Ecological Informatics 41 (2017) 74–90

Contents lists available at ScienceDirect

Ecological Informatics

journal homepage: www.elsevier.com/locate/ecolinf

A structural equation modeling approach for formalizing and evaluating ecological integrity in terrestrial ecosystems

Franz Mora

Sistema de Información Espacial para el Soporte de Decisiones sobre Impactos a la Biodiversidad (SIESDIB), Comisión Nacional para el Uso y Conservación de la Biodiversidad (CONABIO), Liga Periférico - Insurgentes Sur, Núm. 4903, Col. Parques del Pedregal, Delegación Tlalpan, 14010 Ciudad de México, Mexico

A R T I C L E I N F O

Keywords:
Ecological integrity
Spatial indicators
GIS
SEMs
Predator-prey interactions
Apex predators

A B S T R A C T

Ecological integrity is a functional property that integrates habitat functions and species information for maintaining key ecological interactions in predator-prey systems. As a functional property, ecological integrity can be modeled as a latent concept from observable spatial attributes that measure the ecosystem's capacity to provide suitable habitat conditions for apex predators. Ecological integrity is a tri-dimensional concept that stems from “stable”, “concurrent” and “intact” conditions. A theoretical framework and a methodology is presented here for modeling ecological integrity from observable attributes (as GIS layers) to obtain a spatial representation of the integrity condition. From a theoretical framework, the ecological integrity concept is obtained with a structural equation modeling approach, where several other latent variables are obtained for characterizing a hierarchical network of spatial information. Later on, these observable attributes, and several latent modeled variables are translated into sources of geographic information that can be used to monitor changes in the natural remnant areas due to human impacts. When examining the direct, indirect and total effects of habitat loss and fragmentation on ecological integrity, spatial intactness (e.g., the amount of remnant habitat and connectivity) and stability (resistance in the interaction network and mobile links) are the attributes more affected by the pathway effects. The balance of the formative parameters obtained for the model supports the idea that ecosystems that have a high degree of integrity should maintain a high level of stability, self-organization and naturalness. These attributes are achieved when spatial habitat intactness and species interactions are maintained.

1. Introduction

The human transformation of natural landscapes is still the major contributing factor for loss and degradation of the complexity and condition of ecosystems, by promoting habitat fragmentation and species loss (Ewers et al., 2010; Jantz et al., 2015; Sih et al., 2000). As historical natural ecosystems become highly impacted by human activities, the capacity for recovering their self-organization and self-regulation towards stable conditions after impacts is greatly affected by the ecological integrity of surrounding natural areas. Due to habitat loss effects, changes in community assemblages and composition lead to a subsequent loss of species interactions, particularly disrupting functions at the top of ecological hierarchy (Valiente-Banuet et al., 2015). However, large carnivores, as top predators, are necessary for maintaining biodiversity and ecosystem function (Ripple et al., 2014). Habitat loss is the main process reducing ecological integrity for top predators by modifying key ecological processes (Haberl et al., 2007) and by producing negative effects on their habitats (Ripple et al., 2014; Theobald, 2013).

Ecological integrity is a key concept in natural resource management (Brown and Williams, 2016; Thompson, 1999; Tierney et al., 2009). With landscape transformation targeting remnant natural areas, ecological integrity is the primary feature that is highly at risk due to human impacts. Integrity in ecological systems has been defined as “the capacity of the ecosystem to support and maintain a balanced, integrated, adaptive biological system having the full range of elements and processes expected in the natural habitat of a region” (Angermeier and Karr, 1994; Karr, 1990; Parrish et al., 2003). The lack of ecological integrity in human transformed landscapes is directly linked to changes in ecosystem's structure and function, which result in degradation processes that lead to biodiversity loss (Millenium Ecosystem Assessment, 2005a,b).

As a theoretical concept, ecological integrity is a latent, complex variable that stems from the complexity of ecological processes and from mechanisms that sustain ecological interactions resulting from the complexity of biodiversity (Farnsworth et al., 2012; Jax, 2010). Therefore, ecological integrity is a characteristic that emerges from the interaction of several ecological processes. These provide ecosystems

E-mail address: fmora@conabio.gob.mx.

http://dx.doi.org/10.1016/j.ecoinf.2017.05.002
Received 12 October 2016; Received in revised form 4 May 2017; Accepted 6 May 2017
Available online 07 May 2017
1574-9541/

with the ability to self-organize and maintain stability while remaining natural (without human influence). As observed throughout emergent properties, integrity is best described by characteristics associated with concepts of sustainability, naturalness, stability (Andreasen et al., 2001) and self-organization (Jax, 2010). For that reason, ecological integrity evaluations are increasingly being used for guiding and organizing ecological monitoring programs (Wurtzebach and Schultz, 2016).

The main goal of this research is to present a set of concepts translated into spatial information that help to formalize the concept of ecological integrity for monitoring purposes. With a practical definition of ecological integrity, a hierarchical analysis framework can be developed using spatial information as primary source for decision making (Ferretti and Pomarico, 2013; Imam et al., 2011; Lin et al., 2009). Therefore, the ecological integrity concept is used here a main directive to define a set of spatial indicators (manifest and latent) that support an analysis that help to characterize the potential of remnant natural landscapes to sustain predator-prey interactions in Mexico. As observable indicators of ecological integrity, the spatial indicators developed here serve as a way to summarize and describe the status of predator and prey species and their habitat. They can serve to diagnose the current habitat conditions, and to monitor significant changes that jeopardize the sustainability of viable populations. Spatial indicators of ecological integrity also serve to create a structure in decision making, based on hierarchies and networks of relevant information (Saaty and Shih, 2009).

1.1. Ecological integrity and spatial decision support systems

A spatial decision support system (SDSS) for top predators and their habitat conservation in the remnant landscape of Mexico is the goal for ecological integrity evaluations. A SDSS based on ecological integrity must combine spatial information, multicriteria decision analysis and optimizing models (Rushton, 2001), assuming that transformation of the natural landscape in the form of habitat loss and fragmentation directly affects the attributes and processes associated with naturalness, stability and self-organization in ecosystems. Ecological integrity becomes a practical concept for implementing a SDSS when the elements that shape the self-identity characteristics of the concept are clearly defined, and has a practical meaning when the concept of integrity is linked to human impacts.

In order to develop a practical definition for a SDSS, the ecological integrity concept is first associated with a set of emergent properties, which are notions derived from the knowledge gained from analyses of the pattern and processes of biodiversity (Geneletti, 2008). Ecological integrity is considered here as a functional property that integrates habitat functions and the spatial requirements for species, that maintain key ecological interactions in predator-prey systems. The main concept is derived from a collection of several sub-concepts which formalize the procedure of data mining and knowledge discovery when exploring direct and indirect relationships among concepts and observed variables represented as geographic indicators. Then, a practical definition of ecological integrity is primarily sustained by spatial information, and a theoretical model help to establish a plausible ecological hypothesis on how ecosystems are impacted by human transformation. In addition, ecological integrity concepts are connected and interact with other information levels, forming an entire ecological hierarchy. Therefore, both vertical and horizontal connection among concepts and manifest variables come into play to define emergent properties (Jorgensen and Nielsen, 2013) that can be used in an ecological hierarchy framework for decision making (Lin et al., 2009).

Once an operational definition is available, an evaluation and monitoring system of the integrity of predator-prey interactions and their habitat can be implemented. The evaluation system is constructed around spatial indicators that measure changes in ecological integrity attributes by monitoring landscape changes, and by describing the effects that habitat loss and fragmentation may exert on ecosystem properties that sustain viable populations of apex predators. Spatial information regarding complex interaction of apex predators and their habitat, along with mapped effects of habitat loss and fragmentation on mammalian apex predators is used as a surrogate for ecological integrity manifestations.

For a practical definition, structural equation modeling (SEM) is used here as the main methodological approach for describing and monitoring ecological integrity. SEM in natural systems is a methodological framework that has been previously used to analyze latent variables in complex relationships (Grace et al., 2010; Grace and Bollen, 2008). As a latent variable, ecological integrity has been modeled with SEM using habitat functions (Capmourteres and Anand, 2016); for evaluating agricultural impacts on aquatic biological integrity and health (Riseng et al., 2011; Sanchez et al., 2015); for evaluating habitat loss effects on ecological processes (Altamirano et al., 2016); soil ecology mapping (Angelini et al., 2016; Eisenhauer et al., 2015) patterns of species occurrence (Joseph et al., 2015); and for deriving environmental indicators for conservation strategies (Santibáñez-Andrade et al., 2015). Here, an approach suitable for a spatial analysis context is developed based on SEM. The methods rely on a framework that integrates the use of SEM and geographic information systems (GIS) as a way to model ecological integrity as a spatial latent variable. In addition, the SEM provides a framework for implementing an analysis to confirm the presence of latent variables from the interaction among spatial indicators of ecological integrity. The additional information derived from SEM is also useful for evaluation purposes when emerges from the theory that supports the formalization of the proposed ecological integrity concept. Later on, the set of spatial information derived from the modeling framework can be integrated into the spatial decision support system (SDSS) where is presented as a tool for monitoring changes in the ecological integrity condition for the remnant natural landscape.

2. Methods

The methods used for building an ecological integrity model include: (a) spatial analysis to produce several spatial indicators, and (b) structural equation modeling for establishing a hypothetical link between structure and function in ecosystems, based on the interaction of the spatial variables used for defining several concepts. The indicators used as manifest variables of ecological integrity are obtained via cartographic models and spatial analysis. Later on, SEM is conducted with several diagnostic procedures that are used to produce and discuss latent variables as measures of ecological integrity. Finally, confirmatory analysis is implemented and supported by the implementation of a SEM based on ecological processes.

Furthermore, SEM estimates the values of latent variables that are not observable, which are often referred as hypothesis variables. The latent variables and their relationships provide additional information that is used also as indicators of ecological integrity. This is useful for exploring the quantitative spatial representation of ecological integrity, especially when it is represented using qualitative reasoning (Nuttle et al., 2009). Here, ecological knowledge regarding integrity is directly derived from data describing information variables, which influence and depend on the hypothesis variables. Therefore, the main goal for the SEM framework is to obtain a theoretically based and statistically valid model for ecological integrity.

2.1. Spatial analysis for manifest variables

The analysis framework for ecological integrity is theoretically based on species interaction information and evaluates the integrity of a landscape based on the interplay of predator-prey systems (or the lack thereof). The interaction networks (in this case, predator-prey interactions for 239 mammal species) are evaluated for all extant top predators