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Anthropogenic impact on habitat connectivity: A multidimensional human footprint index evaluated in a highly biodiverse landscape of Mexico

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ABSTRACT

Evaluating the cumulative effects of the human footprint on landscape connectivity is crucial for implementing policies for the appropriate management and conservation of landscapes. We present an adjusted multidimensional spatial human footprint index (SHFI) to analyze the effects of landscape transformation on the remnant habitat connectivity for 40 terrestrial mammal species representative of the Trans-Mexican Volcanic System in Michoacán ($TMVS_{Mich}$), in western central Mexico. We adjusted the SHFI by adding fragmentation and habitat loss to its original three components: land use intensity, time of human landscape intervention, and biophysical vulnerability. The adjusted SHFI was applied to four scenarios: one grouping all species and three grouping several species by habitat spatial requirements. Using the SHFI as a dispersal resistance surface and applying a circuit theory based approach, we analyzed the effects of cumulative human impact on habitat connectivity in the different scenarios. For evaluating the relationship between habitat loss and connectivity, we applied graph theory-based equivalent connected area (*ECA*) index. Results show over 60% of the $TMVS_{Mich}$ has high SHFI values, considerably lowering current flow for all species. Nevertheless, the effect on connectivity of human impact is higher for species with limited dispersal capacity (100–500 m). Our approach provides a new form of evaluating human impact on habitat connectivity that can be applied to different scales and landscapes. Furthermore, the approach is useful for guiding discussions and implementing future biodiversity conservation initiatives that promote landscape connectivity as an adaptive strategy for climate change.

1. Introduction

The cumulative human footprint on the landscape has reduced the resilience capacity of ecosystems and their provision of goods and environmental services, generating irreversible effects on biodiversity, such as local speciesí extinction (Bennett, 1990; Saunders et al., 1991; Laurance et al., 2008; Pavlacky et al., 2012). The spatial impacts of this process on the landscape have been quantified either by means of the human footprint indexes (HFI) (Sanderson, 2013) or through indexes of naturalness (Theobald, 2010), both providing opposite readings. These methods to measure the influence of human activities on the landscapes have been applied at different levels: at the global level to understand human impact on biomes (Sanderson et al., 2002), at the national level for the spatial evaluation of human influence on ecosystems and natural regions (Etter et al., 2011; González-Abraham et al., 2015), and at the regional level to evaluate the human impact on terrestrial ecoregions (Woolmer et al., 2008; Trombulak et al., 2010). In a recent study, Venter et al. (2016) updated the spatial human footprint index based on Sanderson et al. (2002) and analyzed spatial patterns of change over time in the human footprint between 1993 and 2009, providing the first set of temporally comparable human footprint maps.

In studies on biodiversity conservation, HFIs have been used to evaluate landscape connectivity, based on the assumption that the

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intensity of the human footprint is positively correlated with the landscapes' resistance to dispersal (Baldwin et al., 2010; Alagador et al., 2012; Hand et al., 2014). The disadvantage of parameterizing HFIs as a surface of resistance is that, in general, it assumes that the effect of the human footprint is the same for all focal species, which can result in an overgeneralized representation of human effect on organisms' dispersal. To correct these biases, several approaches have been proposed (Krosby et al., 2015; Alagador et al., 2012), such as considering multiple species and integrating their response to human footprints, while differentiating the spatial distributions of organisms to identify optimal habitat areas that harbor groups of species with similar environmental requirements (i.e., environmentally similar habitats; Alagador et al., 2012). Additionally, the construction of HFIs with finer spatial resolutions (Leu et al., 2008; Woolmer et al., 2008; Theobald, 2010) or an incorporation of additional variables describing human effects over ecological processes (Leu et al., 2008; Etter et al., 2011) also constitute better inputs for connectivity models.

Following the methodology of Sanderson et al. (2002), González-Abraham et al. (2015) developed a human footprint map for Mexico and identified ecological regions having a higher degree of transformation from human activities. They found that areas with high ecological importance and biodiversity, such as the Trans-Mexican Volcanic System (TMVS), presented a high degree of human disturbance. To date, however, few studies in Mexico have evaluated the effect of the human footprint on landscape connectivity (Fuller et al., 2006; Correa Ayram et al., 2014). By integrating the three spatial footprint dimensions: intensity of land use (F_{int}), the time of intervention on the landscape (F_{time}), and biophysical vulnerability (F_{vul}), the model proposed by Etter et al. (2011) provides a more comprehensive approach for addressing the spatial human footprint for applications in conservation planning (Ocampo-Peñuela and Pimm, 2014; Qiu et al., 2015). Etter et al. (2011) defined F_{int} as the degree of modification of habitat determined by resource extraction and predominant land use, including management forms, F_{time} as the time passed since the landscape has been subject to current human activity, and F_{vul} as the degree to which a system suffers damages caused by land use. However, in the context of connectivity, this methodology could be supplemented by enhancing the incorporation variables of fragmentation and habitat loss and making them explicit either for individual species or from a multi-species approach (Brodie et al., 2015; Rayfield et al., 2015).

Our paper evaluates the effect of using human footprint measures on the assessment of habitat connectivity in the Trans-Mexican Volcanic System in Michoacán ($TMVS_{Mich}$) in western central Mexico. We apply the multidimensional HFI (Etter et al., 2011) modified by the addition of data about habitat loss and fragmentation. We integrated the information on human effects on individual species (single-species approach) and on multi-species scenarios in order to analyze anthropic impacts on groups of species with different spatial requirements.

2. Material and methods

2.1. Study area

The TMVS is a volcanic chain extending across central Mexico from the Pacific Ocean to the Gulf of Mexico (Ferrari et al., 2012). The TMVS covers an area of 160,000 km^2 and is recognized as the most heterogeneous biogeographic province of Mexico in terms of its geological and biotic history, reflected by its richness in biodiversity and endemisms, by being a speciation center (Fa and Morales, 1991; Ramamoorthy et al., 1998) and by being a transitional area between the Nearctic and the Neotropical biogeographical regions (Gámez et al., 2012). Sánchez-Cordero et al. (2005) estimated that 70% of the original habitat in the TMVS has been transformed and presents a high risk of extinction of endemic mammals because of the threats represented by land use and land cover changes, in particular from forest ecosystems to agriculture and urban areas.

Our study encompasses the central portion of the TMVS including the northern part of the state of Michoacán with an approximate area of 28,100 km^2 ($TMVS_{Mich}$; Fig. 1). It covers an altitudinal range from 1000 to 3800 m and includes the following physiographic sub-provinces: Chapala, bajío Guanajuatense, bajío Michoacano, llanuras y sierras de Querétaro e Hidalgo, cordillera Costera del sur, Neovolcánica Tarasca, depresión del Balsas, Mil Cumbres, and depresión del −Tepalcatepec. Anthropic land use and land cover occupy 70% of the $TMVS_{Mich}$, suggesting a strong influence of human footprint on connectivity. Natural land covers are mostly of temperate forests (conifer, mixed conifer and oak forests, and localized mountain cloud forests) and, to a lesser extent, of low deciduous tropical forest and aquatic vegetation (INEGI, 2013). Gámez et al. (2012) and Escalante et al. (2007) consider the central TMVS as a highly biodiverse landscape with an average richness of 105 species of terrestrial mammals. Eight natural protected areas are included within the $TMVS_{Mich}$ (Fig. 1), mostly distributed in the mountainous portions, but covering a meager 2.4% of the study area (Bezaury-Creel et al., 2009).

2.2. Selection of focal species and habitat modeling

Based on a previous study of connectivity in the TMVS (Fuller et al., 2006), we initially selected 99 species of terrestrial mammals. We then compiled occurrence data for each species from the databases of the *Global Biodiversity Information Facility* (http://www.gbif.org/), CONABIO (http://www.conabio.gob.mx/) and from the literature (e.g., Orduña Villaseñor, 2008; Chávez-León and Zaragoza Rivera, 2009; Charre-Medellín et al., 2015), choosing only the points within the $TMVS_{Mich}$. We applied a second filter to eliminate duplicate and overlapping points and selected those species that had at least 10 occurrence points (Pearson et al., 2007). The depurated list resulting from this process included 40 species of terrestrial mammals within the $TMVS_{Mich}$ (Table S1). For each chosen species, we modeled its potential habitat with a 30 m spatial resolution using the software MaxEnt 3.3.3 (Phillips et al., 2006) and updated climatic layers for Mexico as independent variables (Appendix 2, Table S2) (Cuervo-Robayo et al., 2014). We used the *10 percentile training presence logistic threshold* applied by Pearson et al. (2007) and Stiels et al. (2011) to identify the optimal potential habitat, determining which pixel is suitable if its value is higher than the tenth percentile of probability of presence. All pixels above that threshold were preliminarily reclassified as potential habitat. Subsequently, following the methodology of Fuller et al. (2006), we generated actual or remnant habitat by overlapping the natural land covers: oak forest, oyamel forest, pine forest, pine-oak forest, subtropical shrubland and deciduous and semidecidous forest (Fig. 1; INEGI, 2013) with the models of potential habitat, excluding transformed areas. These actual remnant habitat patches of each species were used for the analysis of connectivity (see Section 2.4).

2.3. Adaptation of SHFI and description of data sources

2.3.1. Description of the selected SHFI and adjustment in the context of connectivity

We used the spatial human footprint index (SHFI) proposed by Etter et al. (2011) as a spatial proxy for evaluating the human impact on connectivity. In order to better take into account the effects of the human footprint for the connectivity analysis, we added a new component expressing habitat loss and fragmentation (F_{frag}), to the original index. The incorporation of F_{frag} to the SHFI requires