approximately here**

Principle #1: Over-commitment of natural resources is the root cause of most ecological problems.

The ecological impact of harvesting any natural resource depends on the level of harvest and the
 55 rate at which resources are replenished. Unfortunately, many landscapes are over-committed to human land uses such as livestock grazing, cropping, forestry, and urban development. We define an over-committed landscape as one in which resources are exploited at a level that undermines the key ecosystem services needed to support the replenishment of that resource. There is insufficient ecological margin in over-committed landscapes to maintain environmental
 60 conditions that prevent the degradation of key ecological processes and/or significant levels of biodiversity loss.

Over-committed natural resources in commodity production landscapes have resulted in large losses of biodiversity in many forested and agricultural regions around the world (Millennium Ecosystem Assessment 2005; Vié et al. 2009; Butchart et al. 2010) with the
 65 potential to undermine the key ecosystem services and landscape services (*sensu* Termorshuizen and Opdam 2009) needed to maintain the capacity of ecosystems to sustain wood or food production (e.g. pollination; see Garibaldi et al. 2011), maintain freshwater resources, and regulate climate and air quality (Rockström et al. 2009). For the purposes of this paper, landscape services encompass both ecosystem services and environmental services and are

70 “.....the connection between physical systems (ecosystems or landscapes) and human services”
(Termorshuizen and Opdam 2009).

The problems of over-committed landscapes are magnified when events like major natural disturbances (e.g. wildfires, cyclones, hurricanes and droughts) alter both natural vegetation cover and the availability of natural resources. As an example, many production forests in
75 temperate regions around the world are managed on the basis of long-term sustained yields of timber and pulpwood (Puettmann et al. 2008). Yield calculations are generated from the area of forest available for harvesting but these rarely account for unpredictable losses that might be incurred from natural disturbances like wildfires. When areas are lost to production but the legislated ‘sustained yields’ remain unchanged, this increases harvesting pressure on unburned
80 areas with corresponding negative impacts on other values like the maintenance of ecosystem services and biodiversity conservation. Thus, good landscape management requires that an ecological margin is accounted for and to provide a buffer between the actual level of resource use and the level at which exploitation is expected to undermine ecosystem services or cause significant losses of biodiversity. This ecological margin also must provide for the effects of
85 unpredictable events (such as wildfires) on resource loss and resource yields.

Operationalization

History indicates that people have routinely over-committed natural resources with severe consequences such as economic and social collapse (Harris 1998; Diamond 2005). The risk is that we only recognise ‘over-commitment’ in retrospect. Traditional forms of accounting that
90 track stocks and flows of the natural resource uses by humans are well established (e.g. Smith 2007). However, we suggest that new forms of landscape accounting are needed to determine whether landscapes can ecologically support existing or expanded levels of resource use whilst

maintaining other key environmental values, maintaining ecosystem services, and supporting viable populations of native plants and animals (Termorshuizen and Opdam 2009). Ultimately, many landscape management problems cannot be tackled appropriately until levels of resource use are better planned (Puetteman et al. 2008; Smith et al. 2010) and maintained at levels below which ecosystem services are not degraded and significant biodiversity loss is prevented. This represents a research challenge to identify those critical thresholds, which act as robust indicators of when natural levels of resource use approach over-commitment (Carpenter et al. 2011). For many production forest landscapes, such new kinds of landscape accounting methods will need to accommodate losses in resource availability that will inevitably occur as a result of natural disturbances.

Better planning will demand high quality monitoring (Lindenmayer and Likens 2010) as well as agility among policy makers and resource managers to allow them to respond rapidly to major natural disturbances and revise both the amount and location of resource harvesting. This is problematic because although robust designs are available for guiding effective monitoring programs, the application and maintenance of high quality monitoring programs in landscape management is rare (Gardner 2010; Lindenmayer and Likens 2010). Indeed, there are numerous examples of landscape management programs that have failed because of a lack of monitoring (e.g. Bernhardt et al. 2005; Whitfield 2006; United Kingdom Parliament 2010). We suggest that this problem might be resolved if monitoring was made a mandatory part of resource extraction and supported by a proportion of the economic returns derived from resource exploitation (Franklin et al. 1999).

115 **Principle #2: Not all parts of a landscape are equal in their contribution to species
persistence and ecological processes.**

Some parts of landscapes have values for biodiversity and support of ecosystem functions that are disproportionately large relative to the area they cover. This may be because they provide abundant key resources such as water or nutrients, their spatial context enhances habitat
120 connectivity (see below) and gene flow (Calhoun and deMaynadier 2008), or they are a relatively scarce habitat type. For example, many studies have demonstrated the markedly higher species richness of riparian zones relative to other areas in landscapes (Huggett and Cheeseman 2002; Palmer and Bennett 2006). Other critical areas in landscapes include breeding areas, hibernacula and caves (Culver et al. 2000) and refugia from impacts of drought (e.g. Magoulick
125 and Kobza 2003). Similarly, some landscapes have fire refugia from which post-disturbance population recovery can be seeded (Turner et al. 2003; Banks et al. 2011). Critical areas in landscapes can sometimes be relatively small. For example, rocky outcrops measuring less than 0.5 ha are significant hotspots for reptile biodiversity in Australian agricultural landscapes (Michael et al. 2008). Similarly, individual trees can be critical for the landscape-level
130 persistence of some species (Webb and Shine 1997; Eltz et al. 2003; Manning et al. 2006) and sometimes account for a disproportionately large fraction of the successful pollen pool for the next generation of recruits (Aldrich and Hamrick 1998).

Operationalization

Given the relative importance of some special areas in particular landscapes, it is important to
135 identify where they are located and what organisms or processes they are critical for, so that management actions can be appropriately targeted. For example, in the case of some kinds of moist temperate forest, an understanding of spatial heterogeneity in fire behavior and fire

severity can reveal vital information on the location of fire refugia for native mammals (Lindenmayer et al. 1999). This, in turn, highlights the parts of landscapes where it is important to avoid additional environmental stressors (e.g. post-fire logging operations) that can otherwise compromise the integrity of fire refugia (Lindenmayer et al. 2008a). Studies commenced as soon as possible following major natural disturbances like wildfires and hurricanes can be critical for determining both the location of refugia and how such areas influence post-disturbance ecosystem recovery (Franklin and MacMahon 2000; Turner et al. 2003). Understanding these ‘small but important’ elements offers some of the easiest ‘wins’ in the sustainable management of landscapes that support more biodiversity at little or no cost in lost production.

Principle #3: Connectivity is critical, but it is essential to determine what kind of connectivity is desirable and for what key processes.

Dispersal-limited species are among those most at risk of decline or extinction as a consequence of land use change (e.g. Hoehn et al. 2007; Griffiths et al. 2011). Maintenance of appropriate connectivity is an important component of any strategy for sustainable production landscapes. However, the task of maintaining or enhancing connectivity is not straightforward because the concept of connectivity is complex and multi-faceted. In an attempt to tackle this complexity, Lindenmayer and Fischer (2007) recognized a range of kinds of connectivity. *Habitat connectivity* can be broadly defined as an emergent property of ecosystem mosaics that reflects the influence of landscape structure on a species’ mobility and its probability of survival within and among resource patches. The concept of *landscape connectivity* is based on a human perspective of landscape pattern and typically relates to the connectedness of native vegetation patches. In some circumstances and for some species, habitat connectivity and landscape

connectivity will be closely correlated. In others, habitat connectivity for a given species will be quite different from a human perspective of landscape connectivity. *Ecological connectivity* is the connectedness of key ecosystem processes (Lindenmayer and Fischer 2007). Understanding these relationships is crucial because we generally manage on the basis of habitat connectivity, with the goal of achieving landscape connectivity.

Operationalization

Attempts to maintain connectivity need to be prefaced by questions like: What kind of connectivity? Connectivity for what? And at what spatial scale? Answers to these questions are important because connectivity is different for different organisms and different ecological processes. In addition, connectivity for a given organism can change depending on their life history or between seasons, with foraging movements (e.g. movements occurring at the home range scale) clearly being different from dispersal or migration (Stenseth and Lidicker 1992; Lindenmayer and Fischer 2007). Indeed, in some cases, increased connectivity can have undesirable consequences (Lindenmayer and Fischer 2007). For instance, landscapes can sometimes inadvertently be made *increasingly* connected for processes like fire through such human activities as logging (see also Thompson et al. 2007 and Principle #4). Plantation forests might create an ecological bridge for invasion of native forest by pest species (Cunningham et al. 2005). Similarly, oceanic islands often have very high levels of endemism because they have lacked connectivity, and the species assemblages are susceptible to homogenization (by invasion and extinctions) when ‘connectivity’ is created through human activities (Whittaker 1998).

A clear understanding of the kind of connectivity desired, and for what organisms or processes, can influence whether efforts to maintain or increase connectivity are best addressed through establishing corridors, stepping stones, or a continuous cover of trees (or other

vegetation; see Franklin 1993), or through some other approach like regional-scale connections

185 (Worboys et al. 2010). The options for creating connectivity in production landscapes are strongly influenced by the *contrast* between the production and non-production patches in the landscape (Harper et al. 2005) and the dispersal abilities of various elements of the biota (Franklin 1993). Where the contrast is high (e.g. forest versus crop) and mean mobility is low, connectivity for most organisms will be restricted to corridors or stepping stones (Batary et al.
190 2010). Where the contrast is low (e.g. agroforestry system vs. forest) and mobility is high, there will be much greater scope for managing the whole landscape for permeability, with less dichotomy among different landscape patches (Franklin 1993).

A major problem underpinning better landscape management for connectivity is our limited understanding of animal and plant movement ecology. Yet such information is critical to
195 almost all facets of the ecologically sustainable management of landscapes. For example, it is essential for determining: **(1)** where and when to harvest resources, **(2)** if (and how) populations can recover following disturbances associated with resource harvesting, **(3)** the risks of cumulative spatial and temporal impacts of resource use on biodiversity, **(4)** where to locate protected areas and how large such places should be, **(5)** whether protected areas need to be
200 physically connected (and if so, how they might be best linked), and **(6)** which conceptual models of landscape cover are most appropriate. Given the importance of movement and dispersal, a breakthrough in understanding is needed to advance the knowledge of connectivity required for the ecologically sustainable management of landscapes.

205 **Principle # 4: Land use practices can produce spatial and temporal cumulative effects with negative impacts on biodiversity and ecological processes.**

Human use of landscapes can lead to cumulative effects at different spatial scales that radically alter key ecological processes and have significant negative effects on biodiversity. As an example, major changes in vegetation cover driven by logging many stands of forest alters the frequency, severity and spatial contagion of natural disturbances like wildfires and windstorms (Franklin and Forman 1987; Thompson et al. 2007). Moist temperate and tropical forest landscapes subject to widespread logging are significantly more likely to burn, and burn at a higher severity, than equivalent unlogged landscapes (Cochrane and Schultz 1999; Lindenmayer et al. 2009). Such cumulative effects have led to the development of a new kind of ecological trap, termed a landscape trap, in the Mountain Ash (*Eucalyptus regnans*) forests of south-eastern Australia in which entire landscapes are now in an altered state and are highly unlikely to return to their former functional state (Lindenmayer et al. 2011b). Landscape traps are large-scaled ecological phenomena that arise through a combination of altered spatial characteristics of a landscape coupled with synergistic interactions between multiple human and natural disturbances. Thus, changes in the frequency and spatial contagion of large-scaled disturbances are the key interacting factors driving entire landscapes into an undesirable and potentially irreversible state (i.e. a landscape trap).

The landscape trap in the Mountain Ash forests of south-eastern Australia has arisen because of a combination of logging and fire that favors a regime change (*sensu* Connell and Sousa 1983) from old-growth forest to young fire-prone forests that don't survive to become old-growth (Lindenmayer et al. 2011b). Landscape traps in these forests are likely to result in severely impaired landscape functions such as reduced suitability for biodiversity, reduced carbon storage, and reduced water production (Lindenmayer et al. 2011b).

The potential for landscape traps to develop is likely to be widespread in temperate moist
 230 forest ecosystems around the world that are subject to intensive resource management and where
 wildfire is a major kind of natural disturbance, logging is a widespread form of human
 disturbance, and fire and logging interact in multiple temporal and spatial feedbacks. Rapid
 climate change may further exacerbate such feedback processes such as through altered fire
 regimes (Westerling et al. 2006), increased rates of tree death (van Mantgem et al. 2009) or
 235 combinations of both. Notably, landscape trap phenomena may occur in tropical rainforests
 (Kauffman and Uhl 1991), grassland and rangeland ecosystems (D'Antonio and Vitousek 1992),
 and aquatic and marine ecosystems (Ling et al. 2009). There is considerable potential for
 landscape traps to develop in biofuel-dominated plantation landscapes, which have been touted
 as a 'sustainable alternative' to fossil fuels but may in fact negatively affect entire forest
 240 ecosystems (Fargione et al. 2008).

Operationalization

Better understanding of landscape-level problems like the development of landscape traps will
 remain a research challenge because these cumulative spatial and/or temporal effects are
 notoriously difficult to study (Cocklin et al. 1992). New ways of exploring biotic responses to
 245 landscape mosaics (*sensu* Bennett et al. 2006) that are created by multiple processes and which
 create spatial arrays of different kinds patches (e.g. Haslem and Bennett 2008; Batary et al. 2010;
 Hodgson et al. 2010) offer new perspectives on cumulative effects. Yet the development of
 further improved methods is critical to detecting spatial and temporal effects earlier to aid
 landscape planning and management and, in turn, discourage resource over-commitment (see
 250 Principle #1) as well as prevent unwanted 'ecological surprises' (Doak et al. 2008).

We suggest a key part of landscape management is to limit the number of anthropogenic stressors in landscapes and reduce the potential for cumulative effects to develop. This may equate to a more conservative approach to the harvesting of natural resources to ensure that landscapes are not over-committed (see Principle #1 above) or made more disturbance-prone such as through interactions between logging operations and increase levels of fire proneness (Cochrane and Schultz 1999; Thompson et al. 2007).

Principle #5: Land use decisions on the land sparing–land sharing spectrum are highly scale and context dependent.

Approaches to landscape management that trade off resource exploitation and biodiversity conservation are often couched in the terms of the land sparing–land sharing debate (Phalan et al. 2011). At small spatial scales, decisions about landscape sustainability and conservation are often focused on particular plots of land, be they for commodity production or otherwise. But at larger geographic scales, one can conceptualize a choice between extensive but low input land uses, and mosaics with contrasting patches of intensive production and conservation lands. These options, which can only be conceived at a landscape scale or larger, can be described as bookends of the ‘land sharing vs. land sparing’ spectrum. The ‘sparing’ model is where more intensive land use (leading to increased yields) is adopted in a given location as a kind of ecological offset for increasing the area reserved for conservation in another location (Green et al. 2005; Fischer et al. 2008; Phalan et al. 2011). The ‘sharing’ model is where production and biodiversity conservation goals are integrated in the same location. Thus, land sparing is a land allocation approach in which areas are assigned a primary land use – i.e. intensive production versus biodiversity conservation (e.g. large ecological reserves). In contrast, land sharing occurs where different uses are integrated in the same area. Examples of land sharing include:

‘ecologically sustainable forest management’ (Lindenmayer and Franklin 2002; Puettmann et al.
275 2008) and ‘wildlife friendly farming’ (Fischer et al. 2008).

There is a relatively long history of land sparing versus land sharing discussions in forestry
(Gladstone and Ledig 1990; Lindenmayer and Franklin 2002) with several authors arguing that a
shift to intensive wood production (e.g. timber tree plantations) could relieve pressure on native
forests and create opportunities for an expanded forest reserve system (Paquette and Messier
280 2010). Seymour and Hunter (1999) discussed the case of sustained yields of timber from the
State of Maine in the USA where, at that time, there was extensive (but relatively low intensity)
wood production forestry, but also significant concern about biodiversity conservation and few
areas in formal reserves. They noted that for every hectare of forest transferred into intensive
forestry, between 3-5 hectares of forest could be set aside as ecological reserves and overall
285 sustained yields of timber and pulpwood could be maintained (Seymour and Hunter 1999).

More recently there has been debate about sharing vs. sparing options in agricultural
landscapes (Green et al. 2005; Fischer et al. 2008, 2011; Ewers et al. 2009; Phalan et al. 2011).
While the debate has been at times oppositional, the starting point – that land use decisions and
their consequences are best understood at larger scales – is widely accepted. Critics of land
290 sparing argue that while the off-set principle is possible in theory, in practice it usually does not
occur. That is, intensification occurs, but no conservation land is released (Ewers et al. 2009). In
addition, under a land-sparing model, some landscapes might simply offer few prospects for
conservation of large remnant areas of native vegetation because of the history of exploitation.
Furthermore, the emphasis on intensification in the land sparing model risks eroding key
295 ecosystem processes which underpin production (Garibaldi et al. 2011) and thereby ultimately
undermine yield.

Critics of land sharing argue that the mixed strategy compromises both conservation and production outcomes, leading to a landscape that is less effective on both fronts. Moreover, reduced levels of production in a land-sparing landscape might drive agricultural expansion elsewhere, further undermining possible gains (Gabriel et al. 2010). Conversely, small landscape elements in land-sparing landscapes, such as fencerows or riparian corridors, could provide connectivity for some species with limited mobility (Dowdeswell 1987).

Operationalization

The complexity of issues associated with discussions about land sparing versus land sharing indicate a need for the careful consideration of several key issues. Four of these are:

- (1) Management objectives and policies. Objectives need to be agreed upon and articulated otherwise there are no well defined goals to guide management.
- (2) The quality of the land that is ‘spared’. This includes consideration of land use history and the size and characteristics of areas that remain undisturbed (or relatively undisturbed). This is particularly important because the traditional assignment of land to conservation purposes has too often been because it was poor for production (Scott and Tear 2007), rather than to represent particular conservation values – the so-called worthless lands hypothesis (Hall 1988). Thus, an increase in reserved area of low productivity forest to offset increased land use intensification in more productive areas will exacerbate existing shortcomings of reserve systems, whereby they are not representative or adequate for the protection of many elements of the biota (e.g. Schmitt et al. 2009).
- (3) The species and assemblages being targeted for conservation. If the aim of conservation efforts is to maintain species with limited mobility or that are dispersal or connectivity-limited, then the best option might be low intensity, widespread land management rather

than an allocation strategy based on reserves versus production areas (Franklin 1993).

Conversely, the land sharing approach may not be appropriate for some highly disturbance-sensitive species that need large ecological reserves or protected areas to survive (Peres 2005).

- (4) The potential for multi-scaled and cross-scale impacts. Reducing the level of resource use in one area can increase levels of resource use in others. For example, increasing the amount of forest reserved in western North America (to protect species like the Northern Spotted Owl *Strix occidentalis caurina*) led to increased logging pressure in other regions such as South-east Asia – with corresponding impacts on biodiversity in high biodiversity tropical areas (Yaffee 1994). Thus, an assessment of this outcome depends on whether one takes a geographically narrow or wide perspective. This underlines the point that while trade in commodities can be globalized through similar kinds of products being sourced from different areas, biodiversity cannot because it is geographically constrained. There are other scale issues such as where high-intensity farming has significant off-site effects on biodiversity on adjacent land spared for nature (Hodgson et al. 2010).

The above issues indicate that appropriate application of the land sparing-land sharing approach will be landscape-context-dependent (Ewers et al. 2009) and scale-dependent (Hodgson et al. 2010) and must be guided by a careful assessment of the relative costs of production versus biodiversity benefits at multiple (local, landscape, national, global) spatial scales. Thus, land sparing may not be desirable in some landscapes (e.g. meso-American mixed agricultural region; Harvey et al. 2008) and simply not possible in others, such as landscapes that have already been subject to extremely high levels of native vegetation clearing and land

degradation (e.g. the temperate woodland-dominated wheat-sheep belt of eastern Australia; Fischer et al. 2009). In such over-committed landscapes (see Principle #1), there appears to be
 345 little (if any) capability to significantly increase the area under intensive management. Even where there is a will to relinquish productive use of parts of the landscape for conservation, the cost of restoring currently productive land to a level of ecological function that would represent a biodiversity asset may be too great to be considered sensible.

Finally, we suggest the choice between land sparing and land sharing should not in practice
 350 be treated as a dichotomy. An appropriate land use plan may well use elements of both ends of the spectrum, such as in variegated landscapes (*sensu* McIntyre and Barrett 1992) (see Principle #6 below).

**Principle #6: Different conceptual models of the landscape lead to different management
 355 approaches.**

There are several landscape conceptual models such as the island model (MacArthur and Wilson 1967), the patch-corridor-matrix model (Forman 1995), the variegated landscape model (McIntyre and Barrett 1992) and the continuity or continuum model (Fischer et al. 2004). The selection of a landscape model for addressing a particular objective or problem needs careful
 360 reflection for two key reasons. First, how humans perceive a landscape may not reflect how it is perceived by other species. For example, the patch-matrix model of landscapes is widely used to predict how species might respond to landscape change, but for many taxa it is unrealistic, particularly in its binary assignment of landscape elements as either habitat or non-habitat (Fischer et al. 2004). This is particularly problematic when the surrounding landscape has some
 365 value as habitat for biota that also needs to be managed. Other conceptual models, like the

continuum model or the variegated landscape model, 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 (Lindenmayer and Fischer 2006). Second, different landscape conceptual models can have significant implications for decisions about landscape management including land allocation and land sparing as well as where and what conservation or other investments are made. For example, if the island model (MacArthur and Wilson 1967) of landscapes is being employed in which areas are deemed to be either habitat or non-habitat this may best correspond to a reserve/production area strategy (i.e. a land sparing solution). Conversely, low intensity, widespread forest management might be more congruent with those circumstances where landscapes are conceptualized using other kinds of models like the continuum model in which different areas vary in habitat quality along gradients of suitability (Fischer et al. 2008).

Operationalization

Informed landscape management requires decision-makers to consider what conceptual model they are using, and whether it is appropriate to the species or ecological processes in question. This needs to be preceded by a careful articulation of the goals and problems being addressed and the purpose of using a landscape conceptual model. Notably, very few plans for managing biodiversity consider the underlying landscape conceptual model but rather conceptualize landscapes solely from a human perspective and almost exclusively using the island model of vegetation cover. In some cases, it may be useful to apply more than one landscape conceptual model and consider insights obtained in this way (e.g. Ingham and Samways 1996). This can facilitate cross-comparisons of conceptual models and landscape classifications, particularly in terms of their implications for conservation and management. Therefore, a key area of additional

research will be to compare landscape conceptual models and their impacts on planning and on-
the-ground management strategies for sustainable landscape management.

Concluding comments

We have briefly described six general principles that can help guide the sustainable management of forest landscapes. We have argued that while place-based models of landscapes are important (Kates et al. 2001), they need to be integrated into a broader conceptual domain that encompasses landscape ecology perspectives and sustainability science (Musacchio 2009).

We emphasize first that good decision making requires knowledge of the fundamental biology of the system, both of the drivers of change, but also the way changes are expressed in time and space (Figure 1). Secondly, we argue that interpretations and decisions are strongly shaped by context and prior experience, so we need always to be mindful of how our perspectives are formed (Figure 1). General principles should help frame hypotheses which can then be tested with further empirical work in a given landscape or set of landscapes (e.g. Tscharntke et al. 2011). Moreover, because decisions are often made when knowledge is incomplete, science has an important role to play in characterizing better models for generalization that nevertheless express the most important dynamic features of real landscapes.

Acknowledgments

We thank Laura Musacchio for encouraging us to write this paper. Claire Shepherd assisted in many aspects of manuscript preparation. Comments by Laura Musacchio, Sue McIntyre, Martin Henery and three anonymous reviewers greatly improved earlier versions of this manuscript.

Figure caption

Fig. 1. Inter-relationships between six key principles for landscape management. Principles #1-4 encompass drivers of threatening processes and their expression in landscapes. Principles #5 and
415 #6 correspond to the ways humans interpret evidence for landscape change and identify options for landscape management.

References

- 420 Aldrich PR, Hamrick JL (1998) Reproductive dominance of pasture trees in a fragmented
tropical forest mosaic. *Science* 281:103–105
- Banks SC, Dujardin M, McBurney L, et al. (2011) Starting points for small mammal population
recovery after wildfire: recolonisation or residual populations? *Oikos* 120:26–37
- Batary P, Matthiesen T, Tschardt T (2010) Landscape-moderated importance of hedges in
425 conserving farmland bird diversity of organic vs. conventional croplands and grasslands. *Biol
Conserv* 143:2020–2027
- Bennett AF, Radford JQ, Haslem A (2006) Properties of land mosaics: implications for nature
conservation in agricultural landscapes. *Biol Conserv* 133:250–264
- Bernhardt ES, Palmer MA, Allan JD (2005) Synthesizing US river restoration projects. *Science*
430 308:636637
- Bettencourt EM, Kaur J (2011) Evolution and structure of sustainability science. *Proc Natl Acad
Sci USA* 108:19540–19545
- Beven, K.J. (2000). Uniqueness of place and process representations in hydrological modelling.
Hydrol Earth Syst Sci 4:203–213
- 435 Butchart SHM, Walpole M, Collen B, et al. (2010) Global biodiversity: indicators of recent
declines. *Science* 32:1164–1168
- Calhoun AJ, deMaynadier PG (eds) (2008) Science and conservation of vernal pools in
northeastern North America. CRC Press, New York
- Carpenter SR, Cole JJ, Pace ML, et al (2011) Early warnings of regime shifts: A whole-
440 ecosystem experiment. *Science* 332:1079–1082

- Cochrane MA, Schulze MD (1999) Fire as a recurrent event in tropical forests of the eastern Amazon: effects of forest structure, biomass, and species composition. *Biotropica* 31:2–16
- Cocklin C, Parker S, Hay J (1992) Notes on cumulative environmental change. I. Concepts and issues. *J Environ Manage* 35:31–49
- 445 Connell JH, Sousa WP (1983) On the evidence needed to judge ecological stability or persistence. *Am Nat* 121:789–824
- Culver DC, Master LL, Christman MC, et al. (2000) Obligate cave fauna of the 48 contiguous United States. *Conserv Biol* 14:386–401
- Cunningham SA, Floyd RB, Weir T (2005) Do *Eucalyptus* plantations host an insect community
450 similar to remnant *Eucalyptus* forest? *Austral Ecol* 30:103–117
- D’Antonio CM, Vitousek PM (1992) Biological invasions by exotic grasses, the grass/fire cycle, and global change. *Ann Rev Ecol Syst* 23:63–87
- Diamond JM (2005) *Collapse: how societies choose to fail or succeed*. Viking, New York
- Doak DF, Estes JA, Halpern CS, et al (2008) Understanding and predicting ecological dynamics:
455 Are major surprises inevitable? *Ecology* 89:952–961
- Dowdeswell WH (1987) *Hedgerows and verges*. Allen and Unwin, London
- Eltz T, Bruhl CA, Imiyabir Z, et al (2003) Nesting and nest trees of stingless bees (Apidae: Meliponini) in lowland dipterocarp forests in Sabah, Malaysia, with implications for forest management. *Forest Ecol Manag* 172:301–313
- 460 Ewers R, Scharlemann JP, Balmford A, et al. (2009) Do increases in agricultural yield spare land for nature? *Glob Change Biol* 15:1716–1726
- Fargione J, Hill J, Tilman D, et al. (2008) Land clearing and the biofuel carbon debt. *Science* 319:1235–1238

- Fischer J, Batary P, Bawa KS, et al (2011) Conservation: Limits of land sparing. Letter in
 465 response to Phalan et al. *Science* 334: 93
- Fischer J, Brosi B, Daily G, et al. (2008) Should agricultural policies encourage land sparing or
 wildlife-friendly farming? *Ecol Environ* 6:380–385
- Fischer J, Lindenmayer DB, Fazey I (2004) Appreciating ecological complexity: habitat contours
 as a conceptual landscape model. *Conserv Biol* 18:1245–1253
- 470 Fischer J, Lindenmayer DB, Manning AD (2006) Biodiversity, ecosystem function, and
 resilience: ten guiding principles for commodity production landscapes. *Front Ecol Environ*
 4:80–86
- Fischer J, Stott J, Zerger A, et al. (2009) Reversing a tree regeneration crisis in an endangered
 ecoregion. *Proc Natl Acad Sci USA* 106:10386–10391
- 475 Forman RTT (1995) *Land mosaics: the ecology of landscapes and regions*. Cambridge
 University Press, New York
- Franklin JF (1993) Preserving biodiversity - species, ecosystems, or landscapes? *Ecol Appl*
 3:202–205
- Franklin JF, Forman RT (1987) Creating landscape patterns by forest cutting: ecological
 480 consequences and principles. *Landscape Ecol* 1:5–18
- Franklin JF, Harmon ME, Swanson FJ 1999. Complementary roles of research and monitoring:
 lessons from the U.S. LTER Program and Tierra del Fuego. *In* North American Science
 Symposium: Toward a unified framework for inventorying and monitoring forest ecosystem
 resources, pp. 284–291. U.S. Department of Agriculture, Fort Collins, CO USA, Guadalajara,
 485 Mexico, November 1998
- Franklin JF, MacMahon JA (2000) Messages from a mountain. *Science* 288:1183–1185

- Gabriel D, Sait SM, Hodgson JA, et al. (2010) Scale matters: the impact of organic farming on biodiversity at different spatial scales. *Ecol Lett* 13:858–869
- Gardner T (2010) Monitoring forest biodiversity. Improving conservation through ecologically responsible management. Earthscan, London
- Garibaldi LA, Aizen MA, Klein AM, et al. (2011) Global growth and stability of agricultural yield decrease with pollinator dependence. *Proc Natl Acad Sci USA* 108:5909–5914
- Gladstone WT, Ledig FT (1990) Reducing the pressure on natural forests through high-yield forestry. *Forest Ecol Manag* 35:69–78
- Green RE, Connell SJ, Scharlemann JP, et al. (2005) Farming and the fate of wild nature. *Science* 307:550–555
- Griffiths CJ, Hansen DM, Jones CG, Zuel N, Harris S (2011) Resurrecting extinct interactions with extant substitutes. *Curr Biol* 21:762–765
- Hall CM (1988) The "worthless lands hypothesis" and Australia's national parks and reserves. In: Frawley KJ and Semple NM (eds) Australia's ever changing forests. Australian Defence Force Academy, Canberra, pp 441–59
- Harper KA, Macdonald SE, Burton PJ, et al (2005) Edge influence on forest structure and composition in fragmented landscapes. *Conserv Biol* 19:768–782
- Harris M (1998) Lament for an ocean: the collapse of the atlantic cod fishery. McClelland and Stewart, Toronto, Canada
- Harvey CA, Komar O, Chazdon R, et al. (2008) Integrating agricultural landscapes with biodiversity conservation in the mesoamerican hotspot. *Conserv Biol* 22:8–15
- Haslem A, Bennett AF (2008) Birds in agricultural mosaics: the influence of landscape pattern and countryside heterogeneity. *Ecol Appl* 18:185–196

- 510 Hodgson JA, Kunin WE, Thomas CD, et al. (2010) Comparing organic farming and land
sparing: optimizing yield and butterfly populations at a landscape scale. *Ecol Lett* 13:1358–1367
- Hoehn M, Sarre S, Henle K (2007) The tales of two geckos: does dispersal prevent extinction in
recently fragmented populations? *Mol Ecol* 16:3299–3312
- Huggett R, Cheeseman J (2002) *Topography and the environment*. Prentice Hall, London
- 515 Ingham DS, Samways MJ (1996) Application of fragmentation and variegation models to
epigaeic invertebrates in South Africa. *Conserv Biol* 10:1353–1358
- Kates RW, Clark WC, Corell R, et al. (2001) Sustainability science. *Science* 292:641–642
- Kauffman JB, Uhl C (1991) Interactions of anthropogenic activities, fire, and rainforests in the
Amazon Basin. In: Goldammer JG (ed) *Fire in the tropical biota*. Springer-Verlag, New York, pp
520 117–134
- Lindenmayer DB (2009a) *Forest pattern and ecological process: A synthesis of 25 years of
research*. CSIRO Publishing, Melbourne
- Lindenmayer DB (2009b) *Large-scale landscape experiments: Lessons from Tumut*. Cambridge
University Press, Cambridge
- 525 Lindenmayer DB, Archer S, Barton P, et al. (2011a) *What makes a good farm for wildlife?*
CSIRO Publishing, Melbourne
- Lindenmayer DB, Burton PJ, Franklin JF (2008a) *Salvage logging and its ecological
consequences*. Island Press, Washington DC
- Lindenmayer DB, Fischer J (2006) *Habitat fragmentation and landscape change*. Island Press,
530 Washington, DC
- Lindenmayer DB, Fischer J (2007) Tackling the habitat fragmentation panchreston. *Trends Ecol
Evol* 22:127–132

- Lindenmayer DB, Franklin JF (2002) Conserving forest biodiversity: A comprehensive multiscaled approach. Island Press, Washington
- 535 Lindenmayer DB, Hobbs R (eds) (2007) Managing and Designing Landscapes for Conservation: Moving from Perspectives to Principles. Blackwell Publishing, Oxford
- Lindenmayer DB, Hobbs RJ, Likens GE, et al. (2011b) Newly discovered landscape traps produce regime shifts in wet forests. *Proc Natl Acad Sci USA* 108:15887–15891
- Lindenmayer DB, Hunter M (2010) Some guiding concepts for conservation biology. *Conserv Biol* 24:1459–1468
- 540 Lindenmayer DB, Hunter ML, Burton PJ, et al. (2009) Effects of logging on fire regimes in moist forests. *Conserv Lett* 2:271–277
- Lindenmayer DB, Likens GE (2010) Effective ecological monitoring. CSIRO Publishing and Earthscan, Melbourne and London
- 545 Lindenmayer DB, Mackey BG, Mullen IC, et al. (1999) Factors affecting stand structure in forests - are there climatic and topographic determinants? *Forest Ecol Manag* 123:55–63
- Lindenmayer DB, Wood JT, Cunningham RB, et al. (2008b) Testing hypotheses associated with bird responses to wildfire. *Ecol Appl* 18:1967–1983
- Ling SD, Johnson CR, Frusher SD, et al. (2009) Overfishing reduces resilience of kelp beds to climate-driven catastrophic phase shifts. *Proc Natl Acad Sci USA* 106:22341–22345
- 550 MacArthur RH, Wilson EO (1967) The theory of island biogeography. Princeton University Press, Princeton
- Magoulick DD, Kobza RM (2003) The role of refugia for fishes during drought: a review and synthesis. *Freshwater Biol* 47:1186–1198

- 555 Manning AD, Fischer JF, Lindenmayer DB (2006) Scattered trees are keystone structures – implications for conservation. *Biol Conserv* 132:311–321
- McIntyre S, Barrett GW (1992) Habitat variegation, an alternative to fragmentation. *Conserv Biol* 6:146–147
- Michael DR, Cunningham RB, Lindenmayer DB (2008) A forgotten habitat? Granite inselbergs
560 conserve reptile diversity in fragmented agricultural landscapes. *J Appl Ecol* 45:1742–1752
- Millennium Ecosystem Assessment (2005) Ecosystems and human well-being: biodiversity synthesis. World Resources Institute, Washington, DC
- Musacchio LR (2009) The scientific basis for the design of landscape sustainability: a conceptual framework for translational landscape research and practice about designed landscapes and the
565 six Es of landscape sustainability. *Landscape Ecol* 24:993–1013
- Paquette A, Messier C (2010) The role of plantations in managing the world’s forests in the Anthropocene. *Front Ecol Environ* 8:27–34
- Palmer GC, Bennett AF (2006) Riparian zones provide for distinct bird assemblages in forest mosaics of south-east Australia. *Biol Conserv* 130:447–457
- 570 Peres CA (2005) Why we need mega-reserves in Amazonia. *Conserv Biol* 19:728–733
- Phalan B, Balmford A, Green RE, et al. (2011) Minimising the harm to biodiversity of producing more food globally. *Food Policy* 36:S62–S71
- Puettmann KJ, Coates KD, Messier C (2008) A critique of silviculture. Managing for complexity. Island Press, Washington, DC
- 575 Rockström J, Steffen W, Noone K, et al. (2009) Planetary boundaries: exploring the safe operating space for humanity. *Ecol Soc* 14:32. [online] URL: <http://www.ecologyandsociety.org/vol14/iss2/art32/> (accessed August 2011)

- Schmitt CB, Burgess ND, Coad L, et al. (2009) Global analysis of the protection status of the world's forests. *Biol Conserv* 142:2122–2130
- 580 Scott JM, Tear TH (2007) What are we conserving? Establishing multiscale conservation goals and objectives in the face of global threats. In: Lindenmayer DB and Hobbs RJ (eds) *Managing and designing landscapes for conservation*. Blackwell Publishing, Oxford, pp 494–510
- Seymour RS, Hunter ML (1999) *Principles of ecological forestry*. In: Hunter ML (ed) *Maintaining biodiversity in forest ecosystems*. Cambridge University Press, Cambridge, pp 22–
- 585 61
- Smith MH, Hargroves K, Desha C (eds) (2010) *Cents and sustainability. Securing our common future by decoupling economic growth from environmental pressures*. Earthscan, London
- Smith R (2007) The development of the SEEA 2003 and its implementation. *Ecol Econ* 61:592–599
- 590 Stenseth NC, Lidicker WZ (eds) (1992) *Animal dispersal*. Chapman and Hall, London
- Termorshuizen JW, Opdam P (2009) Landscape services as a bridge between landscape ecology and sustainable development. *Landscape Ecol* 24:1037–1052
- Thompson JR, Spies TA, Ganio LM (2007) Reburn severity in managed and unmanaged vegetation in a large wildfire. *Proc Natl Acad Sci USA* 104:10743–10748
- 595 Tschardt T, Tylianakis JM, Rand TA, et al. (2011) Landscape moderation of biodiversity patterns and processes - eight hypotheses. *Biol Rev*: doi:10.1111/j.1469-185X.2011.00216.x
- Turner MG, Romme WH, Tinker DB (2003) Surprises and lessons from the 1988 Yellowstone fires. *Front Ecol Environ* 1:351–358
- United Kingdom Parliament 2010. HC 611 *The outcome of the Comprehensive Spending*
- 600 *Review - Supplementary written evidence submitted by the Department for Environment, Food*

and Rural Affairs (CSR 01A). House of Commons Environment, Food and Rural Affairs Committee, London

van Mantgem PJ, Stephenenson NL, Byrne JC, et al (2009) Widespread increase of tree mortality rates in western United States. *Science* 323:521–524

605 Vié JC, Hilton-Taylor C, Stuart SN (2009) Wildlife in a changing world: An analysis of the 2008 IUCN Red List of Threatened Species. International Union for Conservation of Nature and Natural Resources, Gland, Switzerland

Webb JK, Shine R (1997) A field study of spatial ecology and movements of a threatened snake species, *Hoplocephalus bungaroides*. *Biol Conserv* 82:203–217

610 Westerling AL, Hidalgo HG, Cayan DR, et al (2006) Warming and earlier spring increase western U.S. forest wildfire activity. *Science* 313:940–943

Whitfield J (2006) How green was my subsidy? *Nature* 439:908–909

Whittaker RJ (1998) Island biogeography: Ecology, evolution and conservation. Oxford University Press, Oxford

615 Worboys GL, Francis WL, Lockwood M (eds) (2010) Connectivity conservation management: A global guide. Earthscan, London

Wu J (2006) Landscape ecology, cross-disciplinarity, and sustainability science. *Landscape Ecol* 21:1–4

Yaffee SL (1994) The wisdom of the Spotted Owl. Policy lessons for a new century. Island Press, Washington, DC

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BIOLOGY

Biological issues
that need to be
understood

INTERPRETATION

Issues of perception
that need to be
made explicit

Landscape management decisions