REVIEW

A systematic review of adaptive wildlife management for the control of invasive, non-native mammals and other human-wildlife conflicts

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ABSTRACT

1. We are entering an era where species declines are occurring at their fastest ever rate, and the increased spread of non-native species is among the top causes. High uncertainty in biological processes makes the accurate prediction of the outcomes of management interventions very challenging. Adaptive management (AM) offers solutions to reduce uncertainty and improve predictability so that the outcomes of interventions can continuously improve.
2. We quantitatively assess the extent to which AM is used for managing vertebrates, with a focus on invasive non-native species (INNS). Using the Web of Science, we evaluated 3992 articles returned by the search terms ‘adaptive management’ or ‘adaptive harvest

management' against seven recommended elements of AM (engagement with stakeholders, defining objectives, forecasting and estimating uncertainty, implementing management, monitoring populations, adjusting management in response to monitoring, and improving forecasting and reducing uncertainty in response to monitoring populations).

3. The use of AM for vertebrates was reported in 56 (1%) of the evaluated studies; including four for managing INNS. Of these, ten studies excluding INNS and no studies of INNS management implemented all seven recommended elements of AM. Those elements infrequently implemented were: the use of analysis or models to forecast and represent uncertainty (44%) and the feedback of monitoring data to improve forecasting and reduce uncertainty (25%).
4. Complete active AM has rarely been implemented and reported for managing INNS, despite the significant advantages it offers. Among studies purporting to have implemented AM, most did not use analyses or models to forecast and represent uncertainty, while most defined objectives, implemented management, and monitored populations.
5. Improvements to ongoing control programmes and much broader adoption of the AM approach are required to increase the efficiency and success of INNS management campaigns and reduce their negative impacts on native species.

Keywords: campaign, conservation, control, global, harvesting, mammals, uncertainty

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INTRODUCTION

Anthropogenic impacts on biological systems are widely accepted to be the cause of recent mass global species declines (Sarukhan et al. 2005), often leading to extinctions (Barnosky et al. 2011). Among the top drivers of species declines are: habitat loss and fragmentation (Collinge & Forman 2009), invasive non-native species (INNS, Vitousek et al. 1997, Simberloff 2010, Blackburn et al. 2019) and climate change (Thomas et al. 2004). Effective and efficient management to prevent these declines is essential (Simberloff 2010), especially where financial resources are limited. Effective management of INNS is challenging, as species can become numerous and widespread before they are detected, and their impacts (often on native species and ecosystems) may require novel and long-term management methods. Examples of invasive mammal species subject to long-term management in the UK include American mink *Neovison vison*, grey squirrel *Sciurus carolinensis*, fallow deer *Dama dama* and muntjac deer *Muntiacus reevesi*. Relatively recent eradications include muskrat *Ondatra zibethicus* and coypu *Myocastor coypus*.

In complex ecological systems, predicting the optimal management intervention among a range of options is difficult, often due to a range of unknowns and uncertainties (Ward et al. 2020). Uncertainties may arise from environmental variation, sampling variation or the response of populations to the management methods. Adopting an adaptive, rather than a fixed approach to management allows management actions to change based on new knowledge while maintaining the same objective (Franklin et al. 2007). Adaptive management (AM) has frequently been proposed as the most effective method for managing ecological resources (here we use the term to include INNS species which may need to be managed or eradicated), where there is high uncertainty (Holling 1978). AM is defined as "flexible decision making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood. Careful monitoring of these outcomes both advances scientific understanding and helps adjust policies or operations as part of an iterative learning process" (National Research Council 2004). The philosophy of AM was first described for adaptive decision making in fisheries management (Beverton & Holt 1957); it was later defined as a term and formalised as a conceptual framework (Holling 1978, Walters & Hilborn 1978).

The aim with using AM is to reduce uncertainty by gaining knowledge of the system using either an active or a passive approach (Williams 2011a). In active AM, learning about the system is a distinct objective, and multiple approaches are tested simultaneously and may result in a sub-optimal management intervention being implemented to improve learning about the system. In passive AM, learning about managing the ecological resource is a distinct objective, and therefore a known sub-optimal management intervention is not implemented (Larson et al. 2013). A passive approach is often adopted where it is impossible to implement multiple interventions concurrently, managers are unwilling to implement sub-optimal management interventions, or there are insufficient funds for the extra time that may be needed for learning about the system (Gregory et al. 2006, Hughes et al. 2007). While a passive approach is more likely to result in effective management than where no AM is applied, it does not facilitate learning about the critical features of the system, and putative relationships between environmental variables and the ecological resource may be misinterpreted, hampering evaluation of the effects of management actions on the ecological resource.

One of the most well-known examples of AM for harvesting populations is to support the hunting of the North American mallard *Anas platyrhynchos* (Nichols et al. 2007). The resource objectives were to maximise the long-term cumulative harvest utility, and the system objectives were to learn about the relationship between harvest rate and survival rate. The management options were liberal, moderate and conservative hunting regulations; daily bag limits were specified for each option. The underlying models which were updated included two models of different levels of density dependence of mallard reproductive rates and a maximal and minimal model of the hunting mortality on total annual survival (Nichols et al. 2007). Population estimates ranged from 6 to 12 million birds over 15 years. AM enabled the additive hunting mortality and weak density-dependent reproductive rate model to be identified as the optimal model, resulting in population sizes being predicted more accurately, and hunting limits could be more liberal (Johnson et al. 2002).

While AM is acknowledged to be the best approach for managing ecological resources where there is a high degree of uncertainty (e.g. McCarthy & Possingham 2007), active AM is not widely implemented (e.g. Schreiber et al. 2004), particularly for managing a resource such as INNS (Foxcroft & Mcgeoch 2011). This lack of implementation might be due to a lack of opportunity (e.g. poorly resourced, limited ability to replicate the management interventions, no control options), or a lack of expertise to implement it properly. However, AM should provide a useful framework for managing INNS because there is high uncertainty in the underlying population processes, environmental variation, and management impacts on INNS. An example of the use of a passive AM approach for INNS management is the removal of American mink from the north-east of Scotland (Bryce et al. 2011). Engagement with a wide range of stakeholders (government agency, national park authority, and local fisheries boards) enabled a checking programme of monitoring and trapping. The monitoring data were analysed on a six-monthly basis, to allow the spatial deployment of traps to be optimised based on environmental variables, ultimately increasing capture efficiency (Bryce et al. 2011). However, if models of mink populations were included in the study, learning about the relationship between management interventions and population sizes would be achieved, and therefore the full potential of AM would be realised.

Given the apparent interest for the management of vertebrate populations and the lack of uptake of formal AM approaches, especially in the management of INNS, we sought to quantify how robust the application of AM has been for INNS and other vertebrates assessed against the AM stages advised by Williams (2011b). We conducted a systematic review of the use of the term Adaptive Management and its described application in wildlife management (a knowledge gap identified by Rist et al. 2013). We use this review to develop practical guidelines for the implementation of AM to increase uptake and determine which criteria need more careful consideration when planning INNS management campaigns.

METHODS

We used the Web of Science to search for studies using adaptive management for wildlife management and conservation. The search terms 'Adaptive Management' and 'Adaptive Harvest Management' were used to identify studies published between 1970 and 2017, generating a database of 3992 articles (search date 23 December 2017). Articles were manually filtered to identify those reporting the use of AM for the management or conservation of vertebrate wildlife taxa (defined herein as vertebrates), thus excluding plants, invertebrates, and domestic animals. We removed articles that included AM or adaptive harvest management as a keyword but did not state that they used AM. Filtering was conducted by sequentially reviewing the title or abstract of the article, or the whole article, as necessary.

We identified 183 articles citing AM for vertebrates: 25 (14%) were review articles without case studies, 63 (34%) were theoretical studies where a framework was described and/or the study suggested AM should be used but it was not implemented, 27 (15%)

reported on the initial stages or parts of an AM study for vertebrates, and the remainder (68, 37%) were studies of AM of vertebrates (including review articles with a case study). Within these, we combined articles that reported on different aspects of the same AM study into a single record, resulting in 56 unique studies. We recorded the taxa of the study species, the region of the study, and the publication year of the article. Studies were further reviewed to categorise AM as active or passive, and the reason for choosing AM. We defined the type of AM as active if the objective was system orientated, and passive if the objective was resource orientated.

We assessed if each study reported the seven recommended elements of AM described by Williams (2011b) as follows: (1) engagement with stakeholders, (2) identification of objectives, (3) forecasting and representing uncertainty, (4) implementation of more than two management options (Williams 2011b states that a range of management options should be implemented, which we interpreted as more than two), (5) implementation of a regular monitoring programme, (6) management practices that are adjusted in response to the results of monitoring, and (7) monitoring data that are used to improve forecasting ability and reduce uncertainty. We assessed studies against meeting all these elements and against our reduced criteria of meeting elements 2, 3, 5, 6 and 7 (see Discussion for an explanation of our removal of elements 1 and 4). Of fully implemented studies that included (2) objectives and (6) modified management in response to monitoring, we calculated the percentage that was successful (defined as meeting their stated objectives).

RESULTS

Among the 56 AM studies of vertebrates, the term AM was used in the title in 38%, as a keyword in 45%, and in the abstract in 70% of studies. Ten studies implemented all seven recommended elements of AM described by Williams (2011b), while 12 implemented at least our five reduced elements (excluding stakeholder engagement and the implementation of a range of management options; Tables 1, 2). Among these 12 studies, examples of AM were active (three studies) and passive (nine). Since 1997, there has been an increasing trend in the number of AM studies produced per year (Fig. 1). AM studies are most common in North America (43% of studies), Europe (25%) and Australasia (16%; Fig. 2). The highest percentages of studies that implemented our reduced elements of AM were in North America (25%), Australasia (22%); and Europe (21%). AM was most commonly used to manage mammals (45% of studies), birds (23%) and fish (18%), only two studies were conducted on reptiles or amphibians (Fig. 3). The highest percentages of studies that implemented our reduced elements of AM were studies conducted on birds (38%), and fish (30%), with only 12% of studies on mammals. AM was most often used for harvesting populations (32% of studies), followed by conservation (23%), reintroductions (11%) and INNS management (7%; Fig. 4). Our reduced elements of AM were more likely to be implemented when used for harvesting populations (39%); no studies implemented all seven recommended elements of AM for conservation or INNS management.

Out of the 56 AM studies, most (94%) implemented a clear, regular monitoring programme and most specified clear objectives for the AM study (90%). The recommended elements of AM least likely to be implemented were forecasting and estimating uncertainty (44%) and the feedback of monitoring data to improve forecasting ability and reduce uncertainty (25%). Half of the studies implemented up to three of the recommended AM elements. Since analysis and models were not often used and accounted for two of the recommended AM elements, a significant percentage of the studies (20%) implemented only five of the seven recommended AM elements. Among the fully implemented studies with defined objectives and management modified in response to monitoring (n = 16), 50% were successful, 25% were partially successful, and 19% were unsuccessful in meeting their objectives (the remaining 6% did not state the outcomes in relation to their objectives); the two studies on managing INNS were both successful.

DISCUSSION

Improving the effectiveness and efficiency of management is increasingly important for the conservation and sustainable use of wildlife; a particular challenge is INNS management where numbers and impacts are increasing in the face of limited resources (Vitousek et al. 1997, Simberloff 2010). When operating under high uncertainty, AM is an effective way of managing human-wildlife conflicts (Holling 1978, Walters 1990). We found that the use of the term AM has been increasing in the literature. However, when we examined the application of AM, we found that most studies had not implemented all the elements of AM recommended by Williams (2011b). Only 10 of the 56 studies identified as using AM for vertebrate management or conservation reported full implementation of the recommended AM elements described by Williams (2011b), and none of these described the management of an INNS. If this pattern of publication reflects the pattern of INNS management, then despite the many advantages offered by AM, it is only being adopted very infrequently and without all the recommended elements. Perhaps there are so few examples of AM being applied to INNS because few researchers have considered the importance of uncertainty when managing INNS (Rout et al. 2009, Ward et al. 2020). Uncertainty in INNS management arises due to many reasons, including variation in the efficiency of trapping devices or immunocontraceptive vaccines (e.g. Cowan et al. 2020), population sizes, reproductive rates, and population ranges (Mehta et al. 2007). These uncertainties have implications for the effort involved in managing INNS, and hence for the duration and cost of management.

Our study showed further quantitative evidence of the misrepresentation of the term AM, despite the publication of detailed descriptions of AM (Williams 2011a, b). For example, the percentage of articles implementing our reduced elements of AM was 22% for articles published before 2012 and 25% after 2011. A lack of uptake of AM may be due to confusion about what AM is how it should be implemented (e.g. Lee 1999, Rist et al. 2013). We found that the number of studies that reported the implementation of all seven recommended elements of AM occurred after 2000, but partial implementation was typical. Most studies defined objectives and conducted regular monitoring, while few studies forecasted the effects of management and estimated uncertainty at the start of the study, and continued to do so with the addition of new monitoring information.

Ongoing evaluation is one of the defining characteristics of AM. We found several studies reported as AM for vertebrates in which the authors assessed the effect of management on an ecological resource at the end of a multi-year study (e.g. Whitehead et al. 2008), rather than assessing and re-evaluating the effects of management on the resource and whether they had met their objectives throughout the study. In AM, predictive models or analyses are used to forecast and estimate uncertainty. These models or analyses are then continually updated with new monitoring information. A common misconception is that AM is something that is assessed once at the end of the study, rather than a cyclic, reiterative process where monitoring, management, prediction, and evaluation are continually conducted, enabling management to be modified and improved continually. To avoid misunderstanding, we advocate that the term AM is used only to describe programmes that implement all seven of the elements defined by Williams et al. (2011b), or our five reduced elements (i.e. defining objectives, forecasting and estimating uncertainty, implementing regular monitoring, adjusting management in response to monitoring, and updating forecasts and uncertainty estimates in response to new monitoring data).

We found that more of the recommended AM elements were likely to be implemented where the managed resource has a monetary value, such as harvest management, and that none of the INNS studies fully implemented all the recommended AM elements or our reduced AM elements. The required commitment of funds for long-term, replicated studies, often required for AM, may explain the lack of use (e.g. Gregory et al. 2006, Hughes et al. 2007). Failure of AM studies at the planning stage, possibly due to lack of funds, has been previously identified (Walters 1997). The predominance of studies published on AM of vertebrates conducted in Europe, North America and Australasia supports the importance of funding for AM studies; the pattern is consistent with the geographical pattern of submission and publication within the field of applied ecology more generally (Nuñez et al. 2019). One of the reasons given for the disparity between the continents is gross domestic product investment in research and development; gross domestic product is a strong predictor of article submission and acceptance rate (Nuñez et al. 2019). This disparity is concerning given that INNS, while globally problematic, are particularly concerning in Africa (MacDonald et al. 1986) and South America (Speziale 2012). Furthermore, the disparity found here in AM studies of vertebrates was more extreme than that found in the general field of applied ecology.

Having clearly defined objectives that are measurable and time-bound is essential in any study, but particularly in AM, since evaluation is an essential stage in each AM cycle, and studies can only be evaluated if there are clear, measurable objectives. Most studies did define measurable objectives, such as the eradication of goats (Cruz et al. 2009), but these were rarely time-bound. When using AM for the prevention of INNS, the European Union's list of priority INNS or the Non-Native Risk Management scheme (a risk management scheme assessing effectiveness, practicality, cost, impact, acceptability, window of opportunity and likelihood of re-invasion) could be used in conjunction with AM to prioritise INNS management (Mumford et al. 2010, Booy et al. 2017). We suggest that implementing specific, measurable, achievable, realistic and time-bound (SMART) objectives would improve the effectiveness of assessment and hence increase the success rate of AM for INNS management. Setting a time to achieve objectives is difficult, but if time frames are at least estimated and continually re-evaluated, this may help reduce the number of studies that fail in the early stages (Walters 1997), and may help secure funds from the outset. For attempted eradications, accurately estimating the time to eradication can be particularly challenging. An alternative strategy may be to set interim objectives which are time-bound. This is consistent with AM, and was implemented for the ongoing eradication of the ruddy duck *Oxyura jamaicensis* (Smith et al. 2005).

The application of AM has been successful in North America, where there is close collaboration between scientists and practitioners in governmental bodies, such as the U.S. Fish and Wildlife Service. This close collaboration is facilitated in North America by the ownership of wildlife resources by the state. In contrast, in large parts of Europe, individual landowners typically own the right to extract wildlife resources, increasing the challenge of promoting the long-term, centrally co-ordinated management at the scales at which wildlife populations operate (Mill et al. 2020), and hence the perceived need for and use of AM. Collaboration between scientists and practitioners facilitates the use of analyses or models to understand underlying structures or processes in management practice, an element of AM implemented in only 44% of the studies we reviewed. Models or analyses are essential for two reasons: they play a crucial role in representing structural or process uncertainty, and they link potential management actions to the ecological resource consequences (Williams 2011a, b). Implementing analyses or models for complex ecological environments is perhaps one of the most significant barriers in AM, reflected by the fact that contrasting models to forecast resource changes through time were identified in only 14% of studies.

One of the elements of AM recommended by Williams (2011b) was a reasonable range of management actions, which we quantified as being more than two management options. Most of the studies we evaluated implemented at least two management options. However, we argue that a single management option, such as a removal target, could be implemented and monitored, allowing removal quotas to be updated each year while still achieving the desired learning. Otherwise, a range of management interventions could be replicated temporally rather than spatially, while controlling for other variables, such as habitat and weather.

Our results show that the importance of monitoring is well understood, and monitoring is frequently conducted. For INNS specifically, one of the significant challenges of the monitoring design is achieving high certainty of true negatives when the probability of detection is low. If eradication or the prevention of invasion is an aim, the use of occupancy modelling, which has been used in AM for threatened species (Bower et al. 2014), Bayesian modelling techniques (C Jones 2019, *personal communication*, 10 September), and spatially-explicit models (e.g. Bertolino et al. 2020) may aid in devising monitoring designs to achieve eradication and detect if re-invasion occurs. Where resources are limited, long-term monitoring methods for AM may be implemented cost-effectively by collating data that are collected by practitioners or volunteers. A successful example of the latter is the control of American mink in Scotland using a passive AM approach, where a skilled workforce of 186 volunteers carried out monitoring activities (Bryce et al. 2011). Through effective communication and co-ordination by paid staff, many volunteers contributed to the success of the project which may be the precursor to the eradication of American mink from the Great Britain (Martin & Lea 2020). Long-term monitoring programmes are becoming more common, in part through the growth of citizen science, which offers affordable methods to collect data (Tulloch et al. 2013). The success of the American mink eradication campaign was, however, mainly due to the self-interests of volunteers (e.g. anglers protecting their fish source), which may not always be present for other INNS projects. Public perception of managing INNS may limit the uptake of volunteers, and their motivation, continuity, and training are potential drawbacks in the use of a volunteer workforce for INNS management.

Engagement with stakeholders is a recommended aspect of AM, and while we agree with this recommendation, we also acknowledge that engagement is study dependent and not necessarily an essential element of AM. Hence, we excluded engagement from our reduced list of AM elements for analysis. Engaging with stakeholders and including diverse perspectives is likely to result in unbiased objectives and avoid inappropriate or unnecessary constraints on management (Beierle 2002, Williams 2011b). However, if, at the outset, AM is not designed into a project, then engagement with all appropriate stakeholders is unlikely to be achieved. Working with and achieving consensus among stakeholders with diverse aims is challenging, but is required if common objectives are to be reached. Achieving collaboration requires careful management, as achieved by Bryce et al. (2011) and Johnson et al. (2002). Among the studies reviewed here, 45% did not achieve engagement with stakeholders, which may be one of the reasons why they were not more successful. It may be that stakeholders were engaged but not reported in articles; however, if this is the case, it demonstrates the lack of importance afforded by authors to this stage of the AM process. Late engagement with stakeholders can lead to increased conflict when applied to the management of mammals, particularly the removal of INNS (Crowley et al. 2017). An example of this is the attempted control of grey squirrels in Italy, which was delayed due to the actions of animal rights activists which eventually resulted in the abandonment of the study (Bertolino & Genovesi 2003). When they are engaged, positive interactions among stakeholders even with conflicting interests is often achieved (Irwin & Kennedy 2008).

We found that most AM studies of vertebrates used passive AM, in which the objective is to learn about managing the ecological resource, rather than active AM, in which the objective is to understand the underlying biological processes (Larson et al. 2013). In passive AM, resource objectives are often specified and are what practitioners are concerned with, such as the eradication of rats from islands in Australasia (Towns & Broome 2003). However, in the long run, INNS management may be more successful if the underlying biological processes are known (C Jones 2019 *personal communication* 10 September), which is only achieved through active AM. In some cases, however, a passive approach may perform similarly well to an active approach (Johnson et al. 2002).

CONCLUSION

To increase the success and the use of AM for INNS management, current and future studies on the use of AM for INNS management need to be published, whether or not they are successful in achieving their objectives. For an INNS campaign to be successful, we recommend that practitioners define a clear AM framework at the outset, so that modifying management, forecasting, and reducing uncertainty in response to monitoring data will not be afterthoughts, but will instead be structured into the study. As stated above, AM is a cyclical process of continuing to reduce uncertainty and improve the forecasting of the effects of management, which is adjusted in light of new knowledge gained by monitoring populations to achieve the study objectives, rather than a single assessment of the effects of management on a population or a trial-and-error process (which AM is often confused with). By being clear about what AM is and the advantages that AM offers, in particular for INNS management, which include learning about underlying processes in active AM to achieve optimal management, AM can be successfully applied to the prevention, rapid response, ongoing control, and eradication of INNS. Ultimately, the use of AM for INNS management will improve the success rate of INNS management campaigns, and hence reduce the impact of INNS on native species.

REFERENCES

Armstrong DP, Castro I, Griffiths R (2007) Using adaptive management to determine requirements of re-introduced populations: the case of the New Zealand hihi. *Journal of Applied Ecology* 44: 953–962.

Bainbridge I (2017) Goose management in Scotland: an overview. *Ambio* 46: 224–230.

Barnosky AD, Matzke N, Tomiya S, Wogan GOU, Swartz B, Quental TB et al. (2011) Has the earth's sixth mass extinction already arrived? *Nature* 471: 51–57.

Beierle TC (2002) The quality of stakeholder-based decisions. *Risk Analysis* 22: 739-749.

Bertolino S, Genovesi P (2003) Spread and attempted eradication of the grey squirrel (*Sciurus carolinensis*) in Italy, and consequences for the red squirrel (*Sciurus vulgaris*) in Eurasia. *Biological Conservation* 109: 351–358.

Bertolino S, Sciandra C, Bosso L, Russo D, Lurz P, Di Febbraro M (2020) Spatially-explicit models as tools for implementing effective management strategies for invasive alien mammals. *Mammal Review*: 50, in press.

Beverton RJH, Holt S (1957) On the dynamics of exploited fish populations. *Fisheries Investigations* 19: 1–533.

Blackburn TM, Bellard C, Cassey P (2019) Alien species as a driver of recent extinctions. *Frontiers in Ecology and the Environment* 12: 1–5.

Booy O, Mill AC, Roy HE, Hiley A, Moore N, Robertson P et al. (2017) Risk management to prioritise the eradication of new and emerging invasive non-native species. *Biological Invasions* 19: 2401–2417.

Bower DS, Pickett EJ, Stockwell MP, Pollard CJ, Garnham JI, Sanders MR, Clulow J, Mahony MJ (2014) Evaluating monitoring methods to guide adaptive management of a threatened amphibian (*Litoria aurea*). *Ecology and Evolution* 4: 1361–1368.

Boyer DC, Kirchner CH, McAllister MK, Staby A, Staalesen BI (2001) The orange roughy fishery of Namibia: lessons to be learned about managing a developing fishery. *South African Journal of Marine Science* 23: 205–221.

Bryce R, Oliver MK, Davies L, Gray H, Urquhart J, Lambin X (2011) Turning back the tide of American mink invasion at an unprecedented scale through community participation and adaptive management. *Biological Conservation* 144: 575–583.

Collinge K, Forman T (2009) *Ecology of Fragmented Landscapes*. John Hopkins University Press, Baltimore, Maryland, USA.

Cowan DP, van derWaal Z, Pidcock S, Gomm M, Stephens N, Brash M, White PCL, Mair L, Mill AC (2020) Adaptive management of an iconic invasvice goat *Cpara hircus* population. *Mammal Review*: 50, in press.

Crowley SL, Hinchliffe S, McDonald RA (2017) Invasive species management will benefit from social impact assessment. *Journal of Applied Ecology* 54: 351–357.

Cruz F, Carrion V, Campbell KJ, Lavoie C, Donlan CJ (2009) Bio-economics of large-scale eradication of feral goats from Santiago Island, Galápagos. *Journal of Wildlife Management* 73: 191–200.

Foxcroft LC, Mcgeoch M (2011) Implementing invasive species management in an adaptive management framework. *Koedoe* 53: 1–11.

Franklin TM, Helinski R, Manale A (2007) Using adaptive management to meet conservation goals. *The Wildlife Society Technical Review* 07–1: 103–113.

Gregory R, Ohlson D, Arvai J (2006) Deconsturcting adaptive management: criteria for applications to environmental management. *Ecological Applications* 16: 2411–2425.

Holling CS (1978) *Adaptive Environmental Assessment and Management*. John Wiley & Sons, Oxford, UK.

Hughes TP, Gunderson LH, Folke C, Baird AH, Bellwood D, Berkes F et al. (2007) Adaptive management of the Great Barrier Reef and the Grand Canyon World Heritage Areas.

AMBIO: A Journal of the Human Environment 36: 586–592.

Irwin ER, Kennedy KDM (2008) Engaging stakeholders for adaptive management using structured decision analysis. *The Third Interagency Conference on Research in the Watersheds*, 8–11.

Jackson G, Moran M (2012) Recovery of inner Shark Bay snapper (*Pagrus auratus*) stocks: relevant research and adaptive recreational fisheries management in a World Heritage Property. *Marine and Freshwater Research* 63: 1180–1190.

Johnson FA, Kendall WL, Dubovsky JA (2002) Conditions and limitations on learning in the adaptive management of mallard harvests. *Wildlife Society Bulletin* 30: 176–185.

Jones ML, Brenden TO, Irwin BJ, Ramcharan C (2015) Re-examination of sea lamprey control policies for the St. Marys River: completion of an adaptive management cycle. *Canadian Journal of Fisheries and Aquatic Sciences* 72: 1538–1551.

Ketz AC, Johnson TL, Monello RJ, Hobbs NT (2016) Informing management with monitoring data : the value of Bayesian forecasting. *Ecos* 7: 1–15.

Larson AJ, Belote RT, Williamson MA, Aplet GH (2013) Making monitoring count: project design for active adaptive management. *Journal of Forestry* 111: 348–356.

Lee KN (1999) Appraising adaptive management. *Ecology and Society* 3: 1–18.

Martin AR, Lea VJ (2020) A mink-free GB: perspectives on eradiating American mink *Neovison vison* from Great Britain and its islands. *Mammal Review:* 50, in press.

MacDonald IAW, Kruger FJ, Ferrar AA (1986) Ecology and management of biological invasions in southern Africa. In: *National synthesis symposium on the ecology of biological invasions*. Oxford University Press, Stellenbosch, South Africa.

Madsen J, Williams JH, Johnson FA, Tombre IM, Dereliev S, Kuijken E (2017) Implementation of the first adaptive management plan for a European migratory waterbird population: the case of the Svalbard pink-footed goose *Anser brachyrhynchus*. *Ambio* 46:

275–289.

McCarthy MA, Possingham HP (2007) Active adaptive management for conservation. *Conservation Biology* 21: 956–963.

McGowan CP, Smith DR, Nichols JD, Lyons JE, Sweka J, Kalasz K et al. (2015) Implementation of a framework for multi-species, multi-objective adaptive management in Delaware Bay. *Biological Conservation* 191: 759–769.

McKenzie R, Shaw JM (2017) Reconciling competing values placed upon goose populations: The evolution of and experiences from the Islay Sustainable Goose Management Strategy. *Ambio* 46: 198–209.

Mehta SV, Haight RG, Homans FR, Polasky S, Venette RC (2007) Optimal detection and control strategies for invasive species management. *Ecological Economics* 61: 237–245.

Mill A, Crowley S, Lambin X, McKinney C, Maggs G, Robinson N, Ward A, Marzano M (2020) The challenges of long-term invasive mammal management: lessons from the UK. *Mammal Review:* 50, in press.

Mumford J, Booy O, Baker R, Rees M, Copp GH, Black K et al. (2010) Invasive non-native species risk assessment in Great Britain. *Aspects of Applied Biology* 104: 49–54.

National Research Council (2004) *Adaptive Management for Water Resources Planning.* National Academies Press, Washington DC, USA.

Nichols JD, Runge MC, Johnson FA, Williams BK (2007) Adaptive harvest management of North American waterfowl populations: a brief history and future prospects. *Journal of Ornithology* 148: 343–349.

Nuñez MA, Barlow J, Cadotte M, Lucas K, Newton E, Pettorelli N, Stephens PA (2019) Assessing the uneven global distribution of readership, submissions and publications in applied ecology: obvious problems without obvious solutions. *Journal of Applied Ecology* 56: 4–9.

Rist L, Campbell BM, Frost P (2013) Adaptive management: where are we now? *Environmental Conservation* 40: 5–18.

Rout TM, Hauser CE, Possingham HP (2009) Optimal adaptive management for the translocation of a threatened species. *Ecological Applications* 19: 515–526.

Sarukhan J, Whyte A, Hassan R, Scholes R, Ash N, Carpenter S, Pingali P, Bennett E, Zurek M, Chopra K (2005) *Millenium Ecosystem Assessment: Ecosystems and Human Well-being. A Report of the Millenium Ecosystem Assessment*. Island Press, Washington DC, USA.

Schreiber ESG, Bearlin AR, Nicol SJ, Todd CR (2004) Adaptive management: a synthesis of current understanding and effective application. *Ecological Management and Restoration* 5: 177–182.

Simberloff D (2010) Invasive species. In: Sodhi S, Ehrlich NR (eds) *Conservation Biology for All*, 131–152. Oxford University Press, Oxford, UK.

Smith GC, Henderson IS, Robertson PA (2005) A model of ruddy duck *Oxyura jamaicensis* eradication for the UK. *Journal of Applied Ecology* 42: 546–555.

Speziale K, Lambertucci S, Carrete M (2012) Dealing with non-native species: what makes the difference in South America? *Biological Invasions*: 14:1609-1621.

Thomas CD, Cameron A, Green RE, Bakkenes M, Beaumont LJ, Collingham YC, Erasmus BFN (2004) Extinction risk from climate change. *Nature* 427: 145-148.

Towns DR, Broome KG (2003) From small Maria to massive Campbell: forty years of rat eradications from New Zealand islands. *New Zealand Journal of Zoology* 30: 377–398.

Tulloch AIT, Possingham HP, Joseph LN, Szabo J, Martin TG (2013) Realising the full potential of citizen science monitoring programs. *Biological Conservation* 165: 128–138.

Varley N, Boyce MS (2006) Adaptive management for reintroductions: updating a wolf recovery model for Yellowstone National Park. *Ecological Modelling* 193: 315–339.

Vitousek PM, Antonio CM, Loope LL, Rejmanek M, Westbrooks R (1997) Introduced species: a significant component of human-caused global change. *New Zealand Journal of Ecology* 21: 1–16.

Walters CJ, Hilborn R (1978) Ecological optimization and adaptive management. *Annual Review of Ecology and Systematics* 9: 157–188.

Walters CJ, Holling CS (1990) Large-scale management experiments and learning by doing. *Ecology* 71: 2060–2068.

Walters C (1997) Challenges in adaptive management of riparian and coastal ecosystems. *Conservation Ecology* 1: 1.

Ward A, Richardson S, Macarthur R, Aileen M (2020) Using and communicating uncertainty for the effective control of invasive non-native species. *Mammal Review*: 50, in press.

Whitehead AL, Edge KA, Smart AF, Hill GS, Willans MJ (2008) Large scale predator control improves the productivity of a rare New Zealand riverine duck. *Biological Conservation* 141, 2784–2794.

Williams BK (2011a) Passive and active adaptive management: approaches and an example. *Journal of Environmental Management* 92: 1371–1378.

Williams BK (2011b) Adaptive management of natural resources-framework and issues. *Journal of Environmental Management* 92: 1346–1353.

Wright GJ, Peterson RO, Smith DW, Lemke TO (2006) Selection of northern Yellowstone elk by gray wolves and hunters. *Journal of Wildlife Management* 70: 1070–1078.

Figure legends

Fig. 1. The number of studies on the adaptive management of wildlife published in each year between 1970 and 2107, showing studies not including invasive non-native species (INNS, black bars) and studies of INNS (white bars; total n = 56). The numbers above the bars are the numbers of studies which implemented the reduced number of elements we defined as necessary for AM (n = 12); the numbers in brackets are the numbers of studies which implemented all seven AM elements, (if different from the redefined elements), described by Williams (n = 10; 2011b).

Fig. 2. The number of studies in each country in which adaptive management for wildlife was conducted, published between 1970 and 2017 (total n = 56).

Fig. 3. The number of studies on the adaptive management of several wildlife taxa, published between 1970 and 2017, showing studies not including invasive non-native species (INNS, black bars, n = 52) and studies of INNS (white bars, n = 4). The numbers above the bars are the numbers of studies which implemented the reduced number of elements we defined as necessary for AM (n = 12); the numbers in brackets are the numbers of studies which implemented all seven AM elements, (if different from the redefined elements), described by Williams (n = 10; 2011b).

Fig. 4. The reason for conducting adaptive management (AM) for wildlife for studies conducted between 1970 and 2017 for all studies not meeting all the AM criteria (black bars) and for those that met all the AM criteria (white bars) (n = 56), INNS = invasive non-native species.

Tables

Table 1. Summary of whether articles identified as adaptive management (AM) articles for vertebrates (n = 56) implemented all the elements of AM described by Williams (2011b), for all studies (n = 52) and for invasive non-native species management (INNS; n = 4). *Implementing our reduced elements of AM (excluding 1 and 4).

AM recommended elements	All studies (%)	INNS management (%)
(1) Engagement with stakeholders	54	75
(2) Identification of objectives	90	100
(3) Forecasting and estimating uncertainty	44	0
(4) More than two management options	63	75
(5) Regular monitoring	94	100
(6) Management practice adjusted in response to monitoring	48	50
(7) Monitoring data feedback to improve forecasting and reduce uncertainty	25	0
All the above AM criteria implemented	23 (19*)	0

Table 2. The 12 studies of adaptive management (AM) of wildlife in which at least five elements of AM were included. Ten studies implemented all seven elements of adaptive management (AM) as recommended by Williams (2011b): (1) engagement with stakeholders, (2) identification of objectives, (3) forecasting and estimating uncertainty, (4) implementation of more than two management options, (5) implementation of a regular monitoring programme, (6) management practices adjusted in response to the results of monitoring and (7) monitoring data feedback to improve forecasting ability and reduce uncertainty. Two studies (indicated with *) implemented our reduced number of five elements of AM, excluding (1) and (4).

Type of AM	Reason for AM	Country	Taxa	Species	References
Active	Harvesting	USA	Avian	North American mallard *Anas platyrhynchos*	Johnson et al. 2002
Passive	Multiple	Norway & Denmark	Avian	Pink-footed goose *Anser brachyrhynchus*	Madsen et al. 2017
Passive	Agricultural damage	Scotland	Avian	Greenland white-fronted geese *Anser albifrons flavirostri*, barnacle *Branta leucopsis*, greylag goose *Anser anser*	McKenzie & Shaw 2017
Passive	Reintroduction	New Zealand	Avian	Hihi *Notiomystis cincta*	Armstrong et al. 2007
Passive	Harvesting	Scotland	Avian	Greylag goose *Anser anser*	Bainbridge 2017
Active	Invasive species	USA	Fish	Sea lamprey *Petromyzon marinus*	Jones et al. 2015
Passive	Harvesting	Namibia	Fish	Orange roughy *Hoplostethus atlanticus*	Boyer et al. 2001
Passive	Harvesting	Australia	Fish	Snapper *Pagrus auratus*	Jackson & Moran 2012
Active*	Reintroduction	USA	Mammal	Grey wolf *Canis lupus*	Varley & Boyce 2006
Passive	Harvesting	USA	Mammal	Elk *Cervus canadensis*	Wright et al. 2006
Passive*	Harvesting	USA	Mammal	Elk *Cervus canadensis*	Ketz et al. 2016
Passive	Harvesting	USA	Multiple	Shorebirds *Calidrius canutus rufa*, horseshoe crab *Limulus polyphemus*	McGowan et al. 2015