



## Review

## Adaptive management of biological systems: A review

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## ABSTRACT

Adaptive Management (AM) is widely considered to be the best available approach for managing biological systems in the presence of uncertainty. But AM has arguably only rarely succeeded in improving biodiversity outcomes. There is therefore an urgent need for reflection regarding how practitioners might overcome key problems hindering greater implementation of AM. In this paper, we present the first structured review of the AM literature that relates to biodiversity and ecosystem management, with the aim of quantifying how rare AM projects actually are. We also investigated whether AM practitioners in terrestrial and aquatic systems described the same problems; the degree of consistency in how the term 'adaptive management' was applied; the extent to which AM projects were sustained over time; and whether articles describing AM projects were more highly cited than comparable non-AM articles. We found that despite the large number of articles identified through the ISI web of knowledge ( $n = 1336$ ), only 61 articles (<5%) explicitly claimed to enact AM. These 61 articles cumulatively described 54 separate projects, but only 13 projects were supported by published monitoring data. The extent to which these 13 projects applied key aspects of the AM philosophy – such as referring to an underlying conceptual model, enacting ongoing monitoring, and comparing alternative management actions – varied enormously. Further, most AM projects were of short duration; terrestrial studies discussed biodiversity conservation significantly more frequently than aquatic studies; and empirical studies were no more highly cited than qualitative articles. Our review highlights that excessive use of the term 'adaptive management' is rife in the peer-reviewed literature. However, a small but increasing number of projects have been able to effectively apply AM to complex problems. We suggest that attempts to apply AM may be improved by: (1) Better collaboration between scientists and representatives from resource-extracting industries. (2) Better communication of the risks of *not* doing AM. (3) Ensuring AM projects "pass the test of management relevance".

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## 1. Introduction

It is widely accepted that biodiversity is in rapid and global decline as a result of human alteration of natural systems (Kingsford et al., 2009; Millenium Ecosystem Assessment, 2005; Sala et al., 2000), a situation sometimes called the ‘sixth mass extinction’ (Wake and Vredenburg, 2008). Many biologists believe there is a critical need to conserve biodiversity more effectively (Sodhi et al., 2010), and that this can occur through scientifically informed management of populations, species, landscapes and ecosystems (Lindenmayer et al., 2008; Nichols, 2012; Pullin and Knight, 2009). However, human effects on natural systems take many forms including habitat loss, alteration and fragmentation (Collinge, 2009; Fahrig, 2003; Lindenmayer and Fischer, 2006), spread of invasive plants and animals (Simberloff, 2010; Vitousek et al., 1997), and climate change (Lawler et al., 2010; Thomas et al., 2004). In any given ecosystem, it is often difficult to identify which are the most important stressors underpinning environmental change, and therefore driving population declines (Caughley and Gunn, 1996). Anthropogenic changes to ecosystems are complex, and hence it may be unclear what actions by landscape managers will reduce impacts on biodiversity, or how to prioritize potential impact-mitigation efforts (Nicholson and Possingham, 2007).

Adaptive Management (AM) can be thought of as ‘learning by doing’ (Walters and Holling, 1990) and it aims to combine the need for immediate action with a plan for learning (Gunderson and Holling, 2002; Van Wilgen and Biggs, 2011). But like any approach to evidence-based ecosystem management, it faces a number of challenges. For example, Theberge et al. (2006) highlight that variability within natural systems makes it difficult to plan and implement studies that reliably differentiate between management options, or between alternative models of ecosystem processes (see also Sutherland, 2006). Further, AM should ideally involve compromise between groups with different motivating values, but this may lead to a stalemate where controversial management interventions are suggested to improve knowledge of the system (Gregory et al., 2006; Hughes et al., 2007). Finally, AM is dependent on well-designed monitoring programs (Nichols and Williams, 2006), but such programs are notoriously difficult to implement and maintain (Lindenmayer and Likens, 2010a). Therefore, considerable barriers exist which can limit the implementation of AM (Lindenmayer et al., 2008; Stankey et al., 2003), and these barriers in turn curtail its usefulness as a tool for improving biodiversity outcomes.

Despite these difficulties, the use of AM has been widely advocated, largely because of the intuitive appeal of evidence-based systems for environmental and biodiversity management (Gregory et al., 2006; Sutherland et al., 2004). Therefore, a valuable question is: How rare are effective AM projects, and how might practitioners overcome key problems hindering greater implementation? While successful AM projects – in which monitoring provides feedback that improves understanding of the system and guides future management decisions – are generally considered to be rare (Walters, 2007), we are unaware of any review that provides a comprehensive, literature-wide search for examples of the AM process being applied to biological systems. Such a review would highlight the range of activities currently being described as AM in the literature, and demonstrate the extent to which collaborations between scientists and management practitioners can achieve meaningful outcomes for biodiversity conservation. Such partnerships are often difficult to achieve and maintain (Caudron et al., 2012; Knight et al., 2008), but remain a vital component of applied ecological research (Gibbons et al., 2008; Russell-Smith et al., 2003). Demonstrating the applicability of theoretical concepts using real-world examples is a valuable means of translating ideas into action (Hall and Fleishman, 2010).

As a means of providing both direction and inspiration, we conducted a review designed to evaluate the degree of empirical support for AM in the ecological literature. This is a slightly different aim from thematically describing the entire literature, which is a more common method for conducting a review (e.g. Driscoll et al., 2010; Sutherland, 2006). Nor was it our aim to describe the taxonomic and geographic bias of AM research, issues that are well understood for the ecological literature in general (e.g. Fazez et al., 2005; Felton et al., 2009; Teague et al., 2011). Instead, our overall goals in this study were to: highlight the major issues and misunderstandings of what the term ‘adaptive management’ means; quantify the degree of empirical support for AM in the literature; discuss some reasons why AM might be so difficult to achieve; and provide some ways to overcome these difficulties. Such a systematic, quantitative approach has not been applied to the AM literature before, despite a number of qualitative reviews or essays (Fessehazion et al., 2011; Heinimann, 2010; Keith et al., 2011; Loeb et al., 1998; Lyons et al., 2008; Medema et al., 2008; Pahl-Wostl et al., 2007; Shea et al., 2002; Thom, 2000; Wilhere, 2002). Our work therefore builds upon, and is complementary to, a number of articles that provide advice on those situations in which AM is appropriate (e.g. Gregory et al., 2006; McCarthy and

Possingham, 2007; McDonald et al., 2007; McDonald-Madden et al., 2010a; Rout et al., 2009).

In addition to the overall goals listed above, we wished to address a number of important questions regarding the extent to which AM has been applied to real-world problems. Our questions were: (1) What kinds of problems are authors in the AM literature attempting to address? (2) How rare are examples of AM in the ecological literature? (3) Is there confusion regarding what AM is and how to do it? (4) Has AM been limited by difficulties associated with long-term monitoring? (5) Is there a lack of incentives for ecologists to overcome the above barriers? Despite the importance of these questions, we do not know of any attempt to find quantitative evidence to resolve them in the literature.

Given that AM is often difficult to enact, but could be highly beneficial for enhanced ecosystem management, there is a need for retrospection and guidance on how AM can be implemented to improve biodiversity conservation outcomes. We hope that the approach that we use to summarize the literature on AM will assist those who, despite the array of 'bad news' papers on this topic, still wish to undertake AM projects.

## 2. Defining adaptive management

Before moving on to a methodology for reviewing the AM literature, it is necessary to define what AM is, as well as what it is not. Providing a clear definition is necessary because there appears to be both confusion and genuine disagreement about what AM is (Allen et al., 2011). Therefore, in this section, we highlight some of the subtleties and complexities of the language in the AM literature.

Management of biological systems universally involves some form of intervention aimed at maintaining or improving the state of the system ('system state' is a common term in the literature to which we will refer again; see Nichols and Williams, 2006; Walters and Hilborn, 1978; Williams, 2011a). Unfortunately, there are many potential management actions, and it is often unclear what actions will improve system state most effectively. This means that managers have to make a trade-off between actions that are expected to improve the system state, and actions designed to improve knowledge. This is the 'dual control problem' (Walters and Hilborn, 1978), which AM addresses by combining the need for action with a plan for learning (hence the commonly-used phrase 'learning by doing'; Walters and Holling, 1990). The clearest and most succinct definition that we are aware of is given by Williams et al. (2009, p. 1), although note that these authors also provide a more thorough definition:

*Adaptive management is a systematic approach for improving resource management by learning from management outcomes.*

This general goal can be implemented using a range of methods, as appropriate to each study system. Although different authors provide different advice for how to implement AM, there is general agreement that the process typically involves several steps (this list is modified from Duncan and Wintle (2008), Keith et al. (2011), Williams et al. (2009)):

1. Identification of management goals in collaboration with stakeholders.
2. Specification of multiple management options, one of which can be 'do nothing'.
3. Creation of a rigorous statistical process for interpreting how the system responds to management interventions. This stage typically involves creation of quantitative conceptual models and/or a rigorous experimental design (see Section 2.2).
4. Implementation of management action(s).

5. Monitoring of system response to management interventions (preferably on a regular basis).
6. Adjust management practice in response to results from monitoring.

It is these criteria that we use to classify articles in the remainder of our review.

### 2.1. Active versus passive AM

The dichotomy between active and passive AM has been discussed widely in relation to ecosystem management, although not without some confusion. Walters and Holling (1990) describe passive AM as an approach that takes a single conceptual model of system function and improves it over time, while active AM tests multiple competing models simultaneously (for an implementation of the latter approach see Nichols et al., 2007). Williams (2011b) gives a more general definition, stating that both passive and active AM include management interventions to improve system state, but that active AM has the additional aim of using management actions to reduce uncertainty in the underlying conceptual model(s) (see also Rout et al., 2009). In both definitions, active AM is intended to increase the rate of learning.

We favor Williams' (2011b) definition, because it emphasizes that passive and active AM can be thought of as different solutions to the dual-control problem. Both approaches can be appropriate in certain circumstances, depending on the extent to which learning will improve management effectiveness (McDonald-Madden et al., 2011). According to Williams' definition, it is overly simplistic to argue that active AM should always be the preferred approach. In particular, active AM can be controversial in cases where management interventions are used to improve knowledge of the system state, but which are not necessarily advantageous to all parts of the system (e.g. Hughes et al., 2007). Further, passive AM is the logical choice when little improvement in management outcomes could be achieved by collecting further information (Walters, 1986). Passive AM can typically be more readily implemented than active AM, and may provide useful information for lower financial cost in certain circumstances (McCarthy and Possingham, 2007).

### 2.2. Learning from management experiments

In practice, different AM projects can have very different experimental designs, and this variety is potentially confusing for new practitioners. Some AM projects concurrently test multiple management treatments in spatially distinct trials. Such methods provide useful results in some applications (e.g. Lindenmayer et al., 2010a; Waterhouse et al., 2010; Whitehead et al., 2008), but not others. For example, ecological responses to AM of the middle Colorado River are predominantly influenced by a single type of management treatment, namely release of water from the Glen Canyon Dam (situated in northern Arizona, USA; see Meretsky et al., 2000; Stevens et al., 2001; Walters et al., 2000). Further, this treatment can only be implemented at a single location (i.e. the Colorado River), rather than with strict controls (multiple dams) that would enable separation of the effects of treatment and location (Likens, 1985). Therefore, the influence of management is ascertained by creating several competing models of system function (Johnson et al., 2002; Probert et al., 2011), and determining which model best explains change in the system following management interventions (Nichols et al., 1995; Rout et al., 2009).

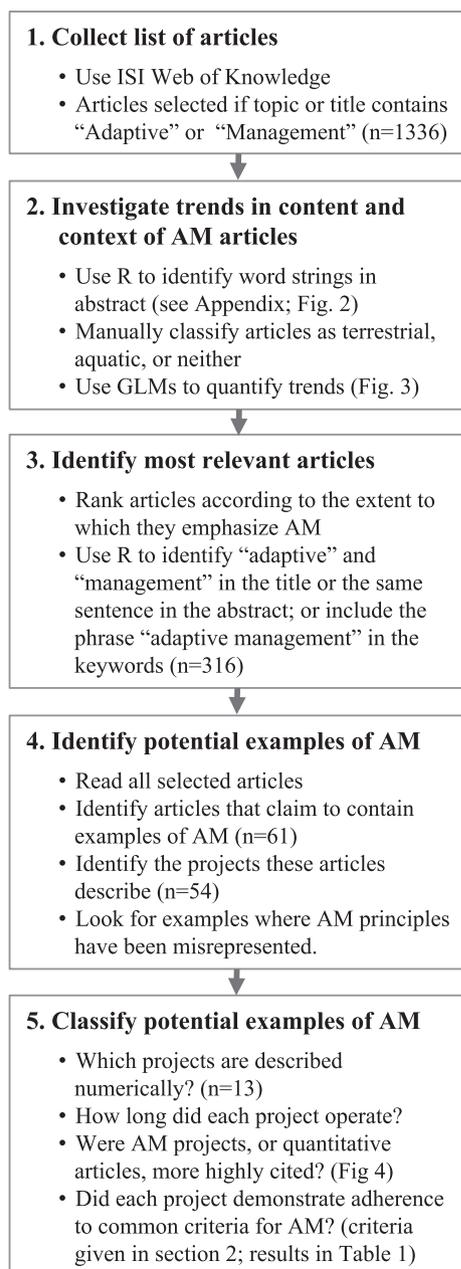
Without an underlying conceptual model (or models), studies lacking spatially replicated treatments are at risk of becoming exercises in trial-and-error management (Duncan and Wintle, 2008; Keith et al., 2011; Walters and Holling, 1990), a process also

described as ‘reactive’ management (Sutherland, 2006). However, we remain agnostic on the extent to which projects must include both quantitative conceptual models and multiple management interventions to be classified as AM. Our approach in this review was to identify how studies were conducted, without arguing that they are (or are not) AM on the basis of these distinctions.

### 3. Methods

#### 3.1. Review structure

We used a multi-stage process to empirically review the AM literature (see Fig. 1). Our first stage involved using the ISI ‘web of science’ to search for articles that included either the phrase ‘adaptive management’ in the topic (i.e. keywords or abstract), or included both of the words ‘adaptive’ and ‘management’ in the title



**Fig. 1.** Flowchart describing the article evaluation process undertaken for this review.

(at this stage, articles did not have to linearly combine the two words, e.g. ‘adaptive ecosystem management’). The web of science groups articles into categories and we used this feature to exclude articles from non-relevant fields, retaining articles with a focus on ecology, fisheries, forestry or biodiversity conservation. We then restricted our search to articles or reviews (excluding conference proceedings) that were published in English. Although we did not restrict our search to a subset of years, the earliest article that we found was from 1978 (Walters and Hilborn, 1978). We ran our search on 25th October 2011, which identified a total of 1336 papers that met our search criteria.

For the second stage of our review, we used an automated approach to classify identified articles, by searching for selected words in the titles, abstracts and keywords of each article (see Appendix A) using the R statistical language (R Core Development Team, 2011). We chose words that were indicative of three topics of interest: applications of AM to biodiversity conservation (see McCarthy and Possingham, 2007; McDonald-Madden et al., 2010b), the importance of social engagement (e.g. Armitage et al., 2009), and methodological issues (e.g. Williams, 2011a). We then supplemented these results by manually classifying each article into one of three categories: those that described studies specific to either terrestrial or aquatic systems, or those articles that were location non-specific (i.e. that aimed to be generally relevant to AM projects).

Our first and second analysis stages described the AM literature in its broadest sense, using AM articles from the ‘web of knowledge’ identified using ‘or’ commands to give a general representation of the work in this field. Although such an overview was important, we wished for our next section to refine our selection to only those articles whose primary focus was enacting AM projects. Therefore, our third stage was to apply supplementary filters to our automatic search, so as to identify those articles that most strongly emphasized AM. To be included in subsequent analysis (i.e. stage 3 onwards), each article had to meet one of the following criteria: include both of the words ‘adaptive’ and ‘management’ in the title; include the phrase ‘adaptive management’ in the keywords; or include both of the words ‘adaptive’ and ‘management’ in the same sentence in the abstract. This left us with 316 articles that strongly emphasized AM in their searchable information.

For the fourth stage of our work, we read the remaining articles to identify those that claimed to describe actual AM projects, either as part of a review or as a case study. Many authors classified their work as relevant to the AM literature without presenting case studies; but it was case studies only that were the focus of our review. We used the information from these articles to create a dataset of projects that authors described as being examples of AM. This stage (moving from discussion of articles to discussion of projects) was necessary because multiple articles described the same project, while some single articles described multiple projects.

Our final stage was to categorize projects according to the definitions set out in Section 2 (above). However, we limited this stage of our analysis to those projects that included quantitative summaries in the articles we reviewed. Although there were a number of useful qualitative case studies, demonstrating that a project has been able to determine the effects of management actions requires quantitative evidence, even if only in a heavily condensed form. More pragmatically, it is difficult to evaluate the statistical design of a project that is only discussed in general terms, and this was necessary to address some of the criteria that we outlined in our definitions section. Further, projects lacking adequate description would be difficult to emulate in new situations. For those articles that provided quantitative information, we assessed the extent to which the project included the six core elements of AM that we outlined in Section 2.

### 3.2. Addressing research questions

We used data generated using our search methodology to address the five questions of interest that we had previously identified (see Section 1). Below we outline the data and methods used to address these questions in detail.

#### 3.2.1. What kinds of problems are authors in the AM literature attempting to address?

We addressed our first question by using data from our second stage analysis stage (i.e. automatic and manual classification of identified articles) to discuss broad trends in the AM literature. We used logistic regression (Generalized Linear Models (GLMs) with a logit link; see McCullagh and Nelder, 1989) to test for significant differences in the proportion of articles emphasizing biodiversity conservation between three different categories (aquatic, terrestrial, or neither). We then repeated our analysis to test for differences between categories in relation to emphasis on social context (model 2) or statistics (model 3). For each of our three models, we used Tukey post hoc tests to determine whether differences in occurrence of relevant keywords were significantly different between categories.

#### 3.2.2. How rare are examples of AM in the ecological literature?

The rarity of AM articles can be classified in several ways, depending on which criteria are used, and the stringency with which those criteria are applied. To highlight the diversity of possible views, we reported the proportion of articles that were retained as we applied increasingly stringent criteria through sequential methodological stages. We calculated our final value for the rarity of AM projects as the number of articles containing AM projects (stage 5) as a proportion of the total dataset (stage 1).

#### 3.2.3. Is there confusion regarding what AM is and how to do it?

Our remaining questions attempted to investigate trends in the opinions and motivations of authors contributing to the AM literature. In most cases, these aspects of ecological research are difficult to quantify from a review of the existing literature, leading to a reliance on indirect surrogates to address our questions. Consequently, we addressed our third question using two lines of evidence. First, we anecdotally identified any articles that misinterpreted the term AM in our reading of AM articles (stage 3). Second, and more thoroughly, we investigated the extent to which articles matched multiple AM criteria (stage 5). Although not directly indicative of ‘confusion’ by practitioners, the latter approach effectively demonstrated the breadth of opinion regarding how AM should be practiced.

#### 3.2.4. Has AM been limited by difficulties associated with long-term monitoring?

Our fourth question was difficult to address, as authors rarely publish incomplete studies, and those that do rarely give detailed reasons for project cessation. None-the-less, we considered it useful to classify two sources of information on the longevity of AM projects. First, we identified the proportion of articles that described the start-up stage of AM projects as a proportion of all articles that emphasized AM in their searchable information (stage 3). Second, we determined the longevity of ongoing or completed AM projects (stage 5), as well as the frequency with which they enacted monitoring while active. In combination, these sources of evidence give information regarding the longevity of AM projects in the literature.

#### 3.2.5. Is there a lack of incentives for ecologists to overcome the above barriers?

Our final question was the most complex one to address using data from a literature review. Although it is difficult to measure motivations and incentives in a meaningful way, citation rates are a widely-used measure of success in academia. Therefore, we created two separate models to investigate different trends in citation rates in relation to AM articles.

First, tested whether AM articles were more highly cited than non-AM articles. We achieved this by taking each article that claimed to enact AM in our review (stage 5), and comparing its number of citations against the number of citations of the article that immediately preceded it in the same journal (using citations recorded on 27th July 2012). Where the preceding article also discussed AM, we chose increasingly earlier articles from that journal until we found an article on a different topic. We then used a generalized linear mixed model (GLMM; Pinheiro and Bates, 2000) from the nlme R package (Pinheiro et al., 2011) to compare ‘source’ articles against their paired ‘comparison’ article, using ‘article type’ (source or comparison) as a fixed effect. We included ‘source article ID’ as a random factorial variable to account for the paired design of our dataset. We also log-transformed citations for normality and included the number of years since publication as a covariate to account for accrual of citations over time. Finally, we allowed interactions between ‘article type’ and ‘years since publication’ to test whether AM articles accrue citations more quickly than non-AM articles.

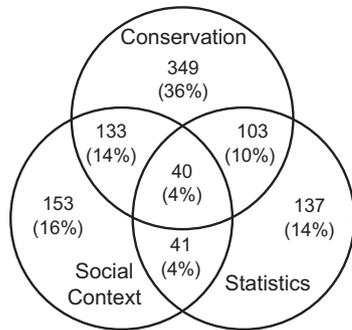
Second, we were interested in whether projects that we described in quantitative terms were more highly cited than projects that were described only qualitatively. We tested this by taking all articles identified in stage 5 and then using Generalized Linear Models (GLMs) to test for differences in the citation rate between qualitative and quantitative articles. We tested for linear effects of ‘article type’ (qualitative versus quantitative), ‘years since publication’, and the interaction between the two.

## 4. Results

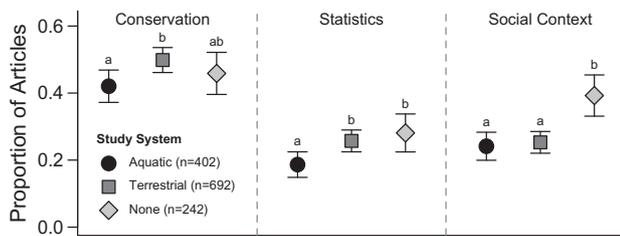
Our search for articles that discussed AM yielded 6962 articles. Restricting our search to relevant subject areas reduced this to 1336 articles. These articles were from a total of 184 sources, including conference proceedings and technical research papers as well as peer-reviewed journals. The majority of sources contained only a small number of articles discussing AM, with 67 sources (36%) publishing only one article each on this topic in the period between 1978 and 2011. Seventeen journals published  $\geq 20$  articles on adaptive management during the same period, cumulatively accounting for 765 articles, or 57% of the total number of abstracts that we read. The vast majority of AM articles were from the 10 years preceding our search in October 2011 ( $n_{(2001-2011)} = 1124, 84\%$ ), corresponding to a massive increase in the AM literature since early work by Walters and Hilborn (1976) and Holing (1978).

#### 4.1. What kinds of problems are authors in the AM literature attempting to address?

We found that, of the three categories of article content that we investigated, biodiversity conservation was most commonly addressed in articles mentioning AM ( $n = 625, 47\%$ ), followed by social context ( $n = 367, 27\%$ ), and finally statistical issues ( $n = 321, 24\%$ ). A total of 380 articles (28%) did not discuss any of these three topics, while of those that did, 40 (4%) discussed all three (Fig. 2). Most articles primarily discussed terrestrial systems (692 articles, 52%), while 402 articles (30%) described aquatic systems and 242



**Fig. 2.** Venn diagram showing the overlap in topics discussed by articles, as identified during stage two of our review. Percentages are based on the 956 articles that occurred in at least one category, which accounted for 72% of the 1336 articles identified for this review.



**Fig. 3.** Proportions of articles describing each of three topics (conservation, statistics, and social context) between three different article categories (terrestrial, aquatic or neither). Values give predicted proportions from a GLM unique to each topic. Error bars give 95% confidence intervals. Unlike letters show significant pairwise differences between contexts for a given topic.

articles (18%) described problems that were general to the field of ecology (i.e. both aquatic and terrestrial systems).

Biodiversity conservation was discussed in a significantly higher proportion of articles describing terrestrial systems (50%) than in aquatic systems (42%,  $\beta_{(terrestrial)} = 0.32 \pm 0.13$ ,  $P = 0.013$ ; see Fig. 3). Studies in aquatic systems also emphasized statistical issues significantly less often than either articles from terrestrial ecosystems ( $\beta_{(terrestrial)} = 0.41 \pm 0.15$ ,  $P = 0.008$ ) or location non-

specific articles ( $\beta_{(other)} = 0.53 \pm 0.19$ ,  $P = 0.005$ ). However, there was no difference in the proportion of terrestrial or aquatic studies that described the social context of AM ( $\beta_{(terrestrial)} = 0.06 \pm 0.15$ ,  $P = 0.67$ ). Instead, a high proportion articles on this topic were essays that did not give a specific study system ( $\beta_{(other)} = 0.71 \pm 0.18$ ,  $P < 0.001$ ).

4.2. How rare are examples of AM in the ecological literature?

Of our original 1336 articles, 137 (10%) included ‘adaptive’ and ‘management’ in the title; a further 179 (13%) either mentioned AM more than once in the abstract, or mentioned AM once and included AM as a keyword, giving a total of 316 articles (24%). Despite finding a relatively high number of articles that emphasized AM, only 61 articles explicitly claimed to enact AM (19% of read articles; 5% of all articles). These 61 contained a total of 54 descriptions of separate AM projects. In total, quantitative results were provided for only 27 projects, while only 13 projects referred to an underlying conceptual model against which results from management experiments were compared (see Table 1).

4.3. Is there confusion regarding what AM is and how to do it?

Our first stage in identifying confusion regarding AM in theory and practice involved identifying unusual applications of the term ‘adaptive management’ during stage 3 of our review process. These findings were largely anecdotal; however, it appeared that only a small number of authors believed they were enacting AM when in fact they weren’t (according to the operation definition of AM that we adopted for this review; see Section 2). For example, two agricultural articles (Fessehazion et al., 2011; Teague et al., 2011) used monitoring data to continually adjust the rate of nutrient application to crops, and described this process as AM. Where a similar definition occurred in other industries (e.g. forestry; see Gong, 1998), this was referred to an ‘adaptive’ approach, but not ‘adaptive management’. Fortunately, it was more common for authors to explicitly acknowledge cases where their work only partially matched a more complete definition of AM (e.g. Hansen and Jones, 2008).

**Table 1**

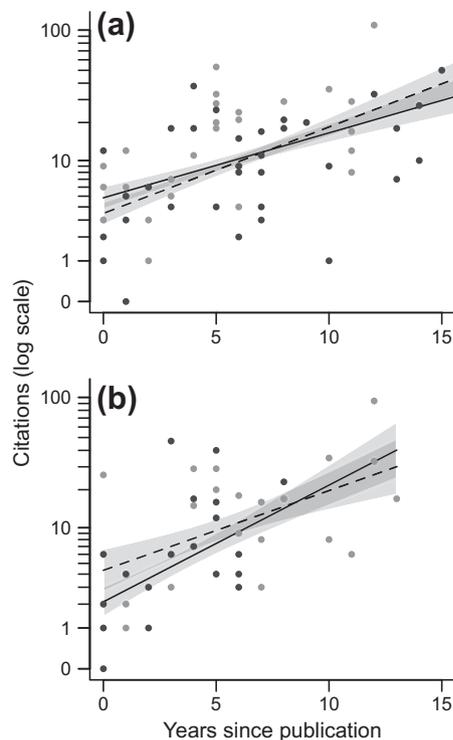
Properties of identified AM Projects (see text for details of selection methodology). Key to AM criteria: (1) Identification of management goals. (2) Specification of  $\geq 2$  management options. (3) Discussion of a rigorous statistical process for interpreting how the system responds to management interventions (quantitative conceptual models and/or a rigorous experimental design). (4) Number of management actions implemented (ideally  $\geq 2$ ). (5) Regular monitoring of system response to management interventions. (6) Adjust management practice in response to results from monitoring. Stars show cases where a criterion has been attained, while question marks show that information is not available in the identified sources.

Project	Country	Duration (years)	AM Criteria						References
			1	2	3	4	5	6	
Waterfowl management	United States	25	*	*	*	Many	*	*	Conn and Kendall (2004), Lyons et al. (2008), Johnson et al. (2002), Williams et al. (1996), Williams and Nichols (2001)
Colorado River, Glen Canyon	United States	13	*		*	1	*		Cross et al. (2011), Hughes et al. (2007), Walters et al. (2000)
Northwest Forest Plan	United States	10	*	*	?	Many	*		Bormann et al. (2007), Gray (2000), McAlpine et al. (2007), Molina et al. (2006), Stankey et al. (2003)
Wolf management – Yellowstone	United States	9	*		*	1	*		Varley and Boyce (2006)
– Yukon	Canada	17	*	*	*	2	*		Hayes et al. (2003)
Reintroduction of Hibi (Mokoia Island)	New Zealand	8	*	*	*	4	*	*	Armstrong et al. (2007)
Predator control – Kokako (North Island)	New Zealand	8	*	*	*	2	*		Innes et al. (1999)
– Whio (Fiord-land NP)	New Zealand	6	*	*	*	2	*		Whitehead et al. (2008)
Woodland management	Australia	7	*	*	*	5			Rumpff et al. (2011)
Restoration of sand-mined locations	Australia	3	*	*	*	6	*	*	Cummings et al. (2005)
Restoration of woodland bird habitats	Australia	2	*	*	*	3	*		Howes et al. (2010)
Management of Sika Deer	Japan	10	*		*	1	*	*	Kaji et al. (2010)
Monitoring of agri-environment schemes	UK	6	*	*	*	2	*	*	Perkins et al. (2011)

Although few authors fundamentally misinterpreted AM principles, the extent to which authors articulated their application of key AM criteria varied enormously (Table 1). Some tested a single management hypothesis (Whitehead et al., 2008); others articulated contrasting hypotheses and tested them (Innes et al., 1999), while the strongest studies developed a range of quantitative models of system function and compared their performance over time (Rumpff et al., 2011; Williams and Nichols, 2001). All projects included management interventions of some kind, although few claimed to be implementing active AM. Although five of the 13 projects were primarily industry-based (with eight primarily focusing on conservation), we found no examples of fisheries projects that claimed to be enacting AM.

#### 4.4. Has AM been limited by difficulties associated with long-term monitoring?

During our review, we found no published examples of authors stating that a requirement to monitor system state over time caused the cessation of an AM project. However, our data suggested two trends regarding longevity in the AM projects. First, during our reading of 316 articles (stage 3), we found 58 articles (18%) that claimed to be in the initial or set-up stages of AM projects. This is almost as many as claimed to describe in-progress or completed AM projects ( $n = 61$ ), suggesting either a massive increase in project start-ups in recent times, or that most projects never progress beyond the early planning stages. We found some evidence for the former, since many 'start-up' articles were recent (mean age = 4.8 years). This result suggests that the number of AM projects currently underway could be larger than a review of existing articles would imply.



**Fig. 4.** Total number of article citations as a function of years since publication. (a) Comparison of AM (dark circles) versus non-AM articles (light circles). Solid lines give slopes of regression line fit to AM article citations, while dashed lines show line for non-AM articles. Shaded regions show 95% confidence intervals, with darker regions showing overlap between 95% CIs of each line. (b) Comparison of quantitative AM articles (dark circles) versus qualitative AM articles (light circles). Lines and shaded regions calculated as for (a).

Second, few projects were long-lasting. Of the 13 projects identified as likely AM examples, only four lasted longer than 10 years. Moreover, although all projects mentioned some form of monitoring, some chose occasional revisits to managed sites after a long interval (e.g. Rumpff et al., 2011), rather than regularly timed, ongoing monitoring (e.g. annual or biannual measurements). Nine projects explicitly stated that they involved regular monitoring at fixed intervals. However, some projects were very short ( $n_{\leq 3 \text{ years}} = 3$ ,  $n_{4-10 \text{ years}} = 8$ ), and it was unclear whether that frequency of monitoring effort could be sustained.

#### 4.5. Is there a lack of incentives for ecologists to overcome barriers to implementation of AM?

Our analysis showed no significant difference between the number of citations of AM versus non-AM articles ( $\beta_{(\text{article type})} = 0.27 \pm 0.23$ ,  $P = 0.26$ ,  $n = 61$  in each class), nor a difference in the rate at which AM and non-AM article accrued citations over time ( $\beta_{(\text{article type:time})} = -0.036 \pm 0.033$ ,  $P = 0.28$ ; see Fig. 4a). Similarly, AM projects supported by empirical results ( $n = 27$ , 50%) were cited marginally less often than were qualitative articles (after time since publication was taken into account), although this difference was not statistically significant ( $\beta_{(\text{quantitative articles})} = -0.54 \pm 0.43$ ,  $P = 0.23$ ). Further, both qualitative and quantitative articles accrued citations at a similar rate with increasing time ( $\beta_{(\text{article type:time})} = 0.063 \pm 0.075$ ,  $P = 0.41$ ; Fig. 4b). This suggests that during the process of writing articles for peer-review, ecologists do not value AM studies more highly than the wider literature, and place roughly equal value on quantitative and qualitative information from existing AM studies.

## 5. Discussion

### 5.1. Why is AM so hard to do?

Our review has indicated that despite the extensive literature on AM, there are surprisingly few practical, on-ground examples of adaptive management (as defined for this review). Evidence from other authors (e.g. Muir, 2010) suggests that this is a real trend in environmental and biodiversity management, rather than the result of difficulty in publishing articles that describe AM projects (although see Bormann et al., 2007). A key question then is: Why is AM so difficult to do? In this section of our paper, we review and reflect on the key reasons that have been suggested to contribute to the paucity of practical, on-ground examples of AM.

#### 5.1.1. What kinds of problems are authors in the AM literature attempting to address?

We found that research emphasizing biodiversity conservation was common in the AM literature, with 47% of articles emphasizing this topic. This concentration of research effort appears to reflect legitimate difficulties in applying AM to some of the kinds of problems that policy-makers and resource managers want addressed. For example, AM projects involving extremely rare and/or endangered species can be very difficult if not impossible (Bakker and Doak, 2009). Although some examples exist (e.g. Mackenzie and Keith, 2009), limited numbers of populations often cause in difficulties in designing robust experiments such as establishing replicates of multiple treatments (e.g. Baw Baw Frog *Philoria frosti* in south-eastern Australia, see Hollis (2004)). What is less clear is why attempts to apply AM to biodiversity conservation are significantly more common in terrestrial systems than aquatic systems, both in absolute and relative terms (Fig. 3). It is possible that this result reflects that marine reserves are generally more recent and contested than terrestrial reserves as tools for

ameliorating biodiversity loss (e.g. see Hughes et al., 2007). Fortunately, it appears that the prolonged research effort focused on applying AM to biodiversity conservation is paying dividends, with a small but growing number of examples appearing in the literature (Table 1).

In other cases, our review suggests that AM may not be well suited to testing management options associated with some large-scale ecological phenomena or factors that are important at multiple spatial scales or across multiple land tenures. It was particularly telling that only three projects in our final list (Waterfowl management (Williams et al., 1996), the Northwest Forest Plan (Stankey et al., 2003), and wolf management in the Yukon (Hayes et al., 2003) involved truly large-scale problems. All three projects were from continental North America, which has a long history of research in this field. At these large scales, conflict between resource users can be exacerbated where the range of potential management interventions is limited, such as in large hydrological systems (Roe and van Eeten, 2002). An example in an Australian context is the coordinated, multi-landscape-scale poison baiting control of feral predators (Parkes et al., 2006) that, to be effective, often needs to occur across areas under different tenures and managed by different organizations and/or private individuals with different management priorities, goals, values and reward systems.

Unfortunately, our results showed that a significantly higher proportion of articles discussed the social context of ecological problems in general terms, rather than describing specific tools for conservation in terrestrial or aquatic systems (Fig. 3). Clearly, more work is required to enable extension of AM to truly 'wicked' problems that occur at large spatial scales and across multiple land tenures.

Although the above points may appear discouraging, there are important counter-arguments to the problems that we have raised. Decision theory provides a mechanism for evaluating the usefulness of information gained by taking risks (see McDonald-Madden et al., 2010b; Rout et al., 2009), and AM can provide useful information even when one or more parts of the project are unsuccessful (e.g. reintroductions of endangered birds in New Zealand; see Armstrong et al., 2007). Further, our results showed that most articles that discussed statistics in the AM literature related to specific study systems, rather than attempting to develop statistical approaches that are generally applicable across AM projects.

As well as highlighting the high level of thought that has gone into developing AM projects – a number of which have been successful (Table 1) – our results suggest that attempts to interpret the outcomes of management experiments remain an area of active research. Finally, it is important to state that no other approach is clearly superior to AM. Approaches such as trial-and-error management can only provide an impression of superiority by masking the sources of uncertainty inherent in any environmental management problem.

#### 5.1.2. How rare are examples of AM in the ecological literature?

Perhaps the most important result of our review has been to quantify how rare AM projects are in the AM literature. Articles claiming to enact AM constitute <5% of all articles on the topic, between them encompassing a total of 54 potential projects. Although some of these projects are very large in scale (e.g. Nichols et al., 2007), overall, our review supports the widely-held view that AM projects are very rare indeed (Allen et al., 2011; Keith et al., 2011; Stankey et al., 2003; Walters, 2007; Williams et al., 2009).

Although our finding reflects genuine difficulties in enacting AM, the appearance of rarity may be reinforced by two processes. First, the scale of the literature hinders effective synthesis. We studied 1336 articles for this review, and it is highly likely that we missed some key papers. This could occur because: (1) articles were mistakenly excluded from our automated search; (2) we

misinterpreted some of the content of articles during manual evaluation; or (3) the authors of articles themselves did not identify their research as AM despite implementing management experiments. Such issues are inevitable in a literature review of this size, and clearly the same difficulty in identifying AM examples exists for any would-be AM practitioners searching for motivating examples. Second, the gray literature of books and technical reports is likely to contain some laudable examples of AM projects. In particular, we speculate that the gray literature is likely to contain some useful studies in fisheries. This may explain why we found few articles claiming to enact AM in fisheries, despite the large amount of early work on AM that focused on that industry (e.g. Hilborn and Sibert, 1988; Smith and Walters, 1981; Walters and Hilborn, 1976; Walters, 1986). Unfortunately, gray literature is often unavailable to most practitioners. In addition to reviews such as ours, the development of websites that aim to share the results of management experiments (e.g. Jenkinson et al., 2006; Sutherland, 2011) is a useful vehicle for reducing information barriers to further AM practice in future.

#### 5.1.3. Is there confusion regarding what AM is and how to do it?

One reason why AM projects appear to be rare may be associated with the myriad of different kinds of investigations that are claimed under the banner of AM (Table 1). Although our results suggest that researchers who publish on this topic generally have a clear understanding of AM principles, there is a risk that the diversity of ways in which AM is applied may lead to confusion for those less familiar with the concept. This might explain why – in our experience of the broader NRM community – there appears to be a lot of confusion and arguments at cross-purposes about what AM actually is (see Section 2; Allen et al., 2011). The concept of AM appears to be differently understood by researchers, policy makers and resource managers, with many agencies claiming they are doing AM but in fact are using *ad hoc* approaches (trial and error management (Duncan and Wintle, 2008) or reactive management (Sutherland, 2006). Thus, robust experimental studies underpinned by well-designed comparisons of different management options may be deemed unnecessary by policy makers and resource managers when they (incorrectly) believe that existing approaches – such as reactively adjusting their management in the light of new information – constitute 'adaptive' management.

#### 5.1.4. Has AM been limited by difficulties associated with long-term monitoring?

A central tenet of the AM paradigm is that monitoring has to be adequate to detect change resulting from management experiments. It therefore follows that where management effects accrue over long time periods, monitoring will also have to occur over a long period of time (Lindenmayer and Likens, 2010a). For example, testing the predictions of competing models that aim to quantify population sizes of migratory birds requires annual monitoring over a number of years (Williams and Nichols, 2001), while comparable studies regarding the distribution of wildfires could span decades (Andersen et al., 2005). Unfortunately, long-term investigations are notoriously difficult to establish and maintain (Lindenmayer and Likens, 2010b). This was exemplified when, during our review, we noted a number of articles ( $n = 58$ ) describing experimental designs for then-incomplete AM projects (e.g. Ascoli et al., 2009; Campbell et al., 2001), or advocating indicators to measure change resulting from future management actions (discussed by Lindenmayer and Likens, 2011). However, comparatively few articles described the results of such projects. While not conclusive that a requirement for long-term monitoring is hindering AM, our results suggest either that a number of AM projects have been established recently (and so are yet to report their

results), or that considerable barriers exist to the establishment of long-term AM projects.

Once established, proposed long-term projects are vulnerable to further problems, such as: (1) Funding cuts (Likens, 1989; Lindenmayer and Likens, 2010a). (2) Policy changes that leave them struggling for management relevance (Russell-Smith et al., 2003). (3) Events like fires and floods that can destroy the design of an experiment (Lindenmayer et al., 2010b). (4) Changes in personnel, leading to the loss of a project champion within an organization and in turn, the erosion of the partnerships necessary to keep AM projects going (Williams et al., 2009; see also below). These difficulties may dissuade researchers from establishing long-term AM projects, despite the ample opportunities such research would provide for investigation into novel, highly relevant and interesting problems.

#### 5.1.5. Is there a lack of incentives for ecologists to overcome barriers to implementation of AM?

Although determining the motivations of AM practitioners from a literature review is inherently difficult, we reasoned that citation rates are a surrogate for the extent to which ecologists value a given piece of research. They are also a metric of academic 'success' used by universities. We therefore expected that academic ecologists might take citation rates into account when making decisions about the kinds of research in which to engage. In this context, we were surprised to find that AM articles were no more highly cited than paired, randomly-selected articles (Fig. 4a), despite the need for better evidence-based approaches to biodiversity management (Pullin and Knight, 2009; Sutherland et al., 2004). This lack of an incentive to publish AM research adds to a number of other known disincentives to academic engagement in the AM process. For example, academic input is often not valued by industry partners in the early stages of AM projects (Molina et al., 2006; Stankey et al., 2003). Fortunately, it appears that ecologists are aware of these issues, and are seeking ways to improve future engagement (e.g. Susskind et al., 2012). This was shown in our study by the lack of a difference in citation rates between quantitative and qualitative AM articles (Fig. 4b), implying that qualitative insights into the successes and failures of AM projects are equally of interest to academics as methodological or statistical aspects of the AM process. But overall, our results imply that reward systems in universities may not encourage academics to overcome the difficulties that we have outlined above, providing little incentive for academics to engage in AM experiments.

Although we have focused here on academic incentives to engagement in the AM process, we are acutely aware there may be many other reasons why combining management and research is rare in biological systems (e.g. see Gray, 2000; Jacobson et al., 2006; Norton, 1998). One of these is the culture and psyche of some natural resource management institutions. First, the personnel in many agencies may be threatened by the risks posed by admitting they do not have complete knowledge about a given issue (Lindenmayer and Franklin, 2002). This, in turn, may be threatening for senior staff in that organization or for politicians whom are inherently risk-averse. Second, some policy makers and resource managers do not see the need for the science which underpins AM as being relevant and nor do they understand how it may help good decision making. They also may believe that key scientific parts of the design of adaptive management projects (e.g. replicated alternative treatments) will lead to projects being "over-engineered" – a criticism of a recent temperate woodland stewardship project in south-eastern Australia (Lindenmayer, personal observation). Third, AM projects may demand that strongly contrasting treatments be tested – but this can require management activities outside the normal prescriptions to be employed (e.g. more frequent burning or higher intensity logging

than usual). Legislative, philosophical and cultural barriers may preclude such treatments from being implemented (see Hughes et al. (2007) for an example in the establishment of AM in the Great Barrier Reef). Fourth, successful AM projects typically require partnerships among people with scientific, policy making and resource management expertise. However, many organizations lack the range of staff with this suite of skills. To overcome this, there may be a need to foster partnerships among people from different institutions with different expertise and sets of skills but who have different reward systems (Gibbons et al., 2008).

#### 5.2. Potential approaches to overcome the impediments to establishing AM

Despite the many difficulties in implementing AM projects, there presently appears to be no alternative, viable, or clearly superior framework. Given this, there is value in seeking to identify ways in which to reduce the barriers to increasing the adoption of AM projects. We argue that three approaches may be important in this regard.

First, the often considerable costs of AM projects might be reduced (making such projects more likely to be maintained, and hence more likely to be successful) if they are "piggy-backed" on existing management and/or resource extraction practices wherever possible (Walters, 1992). In cases where the AM process is truly collaborative, management activities and research are integrated, potentially reducing management costs in the long-term (Zhou et al., 2008). For example, the costs of a recent AM project investigating logging practices were minimized by building a blocked and replicated experiment around ongoing timber harvesting operations (Lindenmayer et al., 2010a). A similar approach was followed during investigation of alternative silvicultural systems in western British Columbia (Bunnell and Dunsworth, 2009). Our review highlighted several more examples of successful AM in industries responsible for extraction of renewable resources (Table 1), suggesting that 'piggy-backing' has been a successful approach, despite problems in some specific industries (e.g. fisheries; Walters, 2007). Such projects require scientists to establish working partnerships with policy makers, resource managers and become more aware of the social dimensions of AM (Davis et al., 2001). These include the reality that policy makers, resource managers and scientists have different cultures and reward systems and are motivated by different kinds of questions and conceptual models (Gibbons et al., 2008).

Second, scientists need to better communicate the benefits of doing AM for cost-efficient and more effective resource management. For example, the US waterfowl management project has generated information capable of answering questions that could not be answered except through an AM process, greatly improving management effectiveness. Similarly, Armstrong et al. (2007) were able to use the AM process to provide valuable information despite failure of their first attempted reintroduction. A related point is that scientists need to communicate the risks of *not* doing AM, such as the problems associated with negative ecological "surprises" that are difficult or impossible to reverse once they have manifested (see Lindenmayer et al., 2010b). Such communication may need to be couched within a framework of risk-aversion, and highlight why evidence-based approaches are important for informed resource management and conservation efforts (Pullin et al., 2004).

Third, more AM projects are likely to be established and maintained if they "pass the test of management relevance" (sensu Russell-Smith et al., 2003). Although this would appear obvious, it was clear from our review that many locations which have been the focus of extensive research efforts are not necessarily effectively managed. For example, the Florida Everglades is a location where much ecological research is done – Redfield (2000) estimated that

**Table A1**

Table of keywords used to identify articles with particular themes.

Category	Keywords
Biodiversity conservation	"biodiversity", "conservation", "restoration", "restore", "protect", "extinct", "endangered" + subject = "Biodiversity and Conservation"
Social engagement	"social", "socio", "policy", "participatory", "education", "sustainable", "sustainability", "collaborative", "economic" + subjects "Business and Economics", "Engineering" or "Urban Studies"
Methodological issues	"model", "statistical", "simulation", "sensitivity", "optimal", "bootstrap", "bayesian", "analysis"

there had been 1500 articles published on this location, while a search conducted for our review in January 2012 (using ISI web of knowledge, for the topic 'Florida Everglades') yielded a further 724 articles published since 2001. Some of this research has evaluated relative support for different models of landscape function (e.g. Hagerthey et al., 2008), but integration of this research into an AM plan for the Everglades has taken a huge amount of time and effort (Brown, 2005; Sklar et al., 2005). Given the potential for a mismatch between publication output and management effectiveness, ecologists should acknowledge that management-relevant research is primarily useful when it is (or can be) applied by management agencies (Russell-Smith et al., 2003). In addition to maintaining publication output, ecologists should also consider sustainable management of natural resources, and meeting of pre-defined goals to be valid and important measures of successful ecological research (see e.g. McDonald-Madden et al., 2009).

## 6. Conclusions

We have presented the first structured review of the AM literature that relates to biodiversity and ecosystem management. We found that despite the enormous literature on AM, articles describing AM projects are extremely rare, consisting of <5% of all reviewed articles. One important consequence of the lack of AM has been inappropriate evaluation of the outcomes of past interventions, and therefore of corresponding future research needs. Application and monitoring of management interventions has been inadequate, limiting our understanding of important ecological processes necessary for effectively managing biological systems. The key goal for future practitioners should not only be to improve their methodologies to allow identification of cause and effect in biological systems (which can be achieved by AM projects), but more importantly to find ways to enact the iterative improvement of management and research questions though time (which is far rarer).

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## Appendix A

Table A1.

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