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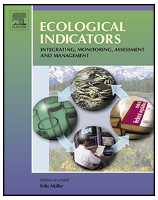

Decision errors in evaluating tipping points for ecosystem resilience

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ABSTRACT

When an ecosystem reaches tipping points for selected indicators, resilience to further changes in external drivers can decrease, regime shifts can occur that diminish the capacity of the ecosystem to provide ecosystem services, and the ecosystem is more vulnerable to collapse. Evaluating tipping points for resilience using crisp decision rules can result in decision errors about whether or not resilience has been compromised. The source and nature of those errors are described and a fuzzy decision rule is proposed for evaluating resilience. Decision errors are evaluated for four cases. Cases 1 through 3 (or case 4) derive conditions for evaluating decision errors when there is a single (or multiple) indicator(s). The primary sources of decision errors for the four cases are discrepancies between measured (or established) and true values of the indicators (or tipping points) and using a crisp decision rule to reach conclusions about whether or not resilience has been compromised. A fuzzy decision rule, based on fuzzy TOPSIS, is proposed that evaluates the extent to which an ecosystem is resilient. Although crisp decision rules provide unambiguous conclusions about resilience, those conclusions can be faulty, particularly when measured indicators and established tipping points deviate substantially from their true values. In contrast, the conclusions from the fuzzy decision rule are less susceptible to the decision errors and, hence, faulty decisions.

1. Introduction

An important dimension of global environmental change and sustainability is the occurrence of ecosystem tipping points. A tipping point is a critical threshold at which the state of a system can be qualitatively altered by a small change in forcing (Lenton et al., 2008). A system's internal dynamics must have a strong positive feedback (i.e., strong 'self-amplification' of external forcing) for it to have a tipping point (Levermann et al., 2011; Lenton, 2012).

Mathematically, a system has a tipping point if a critical indicator of the state of that system (I) has a critical threshold (I^*), such that a small change in the indicator ($\delta I > 0$) caused by natural and/or anthropogenic disturbance triggers a qualitative change in an important attribute of the system (ΔB) (Lenton et al., 2008; Lenton, 2012). The latter increases the risk that the ecosystem shifts from a desirable to an undesirable state (Sasaki et al., 2015). ΔB can occur abruptly or after a period of time, and may or may not be irreversible. The critical threshold (I^*) is the tipping point, beyond which the systems undergoes a qualitative change. For example, if climate change causes the current population of a threatened or endangered species (P) to decrease by δP and $P–\delta P < P^*$ where P^* is the population level below which the species becomes extinct, then, at some point in time, that ecosystem experiences a permanent loss in biodiversity (i.e., $\Delta B = B_{after \delta P} - B_{before \delta P} < 0$ where B is the level of biodiversity).

Tipping points have been used to characterize ecosystem change, such as the effects of anthropogenic global warming on the melting of ice caps, sea ice, and glaciers (Bramson, 2008; Lenton et al., 2008), the habitat, breeding, and survival of threatened and endangered species (Regehr et al., 2007; Hunter et al., 2010), and the effects of high levels of nutrients in fish ponds on eutrophication and associated losses in species richness and aquatic plants (Vanacker et al., 2016).

When tipping points are reached, ecosystem resilience to further changes in external drivers can decrease (i.e., resilience is compromised) and regime shifts can occur, both of which can diminish the capacity of the ecosystem to provide valuable ecosystem services (Jordan et al., n.d.). In addition, reaching tipping points can increase the vulnerability of socio–ecological systems to collapse (Scheffer et al., 2001; Abel et al., 2006). In this paper, ecosystem resilience refers to "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks" (Walker et al., 2004).

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Carstensen and Weydmann (2012) observe that “[t]he existence of ecological tipping points has mostly been investigated by means of theoretical modeling studies and experiments, whereas studies examining long–term monitoring data sets for abrupt changes are few.” This study is primarily theoretical because it describes several decision rules for evaluating tipping points for ecosystem resilience with respect to selected indicators. Unfortunately, the author does not have real–world data with which to demonstrate the empirical application of the decision rules. However, the study does specify the kinds of indicator data that would be required to evaluate ecosystem resilience with those decision rules. In addition, the study employs a hypothetical example to illustrate the steps in applying a fuzzy decision rule to evaluate ecosystem resilience with respect to three ecological indicators: loss of plant biodiversity; proportion of the ecosystem area with moderately or highly suitable habitat for a keystone species; and the proportion of the ecosystem area with moderate or high departure from the natural (historical) fire regime.

Several aspects of tipping points are of general interest, including projecting when and/or under what forcing conditions they might occur and determining whether or not they have already been reached. The objective of this paper is to describe the kinds of errors that can occur when deciding whether or not tipping points for selected indicators of ecosystem resilience have been reached (based on crisp decision rules) or the extent to which ecological resilience has decreased (based on fuzzy decision rules). To make the analytical descriptions less abstract, decision errors are described for an ecosystem manager that uses three ecological indicators and their respective tipping points to determine whether or not ecosystem resilience has been compromised.

2. Materials and methods

This section describes the formulation of crisp and fuzzy decision rules for evaluating ecosystem resilience.

2.1. Crisp decision rules

Crisp decision rules are described in terms of four cases. The first three cases apply when there is only indicator, the indicator is negative (i.e., more of the indicator threatens ecological resilience, such as loss of biodiversity), and there are single or multiple measurements or observations for the indicator. Similar rules can be specified for a positive indicator (i.e., less of the indicator threatens ecological resilience, such as less suitable habitat for a keystone species). The fourth case is applicable when there are multiple indicators and multiple measurements per indicator.

The four cases are described using the following notation:

x_{mi} = measured value of indicator i;

x_{ui} = unknown true value of indicator i;

T_{si} = established tipping point for indicator i; and

T_{ui} = unknown true tipping point for indicator i.

2.1.1. Case 1

In the first case, the value of x_{mi} is measured with error ($x_{mi} \neq x_{ui}$) and established and true tipping points are the same ($T_{si} = T_{ui}$). Two subcases of case 1 are considered: (1) case 1a for which there is only one measurement or observation for x_{mi}; and (2) case 1b for which there are multiple measurements or observations for x_{mi}.

In case 1a, ecosystem resilience with respect to x_{mi} is evaluated using the following crisp decision rule: resilience is (or is not) compromised when $x_{mi\,>}\ T_{si}$ (or $x_{mi} \leq T_{si}$).

In case 1b, decisions about ecosystem resilience with respect to x_{mi} are made using the following crisp decision rule: ecosystem resilience is (or is not) compromised when $p(x_{mi\,>}\ T_{si}) > \alpha_i$ (or $p(x_{mi\,>}\ T_{si}) \leq \alpha_i$). $p(x_{mi\,>}\ T_{si})$ is determined using the best–fitting probability distribution for the sample values of x_{mi}. α_i is the reliability level for the exceedance probabilities (i.e., $p(x_{mi\,>}\ T_{si})$), where $0 \leq \alpha_i \leq 1$. The more (or less) serious the negative consequences of exceeding the tipping point for x_{mi}, the lower (or higher) the reliability level. Given a sample probability distribution for x_{mi} and a value of T_{si}, the smaller (or larger) the value of α_i, the greater (or lessor) the likelihood of deciding that ecosystem resilience has been compromised.

2.1.2. Case 2

In the second case, x_{mi} is measured without error ($x_{mi} = x_{ui}$) and the established and true tipping points are different ($T_{si} \neq T_{ui}$). Two subcases of case 2 are considered: (1) case 2a for which there is only one measurement for x_{mi}; and (2) case 2b for which there are multiple measurements for x_{mi}.

In case 2a, ecosystem resilience with respect to x_{mi} is evaluated using the following crisp decision rule: resilience is (or is not) compromised when $x_{mi\,>}\ T_{si}$ (or $x_{mi} \leq T_{si}$). In case 2b, decisions about ecosystem resilience are based on the same kind of crisp decision rule as used in case 1b.

2.1.3. Case 3

In the third case, indicator values are measured with error and the established and true tipping points for indicators are different. In this case, the likelihood of decision errors is determined by comparing the decision outcomes based on the following equations:

$$p(x_{im>}T_{si}) < \alpha_i$$

$$p(x_{iu} > T_{ui}) < \alpha_i$$

2.1.4. Case 4

Case 4 consists of two subcases (i.e., 4a and 4b). In case 4a, there are multiple indicators and tipping points, and one observation per indicator. In case 4a, the manager identifies which measured indicators exceed their respective tipping points for negative indicators or fall below their respective tipping points for positive indicators. A crisp decision rule is then created that specifies how many indicators must reach their respective tipping points before ecosystem resilience is considered to be compromised. A possible decision rule with four indicators is that ecosystem resilience has been compromised if three or four indicators have reached their respective tipping points. A limitation of this decision rule that it assumes indicators are equally important in terms of evaluating whether or not ecosystem resilience has been compromised.

In case 4b, the value of a composite index of the distances between exceedance probabilities and their respective reliability levels (i.e., $p(x_{im\,>}\ T_{si}) - \alpha_i$) is used to decide whether or not ecosystem resilience has been compromised. The composite index is:

$$D = \mathrm{D}(X_A, T_A) - \mathrm{D}(X_B, T_B)$$

where:

$\mathrm{D}(X_A, T_A)$ = Euclidean distance between exceedance probabilities and their respective reliability levels for indicators with respect to which resilience has not been compromised (i.e., $p(x_{im\,>}\ T_{si}) < \alpha_i$ for negative indicators and $p(x_{jm\,<}\ T_{sj}) < \alpha_j$ for positive indicators); and

$D(X_B, T_B)$ = Euclidean distance between exceedance probabilities and their respective reliability levels for indicators with respect to which resilience has been compromised (i.e., $p(x_{im\,>}\ T_{si}) \geq \alpha_i$ for negative indicators and $p(x_{jm\,<}\ T_{sj}) \geq \alpha_j$ for positive indicators).

Calculation of $\mathrm{D}(X_A, T_A)$ requires the manager to assign weights to the indicators such that the sum of the weights equals one. Unlike