Chapter 1
Threshold Concepts: Implications for the Management of Natural Resources

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Abstract Threshold concepts can have broad relevance in natural resource management. However, the concept of ecological thresholds has not been widely incorporated or adopted in management goals. This largely stems from the uncertainty revolving around threshold levels and the post hoc analyses that have generally been used to identify them. Natural resource managers have a need for new tools and approaches that will help them assess the existence and detection of conditions that demand management actions. Recognition of additional threshold concepts include: utility thresholds (which are based on human values about ecological systems) and decision thresholds (which reflect management objectives and values and include ecological knowledge about a system) as well as ecological thresholds. All of these concepts provide a framework for considering the use of threshold concepts in natural resource decision making.

Keywords Natural resource management · Non-linear · Regime shift · Time series

Natural resource managers face a complex decision-making environment that is not adequately addressed by traditional natural resource planning and decision-making processes. This situation can be partly attributed to changes in the dominant ecological paradigms used in natural resource management. In the past, habitat management has implicitly assumed that ecologists and managers are able to identify a "desired state" for ecosystems and that resource managers are then able to implement actions that can achieve and maintain the desired state. This philosophical strategy, aptly termed "command and control" (Holling and Meffe 1996), has been only partly successful and works best with problems that are relatively simple in terms of cause and effect (Knight and Meffe 1997). Historically, natural resource managers believed that the best way to achieve a "natural" state was to leave an area alone, or if it was

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disturbed, to simply remove the source of disturbance. In theory, a somewhat linear sequence of successional changes would eventually result in formation of a stable climax state (sensu Clements 1936).

With the recent appreciation of the complexity of ecosystem dynamics, the uncertainty associated with management actions, and the adoption of ecosystem management concepts (Grumbine 1994; Link et al. 2002; Tallis et al. 2010), ecologists and managers alike have embraced more quantitative methods and sophisticated models to guide management actions. These contemporary models accommodate a broader range of dynamics, and they often discard simple linear trajectories for those with non-linear behaviors and multiple possible outcomes.

The ideas of non-linear responses, tipping points, and regime shifts are now recognized as more likely the rule than the exception in ecological systems (Folke et al. 2004). Indeed there is growing evidence for strong non-linearities in the shaping of population dynamics (e.g., Stenseth et al. 1999) and the structure of ecosystems (e.g., Carpenter 2003). As a result, the concept of complex non-linear physical, chemical, and biological interactions and feedbacks is now generally accepted (Pielke et al. 2003; Scheffer and Carpenter 2003; Groffman et al. 2006). These ideas are at the core of the ecological threshold concept. This concept originates with the ideas of multiple ecological stable states (Holling 1973) and non-equilibrium systems (DeAngelis and Waterhouse 1987).

Threshold concepts can also have broad relevance to natural resource management. In this context, they are often viewed as triggers that prompt the need for specific actions to maintain a desired condition or keep a specific state variable within a desired range (Eaton et al., Chap. 5). Operational definitions of thresholds and their use by ecologists and managers have been an important area of focus (Briske et al. 2006; Bestelmeyer 2006; Groffman et al. 2006). Groffman et al. (2006) described three non-exclusive definitions of thresholds. The first definition describes abrupt and dramatic "shifts in ecosystem state." This is perhaps the most common use in the ecological community. A second definition describes "critical loads," which more specifically applies to levels of pollutant inputs that result in unacceptable ecosystem responses. The third definition describes "extrinsic factor thresholds" where cross-scale interactions lead to abrupt changes. This final use falls within the conceptual framework of hierarchy theory, where broad-scale factors constrain system dynamics (Allen and Hoekstra 1992).

Bestelmeyer (2006) offers contrasting definitions of thresholds, focusing on use of threshold concepts in rangelands and identifies ambiguities related to ecological scale, pattern, and process. To address the need for a unifying framework, Bestelmeyer (2006) proposed a classification of thresholds consisting of pattern thresholds, process thresholds, degradation thresholds, and a more synthetic set of classification thresholds based on either preventative management or restoration of rangeland. This framework accommodates many of the requirements for rangeland managers and places an emphasis on broadening the attributes used to define thresholds.

Others have proposed a more general definition of thresholds that include "a defined target level or state based on the avoidance of unacceptable outcomes or an ecologically defined shift in system status" (Polasky et al. 2011). Martin et al. (2009) distinguish between three broad threshold concepts that are relevant for natural resource managers and add the concept of decision and utility thresholds to that of ecological thresholds. Decision thresholds represent values of a state variable that when exceeded should elicit management action. "Utility thresholds" are derived from management objectives and indicate where "small changes in environmental conditions produce substantial improvements in management outcomes. . . " (Samhouri et al. 2010). These alternative concepts are not easily reconciled with the identification of ecological thresholds, nor do they provide a general conceptual basis that fully integrates our understanding of thresholds into a comprehensive decision-making process (Martine et al. 2009; Polasky et al. 2011).

Increasingly, the importance of understanding interactions between and among biotic and abiotic factors in ecosystems and how these interactions lead to complexities are factored into resource management actions (Huggett 2005; Groffman et al. 2006; Bestelmeyer 2006; Andersen et al. 2009; Suding and Hobbs 2009; Hobbs and Suding 2009). However, the widespread acceptance of threshold concepts in ecological models—"ecological thresholds"—has not been followed by their widespread adoption and incorporation into management goals (Hobbs and Suding 2009). The ability to move from theory to application and make threshold concepts a problem-solving tool for natural resource management remains a daunting challenge. One of these impediments involves confusion over the appropriate use of threshold concepts in natural resource decision-making processes. Bennetts et al. (2007) described seven concepts widely used by natural resource management agencies in identifying points or zones of interest to managers and that could be used to inform the management of natural resources. In addition to ecological thresholds, these include: critical loads, regulatory or policy standards, management thresholds, desired condition, range of natural variation, and thresholds of potential concern. The typical implementation of these concepts ranges from precisely defined quantities to more qualitative descriptions; and each of these concepts contributes to our broader understanding of the use of threshold concepts in natural resource management. These seven concepts encompass the three types of thresholds proposed by Martin et al. (2009) as relevant for natural resource decisions: ecological thresholds, utility thresholds, and decision thresholds. Decision thresholds have often been referred to as management thresholds, and utility thresholds can in certain cases coincide with ecological thresholds (Samhouri et al. 2010). The other concepts identified by Bennetts et al. (2007) can be used to develop utility and decision thresholds. When regulatory thresholds like water or air quality standards or critical loads are exceeded, the responses may be clearly dictated by law, with little latitude for local decision making. However, for many natural resource management situations, the use of desired condition, range of natural variation, and thresholds of potential concern may result in a variety of reasonable responses when attributes approach or exceed a (sometimes arbitrarily defined) value.

So, beyond agreeing that ecological thresholds may be common and sometimes important, there is no shared understanding or agreement on the role or appropriate use of this concept in natural resource management in spite of the fact that there is a rich literature that addresses the concept of ecological resilience and alternative stable states. Likely, this largely stems from the uncertainty revolving around threshold levels and the post hoc analyses that have generally been used to identify them. Advances in and new applications of statistical techniques (Andersen et al. 2009; Ficetola and Denoel 2009) have greatly enhanced our ability to detect the locations of thresholds once they have been crossed, but most techniques still rely on long-term temporal series of observations (e.g., Carpenter and Brock 2006, Andersen et al. 2009). Identifying the level at which threshold behavior occurs may be possible if we can accumulate a large body of empirical observations. Otherwise, new work in identifying generic early warning metrics may provide our best opportunity for identifying the probability of such an event occurring (Scheffer et al. 2009; Biggs et al. 2009; Scheffer et al 2012).

Natural resource managers have a need for new tools and approaches that will help them assess the existence and detection of conditions that demand management actions. This book addresses several of the issues that have profoundly affected the use of thresholds in natural resource management—uncertainty, different types of thresholds, appropriate use of thresholds in decision making, and the development of a comprehensive decision framework as a unifying approach for threshold concepts.

The first set of chapters in this book provide a conceptual framework for threshold concepts in natural resource management and conservation based on the theory of structured decision making. Risk analysis (Suter 2007), decision theory (Morgan et al. 1990), and structured decision making (Martin et al. 2009) have all been promoted as a means to advance natural resource management decisions. These approaches provide a structured process that enables natural resource decision makers to identify interventions that can lead to improvement or to avoid future problems. Each of these frameworks has three elements—a clear statement of the problem and objectives, a list of discrete management actions, and quantitative scientific information in the form of one or more models that can be used to predict the outcome of different management actions. Nichols et al. (Chap. 2) provide a conceptual framework (Structured Decision Making) for the use of threshold concepts in natural resource decision making and discuss the important distinctions between utility, decision, and ecological thresholds. Runge and Walshe (Chap. 3) provide a more expanded description of identifying objectives and alternative actions needed to frame a natural resource decision problem. Williams and Nichols (Chap. 4) then describe the role of optimization in providing an objective approach for deciding which potential action to take. Finally, Eaton et al. (Chap. 5) illustrate an application of the various classes of thresholds introduced by Nichols et al. (Chap. 2) and their use in structuring a decision process for the management of human recreational activities and the impact of nesting Golden Eagles in Alaska's Denali National Park.

The next four chapters discuss the role of monitoring for threshold-dependent decisions and the evaluation of bioassessment designs. Smith et al. (Chap. 6) review the literature on monitoring for threshold-dependent management decisions and compare adaptive management with targeted monitoring with the sequential evaluation of resource condition with surveillance monitoring. They further build on the prior section by examining the threshold concepts of ecological change, utility value, and decision threshold in resource management and how these concepts are incorporated into resource management and monitoring. Bowker et al. (Chap. 7) use case studies from the dryland ecosystems of the Colorado Plateau to illustrate how state and transition models can be used to identify transition and triggers likely to be detectable by monitoring programs. Symstad and Jonas (Chap. 8) examine how our understanding of the natural range of variation for plant communities can be used in developing decision thresholds when ecological thresholds are unknown or do not exist. Snyder et al. (Chap. 9) illustrate how simulation techniques may be used to optimize bioassessment decision thresholds and sampling designs with a case study of benthic macroinvertebrate communities in a US National Park. Finally, Mitchell et al. (Chap. 10) use ongoing monitoring data by the US National Park Service Vital Signs Program to illustrate how threshold detection can be used in establishing ecological assessment points and how the concept of ecological integrity can be reported to resource managers and decision makers. They describe and illustrate how concepts of ecological integrity, thresholds, and reference conditions (natural range of variability) can be integrated into a research and monitoring network.

Field data are being explored with new statistical and graphical techniques, and more sophisticated models are being used in the monitoring and management of ecosystems and the detection of response patterns. The final series of chapters in this book describe different quantitative approaches to estimate ecological thresholds. King and Baker (Chap. 11) describe how a new method Threshold Indicator Taxa Analysis (TITAN) uses ecological community data for estimating community thresholds. They use a case study that examines macroinvertebrate community response to a phosphorus gradient in the Everglades, a large subtropical wetland in the southern USA. Carstensen (Chap. 12) introduces a statistical inferential approach based on generalized additive models to examine ecosystem trajectories during degradation and recovery phases using observations from four monitoring programs of phytoplankton communities in northeastern European coastal waters. Washington-Allen and colleagues (Chap. 13) used biophysical models Normalized Difference Vegetation Index (NDVI) from a time series of Landstat images of the Mojave Desert of the western USA to examine the hypothesis that changes in the variance, as a threshold is approached, may provide an early warning signal of change. The concluding chapter by James Pirri et al. (Chap. 14) illustrates how threshold concepts can be used by managers to evaluate responses to restoration activities or describe the overall condition of salt marsh ecosystems along the northeastern Atlantic coast of the USA. They use multivariate methods to illustrate how shifts in the characteristics of vascular plant and nekton communities can be used as ecological thresholds upon which decision thresholds for natural resource managers can be used.

The threshold concept has become a major theme in ecology, and advocates suggest that it can also play a key role in natural resource management, restoration, conservation, and land policies. Like many issues and concepts, threshold concepts can mean different things to different people. The discussion of thresholds in the literature has largely emphasized the identification of ecological thresholds and their role as components of ecological models in predicting system responses to management actions, but has not always been clear about the distinctions among different threshold types. Managers and scientists are not necessarily limited to the ideas and concepts of ecological thresholds when considering the management of natural systems. Increasingly, utility thresholds (which are based on human values about ecological systems) and decision thresholds (which reflect management objectives and values and include ecological knowledge about a system) have also been promoted (Martin et al. 2009). The chapters and case studies in this book illustrate how these different threshold concepts can be applied in conservation and land management decisions.

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