2011

Confronting socially generated uncertainty in adaptive management

Andrew J. Tyre
University of Nebraska at Lincoln, atyre2@unl.edu

Sarah Michaels
University of Nebraska-Lincoln, michaels2@unl.edu

Published in *Journal of Environmental Management* 92 (2011), pp. 1365–1370; doi: 10.1016/j.jenvman.2010.10.014

Submitted September 16, 2010; accepted October 4, 2010; published online October 20, 2010.

Confronting socially generated uncertainty in adaptive management

Andrew J. Tyre
School of Natural Resources, University of Nebraska–Lincoln

Sarah Michaels
Department of Political Science and Public Policy Center, University of Nebraska–Lincoln

Corresponding author — A. J. Tyre, email atyre2@unl.edu

Abstract
As more and more organizations with responsibility for natural resource management adopt adaptive management as the rubric in which they wish to operate, it becomes increasingly important to consider the sources of uncertainty inherent in their endeavors. Without recognizing that uncertainty originates both in the natural world and in human undertakings, efforts to manage adaptively at the least will prove frustrating and at the worst will prove damaging to the very natural resources that are the management targets. There will be more surprises and those surprises potentially may prove at the very least unwanted and at the worst devastating. We illustrate how acknowledging uncertainty associated with the natural world is necessary but not sufficient to avoid surprise using case studies of efforts to manage three wildlife species: Hector's dolphins, American alligators and pallid sturgeon. Three characteristics of indeterminism are salient to all of them; non-stationarity, irreducibility, and an inability to define objective probabilities. As an antidote, we recommend employing a holistic treatment of indeterminism, that includes recognizing that uncertainty originates in ecological systems and in how people perceive, interact and decide about the natural world of which they are integral players.

Keywords: adaptive management, uncertainty, diversity of opinion, probability and risk, indeterminism

1. Introduction

In approaching the management of socio-ecological systems, Holling (1973) distinguished between decisions made under "scientific certainty" and decisions where the science on which they were based was not clear. In this context, scientific *un*certainty arises when more than one model of reality is plausible and scientists need more information to differentiate between the utility of the different models employed. Holling's distinction between decisions made under conditions of scientific certainty and those made where the scientific basis was less certain led to our current era of trying to manage adaptively - to use the results of management actions to improve scientific knowledge and subsequent decisions. Adaptive management of socio-ecological systems (SES) refers to the feedback process in which decision makers regard policies as scientific experiments that generate information improving the pursuit of long-term goals (Sarewitz, 2000). The use of adaptive management is encouraged by advocates when the following conditions exist: urgent, high stakes decisions that must be made, disputes about the relevant values, and a lack of scientific certainty about the consequences of those decisions (Gregory et al., 2006). These conditions are commensurate with those described as requiring "post-normal science" (Funtowicz and Ravetz, 1991).

Adaptive management of socio-ecological systems focuses on iterative decision making under uncertainty (Parma and the NCEAS Working Group on Population Management, 1998) because uncertainty "is fundamental and persistent" in policies pertaining to biodiversity and natural resources (Dickson and Adams, 2009 110). Iterated decisions provide opportunities to learn, but also for constituencies to enter and exit the management process, and for those engaged to alter the value sets with which they entered into the process. In other words, iteration is a fundamental characteristic of a process intended to develop the capacity of the social system to adapt.

Much of the attention in advancing adaptive management is focused on testing hypotheses about system function by improving the quality of evidence derived from the natural world; that is, on reducing uncertainty. Still, not all ecological uncertainty can be reduced, let alone eliminated. It is also important not to discount the dynamics generated by the interplay of human values and knowledge leading to interventions in the natural world. These dynamics are also a source of irreducible uncertainty because although "… evidence indicates that human choices are orderly," they are "not always rational in the traditional sense of the word" (Kahneman and Tverskey, 2000 65). If human choices are not necessarily rational, then we cannot say with certainty at the outset what the outcome will be of negotiations among constituencies responsible for a decision, especially among those who do not have a tradition of jointly generating management recommendations. Lee (1993) referred to this source of uncertainty as "management turbulence"; this is an attractive image because although the onset of turbulence in a fluid is relatively predictable, the actual outcomes are not.

A helpful initial step in developing a nuanced understanding of uncertainty stemming from human induced considerations is to place uncertainty in the context of indeterminism and to distinguish uncertainty from risk. Consequently, we review an influential, historic distinction between risk and uncertainty and introduce three characteristics of indeterminism that are problematic for SES management. After that, we present three case studies illustrating the necessity of appropriately understanding the nature of the uncertainty involved and its implications. In the penultimate section, we discuss the three characteristics of uncertainty in the context of our case studies to illustrate how the prospect of addressing ecological uncertainty does not lay the basis for addressing socially induced uncertainty.

2. Indeterminism, uncertainty and risk

We use "indeterminism" to refer to all forms of not knowing and argue that it is important to recognize that uncertainty is a *subset* of indeterminism. One approach to understanding indeterminism and uncertainty specifically has been to classify the sources. For example, Regan et al. (2002) distinguished between aleatory and epistemic indeterminism. Aleatory indeterminism refers to states of reality e what is out there, whether we try to describe it or not. Consequently it is irreducible; no amount of observation and investigation will diminish it. Epistemic indeterminism arises from the limitations of our ability to describe reality such as linguistic indeterminism, estimation errors and Holling's (1973) "scientific uncertainty". Linguistic indeterminism stems from the shortcomings of using language to describe reality, such as ambiguity and under specification. Estimation errors arise when using statistical tools to estimate probability distributions. Holling's (1973) "scientific uncertainty" occurs when there is more than one plausible model of reality and we do not know which is correct. Epistemic indeterminism in socio-ecological systems is potentially reducible through ongoing efforts to improve our understanding of the dynamics of socio-ecological systems. Recognizing and communicating epistemic indeterminism appropriately in environmental management is vital to avoid generating oversimplistic results that do not reflect the plurality of possibilities.

The distinction between aleatory and epistemic indeterminism can be understood through a familiar example: the variation in the annual amount of rainfall in a river basin. Although it might be possible to predict the average rainfall for a basin based on past observations, the precise amount that will fall in a particular year is unknown. Some of that indeterminism is epistemic e if we constructed models of the atmosphere with greater spatial and temporal resolution and took many more measurements than we do, we could make better predictions of annual rainfall. The complex nature of a SES, however, is such that there will always be a growing mismatch between observation and prediction e the famous "butterfly effect" (Hilborn, 2004). Even if it were possible to measure instantly the location of every particle in the atmosphere, Heisenberg's uncertainty principle dictates that we could not then know the velocity of those particles. Thus, we can never specify the initial conditions of the atmosphere exactly, and even the most sophisticated simulation of every particle in the atmosphere will diverge from observation to a greater and greater extent with time. This remaining indeterminism is aleatory and is a fundamental part of the SES. Undoubtedly, the boundary between epistemic and aleatory indeterminism is a fuzzy one, even if the extremes are unambiguous.

Stationarity is the notion that "systems fluctuate within an unchanging envelope of variability" (Milly et al., 2008 573). It has been a guiding assumption in science, engineering and management of natural systems. It refers specifically to aleatory indeterminism. Only recently in light of changes experienced and anticipated for global climate change has this assumption been challenged and the search for how to understand and manage non-stationary socioecological systems invigorated. For ecological processes it may be possible to develop models of the underlying changes, and thus develop objective probabilities of particular events; this is the goal of the large-scale climate modeling efforts (Chandler et al., 2010).

Objective probabilities (also known as frequentist probabilities) include those derived from observations of events (Clark, 2007), estimated from data, or *a priori* probabilities such as those arising from a roll of dice. As did Knight (1921), Burgman et al. (1993) defined risk as the objective probability of the occurrence of an undesirable outcome. Knight (1921) reserved the term "uncertainty" for when objective probabilities cannot be assigned to potential outcomes. Some environmental researchers recognize this distinction but it is not widespread (Burgman, 2005). For example, Ludwig et al. (2001) divided uncertainty into probabilistic quantities associated with statistical estimates, and non-probabilistic "radical uncertainty" associated with natural catastrophic events and "unforeseen consequences of human interventions."

In contrast to objective probabilities, we can derive subjective probabilities from one or more individuals beliefs about reality (Clark, 2007). Unlike objective probability, which Knight used to distinguish between risk and uncertainty, subjective probability falls into the category of uncertainty as defined by Knight.

Since different people may well have different beliefs about reality, each person may assign a subjective probability to an event that differs from someone else. As a result, methods to combine belief distributions from multiple people into single distributions have been developed (e.g. Rothlisberger et al., 2010). In addition, Bayesian statistics can be used to combine belief distributions with new, objective information (Wade 2000). An area of active research with profound implications for management is developing means to represent uncertainty without using subjective probabilities (Burgman, 2005).

Irreducibility and non-stationarity are aspects of aleatory indeterminism and are functions of the inherent characteristics of the socio-ecological system. In contrast, the determination of whether objective probabilities exist or don't exist falls into the realm of epistemic indeterminism. It is a function of what we know or think we know about the SES. Consequently, while irreducibility and non-stationarity are "permanent" attributes of aleatory indeterminism, through our efforts to more fully understand SES, our ability to develop objective probabilities may improve and how we quantify epistemic indeterminism may change.

3. Case studies

The following three case studies illustrate how the three characteristics of indeterminism noted above combine in different fashions to produce challenges all too familiar to those who manage socio-ecological systems. We then go on to discuss the implications of the three characteristics of indeterminism in light of the case studies.

3.1. Population decline of Hector's dolphins—Mistreating uncertainty as risk

Our first example of uncertainty comes from Slooten et al.'s (2001) calculation of the effect of gillnet mortality on the population decline of Hector's dolphins. Hector's dolphin (*Cephalorhynchus hectori*) is endemic to New Zealand's coastal waters. Excellent data was available from mark-recapture studies to estimate adult survival rate. Therefore, it was possible to calculate a probability distribution for the quantity "Adult survival probability." In contrast, no data was available for direct estimation of first year survival, so the authors used a uniform probability distribution with bounds derived from the ratio of juvenile to adult survival in studies of two other whale species. This perfectly reasonable and well-accepted procedure generates an extremely precise estimate of juvenile survival with a coefficient of variation of 5% despite the complete absence of data. While precise, we do not know how accurate the estimate is.

Equally if not more problematic is the social conflict over assigning different subjective probabilities. On one hand, the possibility that the subjective probability distribution utilized in decision making is overly pessimistic, places an undue burden on the fishing industry to reduce fishing effort to avoid gillnet mortality. On the other hand, the possibility that the subjective probability distribution utilized is overly optimistic, may lead to a dramatic population decline of Hector's dolphins. Differences of opinion between industry and conservation groups about the relative contribution of gillnet induced mortality compared with other sources of mortality further exacerbate this uncertainty (Conroy et al., 2008).

3.2. American alligator population fluctuation in Florida

The American alligator (*Alligator mississippiensis*) is an apex predator endemic to wetlands in the Southern United States. The first shift in managing American alligators in Florida occurred when the Florida Game and Freshwater Fish Commission closed all harvests in 1962 in response to perceived population declines during the 1950's. In 1967, the American alligator became one of the first species listed as endangered by the US Fish and Wildlife Service. A decade later, alligators appeared to be more dangerous and/or much more abundant than they had been previously, triggering a second shift in management objectives. As a result, in the late 1970s the Florida Game and Freshwater Fish Commission (GFC) requested that the United States Fish and Wildlife Service (USFWS) change the status of the Florida population of alligator from endangered to threatened, to enable greater management flexibility. The USFWS granted this request in 1977, and the GFC immediately initiated an experimental harvest of nuisance alligators (Woodward et al., 1987). Over the next two decades, GFC expanded experimental commercial and recreational harvests statewide. Until 2004, however, the overall objectives for the state harvest remained the same: avoid the risk of declining populations by reducing the nominal quota whenever monitoring indicated that populations were declining. In 2004, continued increases in the number of complaints regarding nuisance alligators led the GFC to develop the most recent objective of keeping populations in a band no more than 25% above or below levels observed in the late 1980s.

Over the last century, in Florida, there have been three discernable and conflicting attitudes among the general public towards alligators: the desire to hunt alligators, the desire to preserve alligators in perpetuity, and fear of alligators. Different combinations of these attitudes have resulted in different objectives for alligator management at different times. Public demand for objectives that match the current dominant attitudes led the Florida Fish and Wildlife Conservation Commission reluctantly to alter its management practices. In the most recent period, for example, the fear of alligators determines the desired upper limit of the population size for the species, while the desire to preserve alligators dictates the lower limit.

Why did it take more than 30 years to recognize the potential for alligator populations to increase and incorporate that knowledge into the harvest objective? One explanation is the difference in attitude between the "general public" and professional resource managers about alligators. Rises in complaints by the public about nuisance alligators prompted each of the shifts in managing an increasing population of alligators. Yet biologists and managers regarded population increases skeptically, since they were more averse than the public to the possibility of population decline and its implications than to an increase and its implications. In no small part this is a function of socialization in managing renewable resources in the late twentieth and early twenty first century where the preoccupation is with avoiding population extinction (Powell et al., 2010). Scientists and managers made decisions about harvest regulations primarily by examining past trends without considering the full range of possible futures that could arise. The scientists and managers fell afoul of the anchoring problem in decision-making. Anchoring arises when historical precedent is weighted more heavily than is warranted by changing circumstances (Hammond et al., 1998).

3.3. Attempting pallid sturgeon recovery in the Missouri River

Pallid sturgeon (*Scaphirhyncus albus*) are large, long-lived top carnivores endemic to the Missouri River and Lower Mississippi River. The US Fish and Wildlife Service (USFWS) listed pallid sturgeon as endangered in 1993 based on a perceived reduction in distribution, incidental take in commercial fisheries for the more abundant shovelnose sturgeon, and loss of habitat caused by the alteration of the natural hydrograph by the Missouri Mainstem Reservoir System (USFWS, 1993). In 2000, the United States Fish and Wildlife Service (USFWS) found that water control operations along sections of the Missouri River by the US Army Corps of Engineers (Corps) jeopardized the recovery of the pallid sturgeon and other endangered species. Consequently, USFWS required the Corps to increase spring flows by 2003 (USFWS, 2000). The need for a more natural hydrological regime along the Missouri River was later confirmed by a National Academy of Sciences review panel (National Research Council, 2002). Although there was substantial scientific consensus that the modified hydrograph was an issue for the persistence of pallid sturgeon, there remained epistemic uncertainty about exactly what features of the natural hydrograph were necessary (Jacobson and Galat, 2008). In 2003, the Corps and USFWS developed an amended biological opinion (USFWS, 2003) based on new analyses conducted by the Corps. The amended biological opinion required, among many other management activities, habitat restoration projects, an intensive and comprehensive monitoring and evaluation program, and the formation of a stakeholder group.

The 2007 Water Resources Development Act created The Missouri River Recovery Implementation Committee (MRRIC) to recommend recovery actions. MRRIC brings together more than seventy representatives of federal agencies, tribes, states, local governments and nongovernmental entities in the Missouri River basin and requires them to act consensually. While the charter of MRRIC states that the committee will make recommendations on "[c]hanges to the implementation strategy as a result of adaptive management" (USACE, 2008 section 1, A, ii, 1, 1), it is unclear how these recommendations will be incorporated into management actions on the river. There are differing expectations of the extent to which these recommendations will affect day-to-day management of this large, complex, infrastructure defined river system. This compounds the reality that members of MRRIC do not necessarily share a common underlying goal in addition to disagreeing about the best way to achieve any one goal. Without this clarity, one challenge will be for the more than seventy representatives to develop a shared articulation of the committee's mission. This ambiguity of mission sets the stage for socially induced uncertainty. This uncertainty is problematic for committee members in generating recommendations and for Missouri River managers accountable for day to day operations. The management of the Missouri River focuses on meeting the set requirements of the 1944 Flood Control Act (FCA); in the past, these requirements were widely regarded as unchangeable. Now the Missouri River Authorized Purposes Study (Omnibus Appropriations Act, 2009; Title 1, Section 108), potentially could lead to redefining the 1944 FCA requirements.

4. Discussion of case studies

While collecting and analyzing data may decrease the indeterminism surrounding the population dynamics of Hector's dolphins, American alligators or pallid sturgeons, it will not for the deliberations about how to manage them. These case studies illustrate how three characteristics of indeterminism are problematic for management of SES: non-stationarity, irreducibility, and an inability to define objective probabilities.

5. Non-stationarity

While it may be possible to elicit a single belief distribution that all stakeholders agree upon, it is by no means guaranteed. In the absence of objective probabilities for juvenile survival of Hector's Dolphins, the problem becomes a non-stationary one because any stakeholder group can provide a different, subjective probability for the connections in the model at any time. Failing to recognize this source of non-stationarity in the social component of the SES could lead to surprises, such as having management recommendations politically overruled (e.g. Conroy et al., 2008).

Another source of non-stationarity in the social components of these case studies arises through the potential for shifting objectives in the management regimes. These can be a function of changed societal values, which have ramifications both for what is investigated about the natural world and the extent to which those in management positions find themselves surprised by what they have not anticipated. In the case of Hector's dolphins, there is no discussion of the potential for shifting objectives. Rather the basis for management is that entrenched interests are pursuing constant objectives. For example, the commercial gillnetters are committed to ensuring the viability of their economic activity necessitated by the considerable investment they have in fishing gear. That managers established a new objective after perceived undesirable fluctuations in the population size of American Alligators is indicative of the failure to anticipate non-stationarity. On the Missouri River, the Omnibus study introduces the possibility of changing objectives, a heretofore-inconceivable notion.

There is no guarantee that the future behavior of the SES will be like the past. Ignoring the non-stationarity induced by social processes increases the possibility of surprise. Under those circumstances, the use of an adaptive management rubric provides a way forward if it spurs the development of capacity to revise management objectives and to undertake a suitably wide range of appropriate actions.

6. Irreducibility

While scientists are optimistic that with enough effort epistemic uncertainty about the ecological environment may be reduced, such optimism may well be misplaced when it comes to socially generated uncertainties. No amount of study of the social dynamics of any natural resources management regime will eliminate this indeterminism. In particular, it would be a mistake to confuse the existence of techniques for reducing differences in subjective values with the acceptance of their results. There is no guarantee that participants in a decision making process will agree to be bound by the results of the analysis, even if they initiated and/or participated in the process. This may be because people's beliefs change over the deliberations or they do not consent to having their values aggregated as part of the process.

7. Objective probabilities

The degree to which objective probabilities can quantify ecological indeterminism as risk varies among the three case studies. Fisheries managers in New Zealand have no data on the survival rates of yearling Hector's dolphins. Consequently, they developed a subjective probability distribution. It is inappropriate, however, for fisheries managers to use this distribution as an estimate of risk. Using this distribution as an estimate of risk leads to a potentially damaging assumption about the amount of gillnet mortality that Hector's dolphins can tolerate without the population declining.

In contrast, alligator managers in Florida have a large database of knowledge of the biology and life history of the species to inform management. Thus, they are able to develop objective probabilities for most, if not all, ecological quantities relevant to management. Pallid sturgeon are an intermediate case; although little was known at the time the Biological Opinion was written, since then researchers have developed a great deal of objective information.

All three case studies have socially generated indeterminism that cannot be represented with objective probabilities. In the cases of the dolphins and sturgeon there are direct negotiations between stakeholders with differing values driving the management outcomes. In the alligator case, there is no formal process for incorporating the general public's attitudes towards alligators, and managers are reluctant to shift population size objectives. Nonetheless, when public concern increases to a point where it cannot be ignored, managers then revise population size objectives. Regardless of the means through which management decisions incorporate public views, we believe any attempt to use subjective probability to weight possible social outcomes would be unlikely to reflect public sentiment completely.

An additional issue arises when there is a need to make an explicit tradeoff between competing demands, such as between conservation of endangered species and commercial fishing or navigation. Managers are often reluctant to make such tradeoffs overt, and may attribute their reluctance to the lack of objective probabilities for ecological quantities. Such a rationale shifts the focus from addressing the societal challenge of deciding which competing demand takes precedence, to the technical challenge of estimating an ecological quantity. This shift has ramifications for who engages in the management process and in what capacity.

The above case studies illustrate the conundrum that while there may be the prospect, however far down the road, of addressing salient uncertainties associated with the ecological system, that prospect leaves the relevant socially induced uncertainty unresolved. No matter how loud the pleas may be from resource managers for a "rational" choice, social dynamics ultimately do not provide deterministic outcomes. All three of these characteristics leave the management of socio-ecological systems subject to surprises. Frustratingly, once a surprise has occurred it will be possible to look back and see the chain of arguments, agreements and compromises that led to what appeared at the time as unanticipated.

8. Conclusion

For adaptive management to address emerging and deepening ecological deficits requires progress in how we address one of the most vexing dimensions of dealing with the future—uncertainty. We agree that "[t]he ultimate goal of decision-making in the face of uncertainty should be to reduce the undesired impacts from surprises, rather than hoping or expecting to eliminate them." (Walker et al. 2003, 11). Distinguishing between ecologically and socially induced uncertainty is a critical first step in acknowledging that source of uncertainty matters in managing socio-ecological systems. As our examples illustrate, best efforts to address ecologically induced uncertainty is a necessary but not sufficient condition for managing socio-ecological systems. This recognition has implications for our efforts to manage SES adaptively. Adaptive managers must expand their traditional focus on reducing uncertainty, because socially induced uncertainty is always irreducible, non-stationary, and not amenable to the tools of probability. As Pritchard and Sanderson (2002 163) note, "If management is to be adaptive, it should be focused on how to handle irreducible uncertainty, [not just about] how to test hypotheses about system function and resilience, [and] how to maintain the adaptive capacity of the ecosystem."

There is not one monolithic school of thought about how to consider the role of indeterminism in adaptive management. McFadden et al. (2011) distinguish between the experimental resilience school and the decision theoretic school. The experimental resilience school (ER school) makes a strong normative assumption that building resilience is a key goal of adaptive management of SES (Gunderson et al., 1995). It focuses on reducing uncertainty by conducting management actions in the context of hypothesis tests and experimental design. In contrast, the decision theoretic school (DT school) focuses on management decisions made in the face of uncertainty (Possingham et al., 2001; Gregory et al., 2006). The DT school, while assuming humans generate management objectives that represent their values and that these objectives remain constant over the life of at least one iteration of the decision making process, does not make normative assumptions about how humans come to those objectives or that they must think about resilience. In addition, while the potential of management experiments to reduce uncertainty is highly regarded, the DT school does not consider experimentation to reduce uncertainty a necessary feature of adaptive management.

What the two schools of adaptive management agree upon is that it essential to learn from the management enterprise with the intent of being able to build on that experience in the future, in other words, to reduce uncertainty (Gunderson, 2003). Iteration, however, also creates opportunities to revisit objectives without first creating a crisis that forces reactive reconsideration of objectives. Thus, iteration is a key means of dealing with non-stationary and irreducible uncertainty arising from social processes e an essential part of developing adaptive capacity.

Calls for scientists to do a better job of describing the uncertainty in data (e.g. McNie, 2007) miss an essential point e that there are sources of irreducible uncertainty beyond the data that the tools of probability theory cannot describe. Consequently, recognizing socially generated uncertainty is an essential component of practicing adaptive management.

Acknowledgments — An earlier version of this paper was presented by Andrew J. Tyre at the 2009 Midwest Fisheries and Wildlife Conference, Springfield, Illinois, December 6, 2009. Partial support for this work was provided by the U.S. Corps of Engineers Missouri River Recovery Program and the National Science Foundation through the University of Nebraska Interdisciplinary Graduate Education and Research Training Program Number 0903469. Helpful comments on a previous iteration of the paper were provided by Ahjond Garmestani, Environmental Protection Agency and Michael Runge, United States Geological Survey.

References

Burgman, M. A., Ferson, S., Akçakaya, H. R., 1993. Risk Assessment in Conservation Biology. Chapman and Hall, London.

Burgman, M. A., 2005. Risks and Decisions for Conservation and Environmental Management. Cambridge University Press, Cambridge.

Chandler, R. E., Rougier, J., Collins, M., 2010. Climate change: making certain what the uncertainties are. Significance 7, 9–12.

Clark, J. S., 2007. Models for Ecological Data: An Introduction. Princeton University Press, Princeton, N. J.

Conroy, M. J., Barker, R. J., Dillingham, P. W., Fletcher, D., Gormley, A. M., Westbrooke, I. M., 2008. Application of decision theory to conservation management: Recovery of Hector's dolphin. Wildlife Research 35, 93–102.

Dickson, P., Adams, W. M., 2009. Science and uncertainty in South Africa's elephant culling debate. Environment and Planning C: Government and Policy 27,110–123.

Funtowicz, S. O., Ravetz, J. R., 1991. A new scientific methodology for global environmental issues. In: Costanza, R. (Ed.), Ecological Economics: The Science and Management of Sustainability. Columbia University Press, New York, pp. 137–152.

Gregory, R., Ohlson, D., Arvai, J., 2006. Deconstructing adaptive management: Criteria for applications to environmental management. Ecological Applications 16, 2411–2425.

Gunderson, L. H., 2003. Adaptive dancing: interactions between social resilience and ecological crises. In: Berkes, F., Colding, J., Folke, C. (Eds.), Navigating Socialecological Systems. Cambridge University Press, Cambridge, pp. 33–52.

Gunderson, L. H., Holling, C. S., Light, S. S., 1995. Barriers and Bridges to the Renewal of Ecosystems and Institutions. Columbia University Press, New York.

Hammond, John S., Keeney, Ralph L., Raiffa, Howard, 1998. Psychological Traps, Chapter 10 in Smart Choices: A Practical Guide to Making Better Decisions. Harvard Business School Press, Boston, MA.

Hilborn, R. C., 2004. Sea gulls, butterflies, and grasshoppers: A brief history of the butterfly effect in nonlinear dynamics. American Journal of Physics 72, 425–427.

Holling, C. S., 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 4, 1–23.

Jacobson, R. B., Galat, D. L., 2008. Design of a naturalized flow regime—An example from the Lower Missouri River, USA. Ecohydrology 1, 81–104.

Kahneman, A., Tverskey, D., 2000. Advances in prospect theory: Cumulative representation of uncertainty. In: Kahneman, A., Tversky, D. (Eds.), Choices, Values, and Frames. Cambridge University Press, Cambridge.

Knight, F., 1921. Risk, Uncertainty, and Profit. Houghton Mifflin, Boston.

Lee, K. N., 1993. Compass and Gyroscope: Integrating Science and Politics for the Environment. Island Press, Washington, D. C.

Ludwig, D., Mangel, M., Haddad, D., 2001. Ecology, conservation and public policy. Annual Review of Ecology and Systematics 32, 481–517.

McFadden, J. E., Hiller, T. L., Tyre, A. J., 2011. Evaluating the efficacy of adaptive management approaches: Is there a formula for success? Journal of Environmental Management 92 (5), 1354–1359.

McNie, E., 2007. Reconciling the supply of scientific information with user demands: An analysis of the problem and review of the literature. Environmental Science & Policy 10, 17–38.

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., Stouffer, R. J., 2008. Stationarity is dead: Whither water management? Science 319, 573–574.

National Research Council, 2002. The Missouri River Ecosystem: Exploring the Prospects for Recovery. National Academy Press, Washington, DC.

Omnibus Appropriations Act, 2009. Title 1, Section 108.

Parma, A. M., the NCEAS Working Group on Population Management, 1998. What can adaptive management do for our fish, forests, food, and biodiversity? Integrative Biology 1, 16–26.

Possingham, H. P., Andelman, S. J., Noon, B. R., Trombulak, S., Pulliam, H. R., 2001. Making smart conservation decisions. In: Soulé, M. E., Orians, G. H. (Eds.), Conservation Biology: Research Priorities for the Next Decade. Island Press, Washington.

Powell, R. A., Ransom Jr., D., Slack, R. D., Silvy, N. J., 2010. Dynamics of content and authorship patterns in the wildlife society journals (1937–2007). Journal of Wildlife Management 74, 816–827.

Pritchard Jr., L., Sanderson, S. E., 2002. The dynamics of political discourse in seeking sustainability. In: Gunderson, L. H., Holling, C. S. (Eds.), Panarchy. Island Press, Washington, pp. 147–169.

Regan, H. M., Colyvan, M., Burgman, M., 2002. A taxonomy and treatment of uncertainty for ecology and conservation biology. Ecological Applications 12, 618–628.

Rothlisberger, J. D., Lodge, D. M., Cooke, R. M., Finnoff, D. C., 2010. Future declines of the binational Laurentian great lakes fisheries: The importance of environmental and cultural change. Frontiers in Ecology and the Environment 8, 233–238.

Sarewitz, D., 2000. Science and environmental policy: An excess of objectivity. In: Frodeman, R. (Ed.), Earth Matters: The Earth Sciences, Philosophy, and the Claims of Community. Prentice Hall, Upper Saddle River, NJ, pp. 79–98.

Slooten, E., Fletcher, D., Taylor, B. L., 2001. Accounting for uncertainty in risk assessment: Case study of Hector's Dolphin mortality due to gillnet entanglement. Conservation Biology 14, 1264–1271.

U.S. Army Corps of Engineers, 2008. Missouri River Recovery Implementation Committee Charter. http://www.moriverrecovery.org/mrrp/MRRP_PUB_DEV.download_documentation?p_file=425

U.S. Fish and Wildlife Service, 1993. Pallid Sturgeon Recovery Plan. U. S. Fish and Wildlife Service, Bismarck, North Dakota, 55 pp.

U.S. Fish and Wildlife Service, 2000. Biological Opinion on the OPERATION of the Missouri River Mainstem Reservoir System.

U.S. Fish and Wildlife Service, 2003. Amended Biological Opinion on the Operation of the Missouri River Mainstem Reservoir system.

Wade, P. R., 2000. Bayesian methods in conservation biology. Conservation Biology 14, 1308–1316.

Walker, W. E., Harremoës, P., Rotmans, J., van der Sluijs, J. P., van Asselt, M. B. A., Janssen, P., Krayer von Krauss, M. P., 2003. Defining uncertainty: A conceptual basis for uncertainty management in model-based decision support. Integrated Assessment 4, 5–17.

Woodward, A. R., David, D. N., Hines, T. C., 1987. American alligator management in Florida. In: Odum, R. R., Riddleberger, K. A., Ozier, S. C. (Eds.), Proceedings of the 3rd Southeastern Nongame and Endangered Wildlife Symposium. Georgia, Athens, pp. 98–113