Chapter 2
Thresholds for Conservation and Management: Structured Decision Making as a Conceptual Framework

James D. Nichols, Mitchell J. Eaton and Julien Martin

Abstract A conceptual framework is provided for considering the threshold concept in natural resource management and conservation. We define three kinds of thresholds relevant to management and conservation. *Ecological thresholds* are values of system state variables at which small changes bring about substantial or specified changes in system dynamics. They are frequently incorporated into ecological models used to project system responses to management actions. *Utility thresholds* are components of management objectives and are values of state or performance variables at which small changes yield substantial changes in the value of the management outcome. *Decision thresholds* are values of system state variables at which small changes prompt changes in management actions in order to reach specified management objectives. Decision thresholds are derived from the other components of the decision process. We advocate a structured decision making (SDM) approach within which the following components are identified: objectives (possibly including utility thresholds), potential actions, models (possibly including ecological thresholds), monitoring program, and a solution algorithm (which produces decision thresholds). Adaptive resource management (ARM) is described as a special case of SDM developed for recurrent decision problems that are characterized by uncertainty. We believe that SDM, in general, and ARM, in particular, provide good approaches to conservation and management. Use of SDM and ARM also clarifies the distinct roles of ecological thresholds, utility thresholds, and decision thresholds in informed decision processes.

Keywords Adaptive management · Decision threshold · Ecological threshold · Structured decision making · Utility threshold

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Introduction

Thresholds and their relevance to conservation are widely discussed by ecologists, conservation biologists, managers, and policy makers (Burgman 2005; Bestelmeyer 2006). These discussions are certainly useful in many respects, but they can also lead to confusion about how thresholds should be used in the conduct of conservation. In this chapter, we provide a conceptual framework for thresholds that we hope will be useful to those involved in conservation and management. We define three general classes of thresholds. Our purpose in doing so is not simply to introduce new vocabulary to a subject area already rich in terminology, but rather to draw distinctions among thresholds that have specific, yet different, uses in conservation programs. Our focus on the use of thresholds in decision processes requires a description of such processes, as they provide the framework required for our discussion.

Structured decision making (SDM; Clemen and Reilly 2001) is a logical and transparent process that requires breaking a decision into its component parts. This decomposition insures that discussions among stakeholders with different opinions are properly focused and helps to clarify points of agreement and disagreement. The components identified in SDM also serve to clarify roles of different participants in the decision process. Some components focus on values and require substantive input from all relevant stakeholders, whereas other components focus on system dynamics and are addressed primarily by managers and scientists. Most relevant to this chapter, adoption of SDM leads naturally to consideration of definitions and roles of different kinds of thresholds in the conservation process.

We will structure this chapter by first defining three types of thresholds relevant to conservation decisions. We then describe the components of the SDM process, emphasizing the position and role of each type of threshold with respect to these components. We next describe adaptive resource management (ARM) as a special case of SDM developed for recurrent decisions characterized by uncertainty. Finally, we provide a discussion of this threshold framework and advocate its use with SDM for conservation decision making.

Thresholds

Ecological Thresholds

Three kinds of thresholds are relevant to making decisions in conservation : *ecological, utility,* and *decision* thresholds (Martin et al. 2009a). *Ecological thresholds* have been defined in many ways, but common to most definitions is a point or zone at which there is a sudden change in the condition or dynamics of a biological system (e.g., Fahrig 2001; Huggett 2005; Pascual and Guichard 2005; Groffman et al. 2006; Bennetts et al. 2007). We operationally define an ecological threshold as a value (or set of values) of a state variable, environmental variable, or rate parameter of a system at which small changes either (1) produce changes in system dynamics of specified

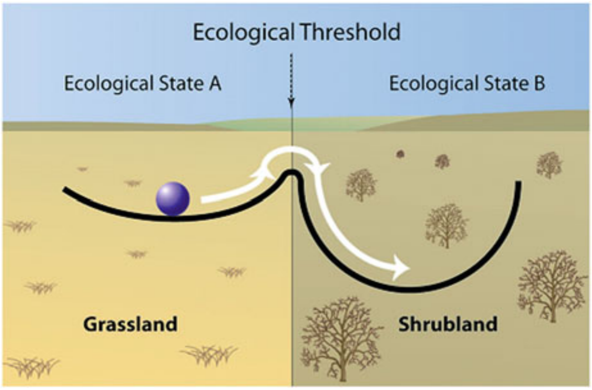

Fig. 2.1 Example of an ecological threshold. In this example a small change in the amount of precipitation (environmental variable) leads to a substantial change in system state from grassland (*ecological state A*) to shrubland (*ecological state B*). The *ball* and *valleys* provide an illustration of the tendency to remain in the same ecological state, or with the possibility to switch to another ecological state. (Reproduced from Bennetts et al. 2007)

magnitude (typically large or ecologically substantial changes) or (2) cause system state variables or rate parameters to attain certain specified values. An example of the first kind of ecological threshold can be found in vegetation communities of the Chihuahuan Desert (Fig. 2.1). Precipitation is a key environmental variable of this system, and an ecological threshold is the level(s) of precipitation at which small changes induce a shift from grass- to shrub-dominated communities and vice versa (Brown et al. 1997; Groffman et al. 2006). An example of the second kind of ecological threshold is Lande's (1987) concept of extinction threshold for metapopulation systems. In this case, the proportion of potentially available habitat that is suitable for the focal species is an important system state variable. The extinction threshold is the proportion of suitable habitat at which probability of metapopulation extinction becomes one (Fig. 2.2; see Lande 1987; Fahrig 2001; Benton 2003).

We have no strict views about the functional forms of ecological thresholds, as illustrated by two examples of thresholds from Martin et al. (2009a). A step function corresponds closely to most views of the threshold concept. For example, Fig. 2.3a depicts an ecological threshold as a value of a state variable (1,500 units of water in a wetland) at which a vital rate (rate of patch colonization) increases from 0 to 0.1. The threshold concept can also apply to regions of a functional relationship at which small changes in one variable produce large changes in another. Figure 2.3b depicts such a case, where changes in water levels within a particular region (600–1,250 units of water) produce large changes in probability of patch extinction. Some discussions of ecological thresholds focus on shifts of state variables to an absorbing state (e.g., permanent extinction) from which transition is not possible (Lande 1987). Discussions of ecological thresholds frequently include other terms relevant to system change and dynamics. The concept of "resilience" (Holling 1973; Gunderson 2000) concerns the magnitude of perturbation required to induce a substantive change in system state. "Elasticity" (Bodin and Wiman 2007) refers to aspects (e.g.,

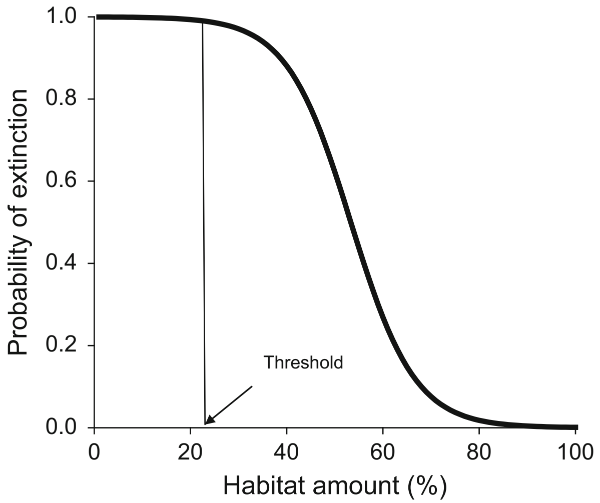

Fig. 2.2 Probability of metapopulation extinction as a function of the amount of suitable habitat remaining. The extinction threshold is the proportion of suitable habitat at which probability of metapopulation extinction becomes one (or very close to one). (Based on Lande 1987; Fahrig 2001)

time elapsed) of transient dynamics following a perturbation as a system returns to equilibrium.

Our definition of ecological threshold is thus very general, and we acknowledge that discussions of related concepts can be very wide-ranging. However, the role of ecological thresholds in management and conservation is very specific: They are components of models used to predict system responses to management actions. Ecological models need not include thresholds, as threshold concepts may not be relevant to the dynamics of all ecological systems. However, when ecological thresholds are relevant to system dynamics and response to management, they are incorporated in the functional relationships of ecological models (Martin et al. 2009a; see also Conroy et al. 2003; Bestelmeyer 2006).

Utility Thresholds

We define *utility thresholds* as values of state or performance variables at which small changes yield substantial changes in the value of the management outcome. For example, we might specify that an objective of management for a particular species in a national park is that the population size should remain above some level, say N^*. Unlike ecological thresholds, which are part of the pattern and process of nature, utility thresholds are determined by human values. In many cases, utility thresholds have some ecological basis; for example, they are frequently based on historical observations of system state variables (e.g., Runge et al. 2006; Martin et al. 2011). But there is no necessary link between utility thresholds and ecology; instead, utility thresholds provide explicit statements of what managers value.

Statements of management objectives need not include utility thresholds. For example, a management objective might be to minimize the probability that an endangered species becomes extinct over a specified time horizon. Utility thresholds

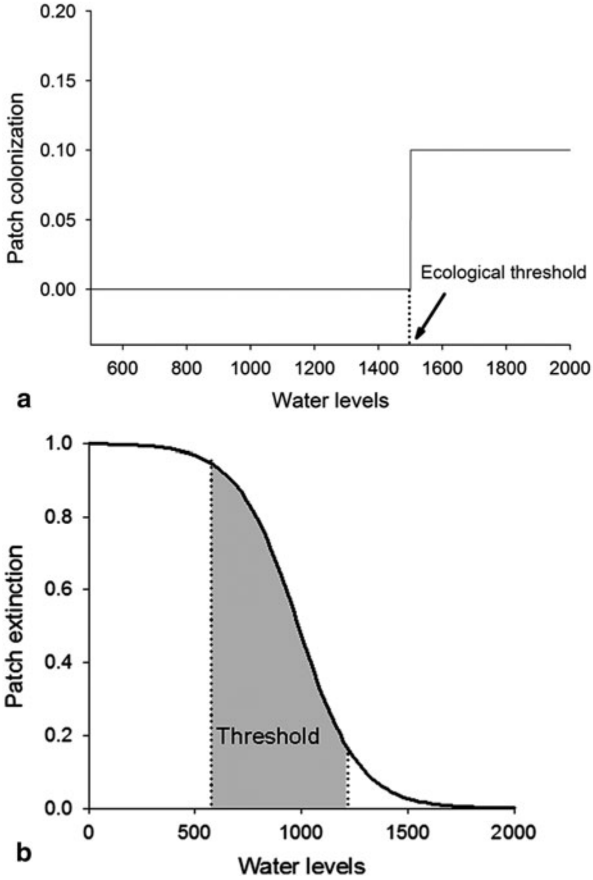

Fig. 2.3 Illustration of two types of ecological threshold based on the example from Martin et al. (2009a). **a** The diagram depicts an ecological threshold as a value of a state variable (1,500 units of water in a wetland) at which a vital rate (rate of patch colonization) increases from 0 to 0.1. **b** The graph depicts a threshold zone where changes in water levels within a particular region (600–1,250 units of water) produce large changes in probability of patch extinction

are frequently used in objective functions that include competing objectives. For example, in Chap. 5 (Eaton et al.) we describe management of potential disturbance by hikers and tourists to golden eagles in Denali National Park (see also Martin et al. 2009b; Martin et al. 2011). Park managers seek to provide a rewarding experience to hikers, but also want to maintain a healthy breeding population of golden eagles. The objective function for this specific decision problem is to minimize the number of eagle nesting territories at which hiker access is restricted, while maintaining the occupancy of potential territories above a specified utility threshold (e.g., 0.8).

Decision Thresholds

We define *decision thresholds* (sometimes referred to as management thresholds, see Bennetts et al. 2007) as values of system state variables that should prompt specific management actions. Decision thresholds are thus conditional on, and derived from,

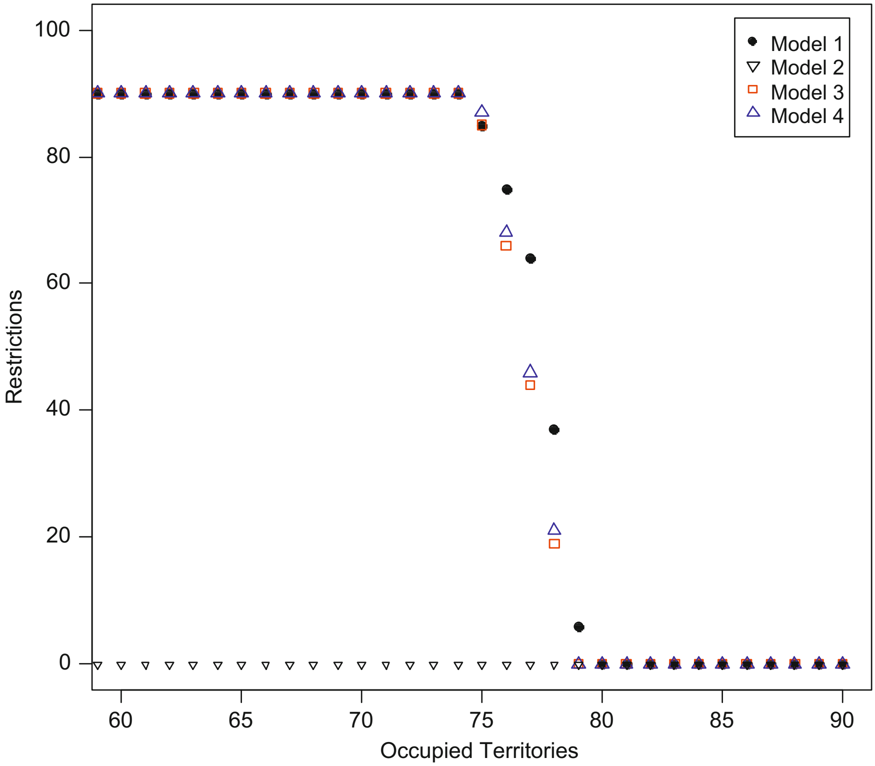

Fig. 2.4 Policy matrix showing the optimal number of restricted territories as a function of the number of eagle territories that are occupied. (From Eaton et al., Chap. 5)

ecological and utility thresholds. In the example of Denali golden eagles and hikers, golden eagle occupancy proportion of potential nest sites is potentially affected by hiker disturbance. The management decision is whether to close hiker access to potential territories. Because of the desire to minimize restrictions to hikers, if projected eagle occupancy is sufficiently high relative to the utility threshold, hikers will not be restricted. However, as current eagle occupancy reaches levels that are sufficiently low that projections indicate a good possibility of dropping below the utility threshold, the optimal action will be to restrict hikers. The value of the state variable(s) (proportion of potential territories that are occupied) at which the recommended action shifts from no hiking restrictions to restrictions can be viewed as a decision threshold.

An example policy matrix for the Denali golden eagle example presented in Chap. 5 (see also Martin et al. 2011) is shown in Fig. 2.4. While the detailed analysis of Martin et al. (2011) focused on 25 out of 93 territories that were believed to have the potential to be disturbed by hikers, Eaton et al. (Chap. 5) focused their analysis on a hypothetical 90 nesting sites, all with the potential for closure. Specifically, the management decision is, “How many of these sites should be closed to hikers in order to minimize closures while keeping the projected number of occupied eagle territories above a utility threshold based on historic data?" A stochastic dynamic programming algorithm (Bellman 1957) was originally implemented using the software of Lubow (1995) to derive the optimal policy (Fig. 2.4). The decision policy is based on the number of these 90 sites that are occupied. The vertical axis in Fig. 2.4 represents the management decision at any level of system state, specified as number of territories restricted. Under any of the four proposed dynamic models, the optimal number of restrictions is 0 sites if the number of occupied sites is between 80 and 90, so there is no decision threshold for these values of the state variable. However, if the number of occupied territories drops to 79, then the optimal number of restricted sites (under one hypothesis of occupancy dynamics) shifts from 0 to 6. This change in number of occupied territories from 80 to 79 thus represents a decision threshold, because different actions are recommended for these two different values of the state variable.

Sources of Confusion

Discussions of thresholds and their role in conservation have not always been clear, especially with respect to the distinctions among the three types of thresholds that we have identified. For example, it is common for managers to equate utility and decision thresholds. One approach to management under the declining population paradigm (Caughley 1994) is to view a finite rate of population increase (λ) of 1 simultaneously as a utility and a decision threshold. A declining population ($\lambda < 1$) is viewed as undesirable, such that $\lambda = 1$ is a utility threshold. The manager periodically tests for a negative trend in abundance (e.g., using monitoring data and statistical models and inference procedures). If a "significant" negative trend is detected, then management actions are taken, so $\lambda = 1$ is also viewed as a decision threshold.

Management under the SDM approach that we advocate tends to produce decision thresholds that are more conservative than this trend-detection approach. If $\lambda = 1$ is our utility threshold, then under optimal management, actions typically occur before the population is actually declining, in an effort to keep $\lambda \geq 1$. Indeed, the trend-detection approach has been criticized as leading to unnecessary delays in management actions (Maxwell and Jennings 2005; Nichols and Williams 2006). In addition, the usual approach of placing trend detection in a hypothesis-testing framework invites discussion about type I and II error rates (e.g., arbitrary α for hypothesis testing) and the relative risks associated with these errors (see Field et al. (2004) for a discussion of this topic). Use of SDM and treatment of decision processes as optimization problems, rather than as problems of hypothesis testing, produce decision thresholds that frequently differ from utility thresholds.

Synthesis

Ecological thresholds may characterize the dynamics of managed ecological systems. When this is true, and when they can be identified (this can be difficult), they should be incorporated into the models used by managers in the decision process. Utility

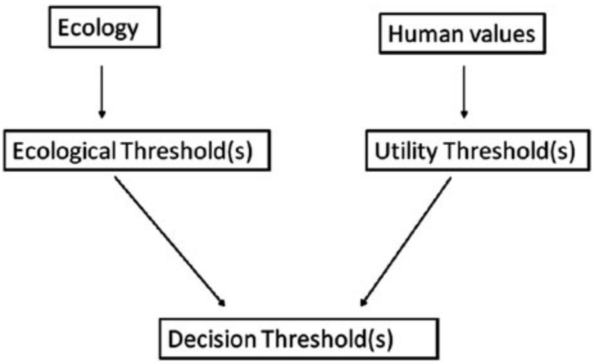

Fig. 2.5 Relationships among ecological, utility, and decision thresholds. (Modified from Martin et al. 2009a)

thresholds reflect human values about ecological systems and may be included in management objectives. Decision thresholds are derived from the ecological and utility thresholds or, more generally, from management objectives, available actions, and models of system dynamics and responses to management. These relationships among the different types of thresholds are depicted in Fig. 2.5.

Structured Decision Making (SDM)

SDM is a formal decision process employed to identify decisions that are optimal with respect to specified objectives. SDM is rooted in decision theory, which provides a useful framework for making decisions about the management of virtually any kind of system (Bellman 1957; Intriligator 1971; Williams et al. 2002; Burgman 2005; Halpern et al. 2006). SDM has been used in a variety of fields, including engineering, economics, and natural resource management (e.g., Johnson et al. 1997; Clemen and Reilly 2001; Miranda and Fackler 2002; Halpern et al. 2006). In the context of conservation, the elements of the decision-making problems often include the following components: objectives, potential management actions, model(s) of system behavior (specifically, models that predict how system state is expected to change with application of each different management option), a monitoring program to provide estimates of system state variables, other variables related to management returns, system vital rates, and finally a method to identify the solution (Williams et al. 2002; Dorazio and Johnson 2003; McCarthy and Possingham 2007). Two of these components, model(s) and estimates of system state, are typically characterized by substantial uncertainties that must be accommodated in the optimization process.

Objectives and Management Actions

The specification of objectives is a critical component of any decision-making process. Objectives should reflect the values of relevant stakeholders and constitute specific statements of what is to be achieved by implementing management actions. Objectives provide the currency by which alternative decision options are judged (Clemen and Reilly 2001; Conroy and Moore 2001). Examples of objectives relevant to conservation include maximizing species diversity in a natural area or minimizing the probability of quasi-extinction of a threatened species (Kendall 2001). As noted above, objectives may be stated as utility thresholds, such as maintaining a population size at or above some specified value.

In cases involving multiple stakeholders with competing interests, utility thresholds are often used as a means of providing constraints on competing objectives. In the example of Denali golden eagles (Martin et al. 2011; Eaton et al., Chap. 5), competing objectives were a desire to permit hikers to fully enjoy Denali National Park and a desire to maintain a healthy breeding population of golden eagles. The hypothesis that disturbance by hikers may limit occupancy and/or reproductive success of golden eagles at potential nesting sites leads to a consideration of trade-offs between objectives. In this case, the objective was expressed as minimizing the number of sites at which hiker access was restricted, subject to the constraint that predicted golden eagle occupancy or successful reproduction exceeded a specified utility threshold (Martin et al. 2011; Eaton et al., Chap. 5). Thus, utility thresholds may be used to specify simple objectives or to serve as constraints for problems with competing objectives.

Objectives (including associated constraints) should generally be determined through discussions among stakeholders (Kendall 2001). This determination can be one of the most difficult steps in a decision process, especially in the common case where different stakeholder groups have competing values and interests. Formal techniques are sometimes used to elicit values and select appropriate objectives (see Clemen and Reilly 2001; Burgman 2005). Once objectives and constraints have been selected, they can be formalized mathematically into an objective function. The objective function quantifies the benefit (or return) obtained by implementing specific decisions at each time step, accumulated over the time horizon of the decision problem (Lubow 1995; Williams et al. 2002; Fonnesbeck 2005).

The other component of SDM that is driven primarily by human values is the selection of the set of management actions to be considered. Frequently in conservation settings, the set of available actions is very small. Actions can include regulations that restrict harvest or various activities that cause human disturbance to a natural area (boating, hiking, using snowmobiles). Actions can also include various forms of habitat management, land acquisition, translocation of animals, etc. Sometimes, actions (e.g., predator control) that may be potentially useful and cost-effective are viewed as unacceptable based on human values. In summary, objectives and the set of potential management actions are not established by managers and scientists alone, but should be based on the values of all relevant stakeholders. Objectives and available actions are extremely important in SDM as they effectively drive the entire decision process.

Model(s) of System Behavior

Informed decisions require some basis for predicting effects of the different actions under consideration. Absent the ability to predict consequences of management actions, such actions might be determined by virtually any random process, but terms such as "management" and "conservation" do not really apply to such uninformed manipulation of a system. Models can be viewed as structures that provide predictions based on hypotheses about how the focal system "works" or, more specifically, how it responds to management actions. Models may reside in the heads of wise managers, or they may be mathematical, perhaps incorporated into computer code. Models that project the consequences of management actions should generally be developed by scientists and managers familiar with both the managed system and general principles of system dynamics. Although input from knowledgeable stakeholders is welcome, stakeholders are generally not as important to model development as they are to determining the value-driven components of SDM (objectives and actions).

Models used in SDM typically incorporate relationships between management actions and either (1) the vital rates that determine state variable dynamics (e.g., Fig. 2.3) or, less frequently, (2) the state variables themselves. These relationships may include ecological thresholds (Fig. 2.3). In the case study of Denali golden eagles (Martin et al. 2011; Eaton et al., Chap. 5), the management action (closure of a nesting site to hikers) is believed to increase the probability of a site making the transition from any state to the desired state of "occupied." However, scientists and managers are uncertain about the importance of disturbance to occupancy by eagles at a site. For this reason, several competing models are considered in the decisions for the Denali golden eagles. The example presented by Eaton et al. (Chap. 5) posits four hypotheses regarding the impact of disturbance and the availability of a particular prey species on eagle occupancy dynamics. Competing models differ in the hypothesized effects of management and prey level on parameters governing occupancy and include one model that incorporates an ecological threshold for prey abundance and another that assumes no effect of prey level or disturbance (and therefore of site closure to hikers) on golden eagle occupancy.

In order to incorporate this uncertainty (four models reflecting very different hypotheses about the effects of management) into the decision process, we must specify the relative influence of each model on the decision. Relative influence should be determined by the relative degree of faith we have in the predictive abilities of the models. We can specify the influence of each model on the decision using model "weights" or "credibility measures." These weights lie in the interval [0, 1] and sum to one for the members of the model set. In our Denali case with four models, for example, we might begin by assigning a weight of one fourths to each model (e.g., if we had no prior information as to which models were better predictors). These weights would indicate that we have equal faith (or equal uncertainty) in each model in the set. There are multiple reasonable ways to determine initial model weights if some prior information exists, including analysis of historical data and expert opinion. In recurrent decision problems, the ability to monitor effects of management actions provides an opportunity to learn. For recurrent decisions, a formal approach can be

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