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Nation-wide indicators of ecological integrity in Mexico: The status of mammalian apex-predators and their habitat

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ABSTRACT

Ecological indicators that evaluate the status and trends of mammalian apex predators are necessary for monitoring the ecological integrity of landscapes. Several nation-wide spatial indicators that describe the status of apex predators after habitat transformation have been developed for México. These spatial indicators show the condition of the remnant natural landscape for maintaining the complexity of predator-prey interactions and habitat selection and use. The indicators were obtained using the concept of ecological integrity, that characterize the landscape based upon manifest and latent variables of naturalness, stability and self-organization, according with the measures of spatial distribution of species and natural habitat. When the current status is evaluated for individual species of apex predators, all species showed less than 50% of their distribution areas with a high degree of ecological integrity. Neotropical predators (such as jaguars and ocelots) are more threatened by the transformation of natural habitat, than their counterparts in Nearctic regions (e.g., bears, cougars, bobcats, and coyotes), which showed nonetheless, a high amount of their distribution areas with a high proportion of degraded habitat. The indicators allowed evaluating the status of still extant top predators in the landscape and their habitat condition within major ecoregions in the country.

1. Introduction

An ecological evaluation of the integrity condition in remnant habitats is necessary for long-term conservation goals and sustainability in areas that support viable populations of predators in natural conditions. Nowadays, the human transformation of natural landscapes is the main threat for sustaining the prevalence of apex predators worldwide due to their high dependency of natural conditions (Estes et al., 2011; Hoffmann et al., 2010; Ripple et al., 2014). With the increasing loss of natural areas, ecological integrity is a pre-requisite for maintaining a collection of ecosystems that support a community of organisms with similar species composition and functional organization as found in adjacent natural systems (Parrish et al., 2003). Therefore, adjacent natural areas might play a significant role in restoring ecological conditions, particularly trophic interactions for degraded and transformed surrounding areas. However, ecological indicators that evaluate the integrity of the ecosystem are limited by the information available on their structure and function (Dale and Beyeler, 2001). For that reason, new approaches for developing spatial information derived from existent data about the status and trends of species and their habitat are necessary for making ecological integrity evaluations.

From a theoretical framework, ecological integrity (EI) in the landscape of apex predators can only be observed when some properties, associated with self-regulation, stability and naturalness are manifested (Mora, 2017). Then a set of observable characteristics (associated with species interaction and the condition of their habitat) can be used to derive latent properties associated with ecological integrity. Therefore, EI 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. Unfortunately, information on ecological integrity can only be indirectly measured; and therefore, basic data describing manifestations of ecological integrity in ecosystems are seldom available. As an alternative, spatial information describing the current patterns of species distributions can be used as manifest information about species, their potential interactions and their habitat condition. Nowadays, new approaches for deriving multi-species geographic information are currently available which are often associated with biodiversity information (Carignan and Villard, 2002; Tierney et al., 2009).

In recent years, spatial biodiversity information based on these new

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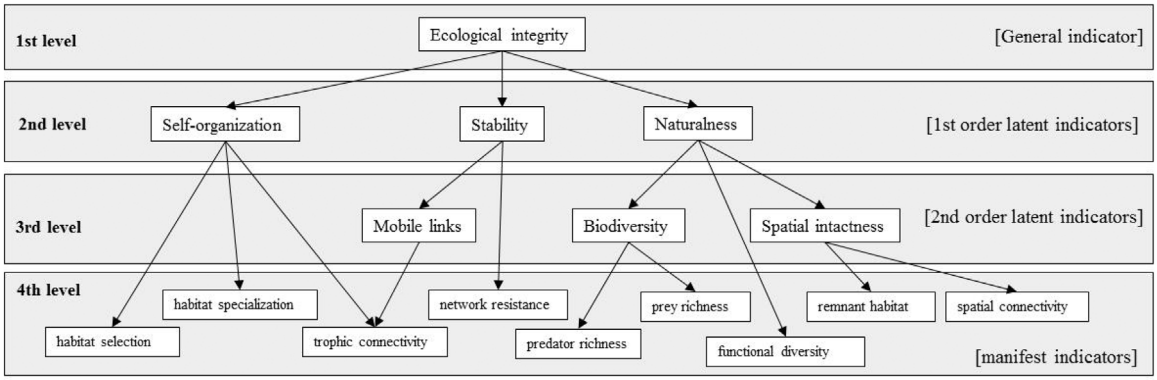

Fig. 1. The ecological integrity hierarchy framework for evaluating the condition in natural ecosystems based on landscape characteristics that sustain predator-prey interactions.

approaches has become increasingly available. The information derived from Species Distribution Models (SDMs) is particularly suitable for ecological integrity analysis. The SDMs integrate the information contained in scientific collections and sampling efforts with expert knowledge and modeling techniques to better represent, according to the best knowledge and data available, the patterns of biodiversity. The SDMs are, to date, one of the most important sources of spatial species distribution information, which is currently used to indirectly analyze the role of species in maintaining ecological processes. Usually, the identity and role of species within ecosystems are used as primary sources of information in ecological modeling efforts because they can be measured directly by recording species' presence and evaluating their abiotic and biotic interactions. Furthermore, the role of species in maintaining ecosystem function requires adequate evaluation and monitoring of key components that are then used as information variables. At present, geographic distribution patterns of species depicted by SDMs are widely used to infer species' composition within ecosystems (Austin, 2007; Cord et al., 2014; Dunstan et al., 2011; Guisan et al., 2006). Therefore, several SDMs can be used as information variables that can describe the ecological integrity condition of processes of interest and derived from species interactions, and, in addition, they can also identify the role of biodiversity in contributing to ecological integrity.

In addition to the current spatial data availability, a collection of artificial intelligence methods are available for building and formalizing ecological concepts associated with ecological integrity that potentially serve as ecological indicators. For example, methods such as structural equation models (SEM) provide a framework that allows statistical testing regarding whether complex notions or concepts can be "*confirmed*" by ecological observations. Then, the ecological integrity concept can be successfully obtained from manifestations of structural and functional attributes using SEM. Therefore, SEM involves more than a way to simply estimate model parameters. It provides a methodological approach in which theoretical ideas are translated into a model for evaluation (or *model specification*) and are then tested for mathematical validity. Additionally, SEM have allowed estimating latent variables that can be then spatially represented as spatial indicators within a GIS for analysis and evaluation (Mora, 2017). Both manifest and latent indicators can be then used for decision making within a spatial decision support system.

The purpose of this research is to show practical applications of stacked-SDMs as manifest variables, or observable landscape characteristics indicating ecological integrity, and later on, their potential for deriving latent spatial indicators of emergent ecosystem properties associated with the concept of ecological integrity. Spatial indicators of ecological integrity are derived from analysis techniques that help formalize the ecological concept within a quantitative framework. It also aims to define a set of observable measures that support a latent analysis, and define several sources of information that can be used to build the concept of ecological integrity within a hierarchical analysis framework. All manifest and latent spatial information is then used to characterize the potential of natural landscapes to support ecological integrity in maintaining biotic and abiotic apex predators' interactions among species and their habitats.

As manifest 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 current habitat conditions, and to monitor significant changes that jeopardize the sustainability of viable populations. Latent indicators serve to monitor the landscape condition to sustain ecological mechanisms that promote the prevalence of species in the long run, and to identify the trends of habitat modification due to human impacts. As a combination, both sources of information (manifest and latent) may be useful for implementing plans towards the conservation and use of biodiversity, as well as implementing land-use plans and programs to sustain viable populations of apex predators.

2. Methods

The overall approach for deriving a set of ecological variables that can be used as indicators of ecosystem integrity is based on an ecological hierarchical network (EHN) as a framework that evaluates changes that occur at several levels in an ecological hierarchy (Fig. 1). The approach includes: (a) the development of spatial indicators that can be used as manifest indicators for ecological integrity as the foundation for the evaluation system; (b) the application of structural equation models (SEM) for deriving a set of latent concepts that build the notion of ecological integrity at two consecutive levels of generalized ecological information (1st and 2nd order latent indicators); and finally, (c) a general indicator that summarizes the integrity in the ecological condition.

Later on, the set of manifest and latent variables are used as properties which characterize the ecological integrity condition of different landscapes and thus, their capability to sustain viable populations of top predators. The set of ecological indicators (latent and manifest) are used as variables to characterize the eco-regions described for Mexico (INEGI, CONABIO, INE. 2007). The evaluation is presented for species (apex predators) and at two scales of geographic evaluation: (a) landscape (nation-wide); and (b) ecoregions.

2.1. Manifest ecological integrity measures as change indicators

Ecological integrity is a complex concept, where some of its emergent properties can be inferred as latent concepts from a hierarchy of manifest (or observed) variables. The emergent properties that the ecological integrity concept conveys are often identified from a reference state or reference dynamics in the ecosystem, and therefore, ecological integrity is essentially an indicator of changing reference