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The use of ecological integrity indicators within the natural capital index framework: The ecological and economic value of the remnant natural capital of México

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ABSTRACT

In this paper, the ecological integrity hierarchy framework (EIHF) and the natural capital index framework (NCI) are integrated as decision-making tools for evaluating the natural capital of Mexico. Two hierarchy-levels of ecological integrity indicators are used to estimate the quality and quantity of the natural capital, the amount of ecological degradation and ecological sustainability. After human transformation, the extent still considered as "natural" in the country is ~67%; while the amount of human transformed areas is ~33%, which gives a total estimate of NCI = 0.334; i.e., only ~33.4% of the national capital remains available, while ~33% is ecologically degraded. Furthermore, the critical natural capital; i.e., the legacy for future generations that remains in the country is only ~12%. The total estimated value of the current natural capital in Mexico is ~$457.1 billion/yr, which is ~435 times greater than the national GDP ($1.051 billion in 2010). The cost of maintaining the degradation of the natural capital is ~$144.6 billion/yr (~138 times greater than national GDP in 2010). The potential value of the natural capital after restoration would be ~$602 billion/yr. Valuing the natural capital can be helpful for strategic environmental evaluations and useful for spatial decision support systems that evaluate natural capital as a decision-making tool.

1. Introduction

In a time of unprecedented global change, Mexico is no exception to the transformation of natural landscapes, which has caused major ecosystem degradation and biodiversity loss. For that reason, sustainability evaluations at national-level are necessary for a '*sustainable development*' that could abate the negative impacts associated with global change. Therefore, the evaluation of the condition of remnant ecosystems has become crucial for evaluating the current biodiversity crisis. Thus, the use of reliable biodiversity indicators is one of the major goals of the Convention of Biological Diversity, in order to describe the state of ecosystems in a factual and responsive manner to set conservation goals (Dobson, 2005; Dobson et al., 2011). For that reason, biodiversity indicators have gone from simple metrics that measure the diversity of organisms, towards more comprehensive monitoring measures that indicate the state of ecosystems (Capmourteres & Anand, 2016; Cowell, 1998; Rempel et al., 2016; Roche & Campagne, 2017). Then, an integrative approach is required for aggregating several biodiversity indexes, which in turn can be used for giving an overall quantitative description of the general ecosystem state at local (site) and regional (landscape) scales, which support sustainability evaluations for the remaining natural capital (Brand, 2008; Ekins, 2003; Fenichel, Abbott, Fenichel, & Abbott, 2014; Reza & Abdullah, 2011).

As evaluation tools, ecological integrity indicators (EII) offer a

Abbreviations: Ai, total area for an ecological unit *i*; CBD, Convention of Biological Diversity; CNC, Critical Natural Capital; EA, Ecosystem Quantity (Area); EA_{deg}, Ecosystem Quantity (Area) degraded; EC_i, ecological condition, as the sum of EIC_i, EDI_i, and HTI_i for an ecological unit *i*; EDI_i, ecological degradation index, for an ecological unit *i*, [$EDI_i = 1 - (HT_i + EIC_i)$]; EIA, environmental impact assessment; $EIAN_i$, the average EI of all natural remnant areas for an ecological unit *i*; EIC_i, ecological integrity condition, for an ecological unit *i*; EIC_p, potential EIC_i for an ecological unit *i*, ($EIC_p = 1 - HTI_i$); EIHF, Ecological Integrity Hierarchical Framework; EII, ecological integrity indicators; EQ, ecosystem quality; EQ_{deg}, ecosystem quality degraded; EV, economic value; GDP, gross domestic product; GIS, geographical information systems; HTI_i, human transformation index, for an ecological unit *i*; NC, natural capital; NCI, natural capital index; NCI_{deg}, degraded natural capital index; NCI_{degi}, degraded natural capital index for an ecological unit *i*; NCIF, natural capital index framework; PES, payment of ecosystem services; UAOT, Environmental Units of Ecological Ordination (Spanish acronym for Unidades Ambientales del Ordenamiento Territorial); SEA, Strategic Environmental Assessment; TAi, transformed area for an ecological unit *i*

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holistic assessment of ecosystem´s state or condition by integrating the role of biodiversity in maintaining the self-regulatory, self-organizing and stabilizing properties of ecological process (Brown & Williams, 2016; Jax, 2010; Kandziora, Burkhard, & Müller, 2013; Medeiros & Torezan, 2013). As related with ecological integrity, *ecosystem condition* refers to the capacity to maintain fundamental ecological functions and sustainably deliver ecosystem services and resources (Roche & Campagne, 2017). As ecological evaluation indexes, EII evaluate the ecosystem´s current condition, the extent of degradation, and the amount of landscape transformed by human activities (Mora, 2017b), based upon direct and indirect measures of self-organization, stability and naturalness. Therefore, ecological integrity can be used as the baseline for evaluating human impacts when the remaining "*quality*" of ecosystems is necessary to perform a complete evaluation that requires policy decisions (Reichert, Langhans, Lienert, & Schuwirth, 2015; Tremblay, Hester, Mcleod, & Huot, 2004).

On the other hand, the natural capital index framework is an aggregation tool that plays a crucial role in integrating biodiversity indicators in several policy contexts. Natural capital relates to ecological integrity when any stock of natural resources or environmental assets that provides a flow of useful goods or services, now and in the future, becomes critical for sustainable use (Brand, 2008; Groot, De, Perk, Van Der, & Chiesura, 2003). In this context, Critical Natural Capital (CNC) has been defined as "that portion of natural capital which enables important ecological functions, in addition to the *condition* that for any particular CNC, and the associated function" "…there is no substitute type of capital natural or man-made, which would enable the same function, i.e., CNC is non-substitutable in respect of the function in question" (Ekins, 2003). From an ecological point of view, critical natural capital is then that part of the natural environment that ought to be maintained, if key ecological processes should prevail for future generations (Brand, 2008; Groot et al., 2003).

In a decision-making context, the natural capital index (NCI) can be a flexible, scale-free indicator, that when used with the ecological integrity concept, can offer a comprehensive view of the natural capital. Furthermore, the NCI framework can provide a tool for spatial characterization at several scales based on a thematic disaggregation of evaluation results, and using different spatial regional models. Previously, the natural capital has been estimated as the product of remaining ecosystem size (quantity) and its quality (Czúcz et al., 2012). Then, a qualification of the remaining status of ecosystems becomes a critical component of the NCI evaluation. Within this context, ecological integrity can be used as the most comprehensive factor for evaluating the remaining quality of the ecosystem after human impacts. Therefore, the NCI can be obtained from an ecological integrity evaluation, offering a quantitative measure of ecosystem quality as an aggregation tool using emergent properties of ecosystems.

Additionally, the notion of natural capital conveys inherently a need for knowing its value. Ecological value is measured as health or *integrity* of functioning ecosystems (de Groot, Alkemade, Braat, Hein, & Willemen, 2010; Roche & Campagne, 2017). Conservation ecology and ecosystem management address *integrity* through the prism of natural dynamics, in which the definition is more process-focused than state-focused. Ecosystem integrity has basically two components: *integrity* — 'the state of being unimpaired, sound' and 'the quality or condition of being whole or complete' and *ecosystem* — the system of interacting physico-chemical environment and wildlife (Czech, 2004; Tierney, Faber-Langendoen, Mitchell, Shriver, & Gibbs, 2009). Economic value, on the other hand, requires the quantification of use and non-use values for both *ecosystem* and *condition,* expressed as monetary units (Costanza et al., 2014; de Groot et al., 2010). Nowadays, there exists a growing necessity for valuing the natural capital since it can be included in the national accounting and allows for the exploration of its role in sustainability and social welfare (Azqueta & Sotelsek, 2007). Then, the Natural Capital value can be expressed as economic value where several tipping points for sustainability can be identified (Costanza et al., 2014; Costanza, Daly, Biology, Mar, & Daly, 1992, 1998; Ullsten et al., 2004). For valuation purposes, ecosystems´ condition plays a role in the evaluation of natural capital since it conveys a spatial dimension of sustainability (Blaschke, 2006; Fath, 2015). It is necessary then, to analyze the spatial dimension of ecological resources; i.e., based upon their quality, quantity and value, for establishing decision-making goals.

The purpose of this paper is to show how the ecological integrity concept can be used within the natural capital index framework for evaluating (ecologically and economically) remnant natural resources after human transformation in Mexico. As three spatial evaluation models are used, the consistency of obtaining evaluation results is tested for different ways to conceptualize the natural capital, for ecological, economic, management and administrative purposes. As a measure of the remnant quality, ecological integrity indicators are used here as a qualifying characteristic of several landscape units, defined by each spatial model of evaluation (eco-regions, environmental management units, and political administrative units). Then, the NCI framework can evaluate the contribution of each landscape unit to the overall value of the natural capital of Mexico, setting priorities for conservation and management goals.

2. Methods

2.1. The geographic information sources for evaluating the natural capital index in Mexico

Several ecological integrity indicators have been previously obtained for Mexico, which are integrated as spatial hierarchical measures, and can be used as surrogate measures of *ecosystem quality* at different levels of ecological complexity (for a description of both, latent and observed hierarchical measures see Annex Tables A1 and A2) (Mora, 2017b). This set of ecological indicators embody an Ecological Integrity Hierarchical Framework (EIHF) that evaluate the remnant condition of ecosystems after human transformation. From this framework, several spatial sources of information can be used for integrating both, the EIHF and the Natural Capital Index (NCI) frameworks, and for assisting a quantitative evaluation of the critical natural capital in a region (Fig. 1). Here, high order indicators of ecological integrity, along with a spatial eco-regions model are used to evaluate the remaining natural capital after human transformation. At the top of the EIHF hierarchy, an overall ecological integrity measure indicates the general state (quality) of the ecosystems, which evaluates the *condition* resulting from landscape transformation, and is summarized from six manifest (observable) attributes of ecosystem functioning and structure (Mora, 2017a).

At the top of the hierarchy, ecological integrity is the first and general indicator of the condition of remnant ecosystems; i.e., the ecosystem`s capacity to maintain predator-prey interactions as a key component of ecological processes that provide an evolutionary legacy. It also serves to establish a comparison point among landscape units, and helps to identify the amount of remaining capital available. Furthermore, the *ecosystem condition* expressed as ecological integrity can be disaggregated into three forms of ecosystem quality measured as three emergent properties; i.e., self-organization, stability and naturalness. Then, by losing of some of the remaining qualities of ecosystems, the interaction among the properties at the 2nd level of the EIHF defines the magnitude in which ecosystems have been degraded (while not completely losing all ecological properties) by human transformation, which can in turn, be subjected to restoration efforts and, consequently, subject to recovery into the natural capital.

All geographic information used here has been integrated into a spatial decision support system, with a national coverage, which uses raster GIS information at 1 km^2 resolution (Mora, 2017a, 2017b). Three spatial evaluation models (or regions) allowed to calculate the amount of remnant natural ecosystems; i.e., ecosystem quantity. Thus, the amount (area in km^2) is directly estimated from the spatial model

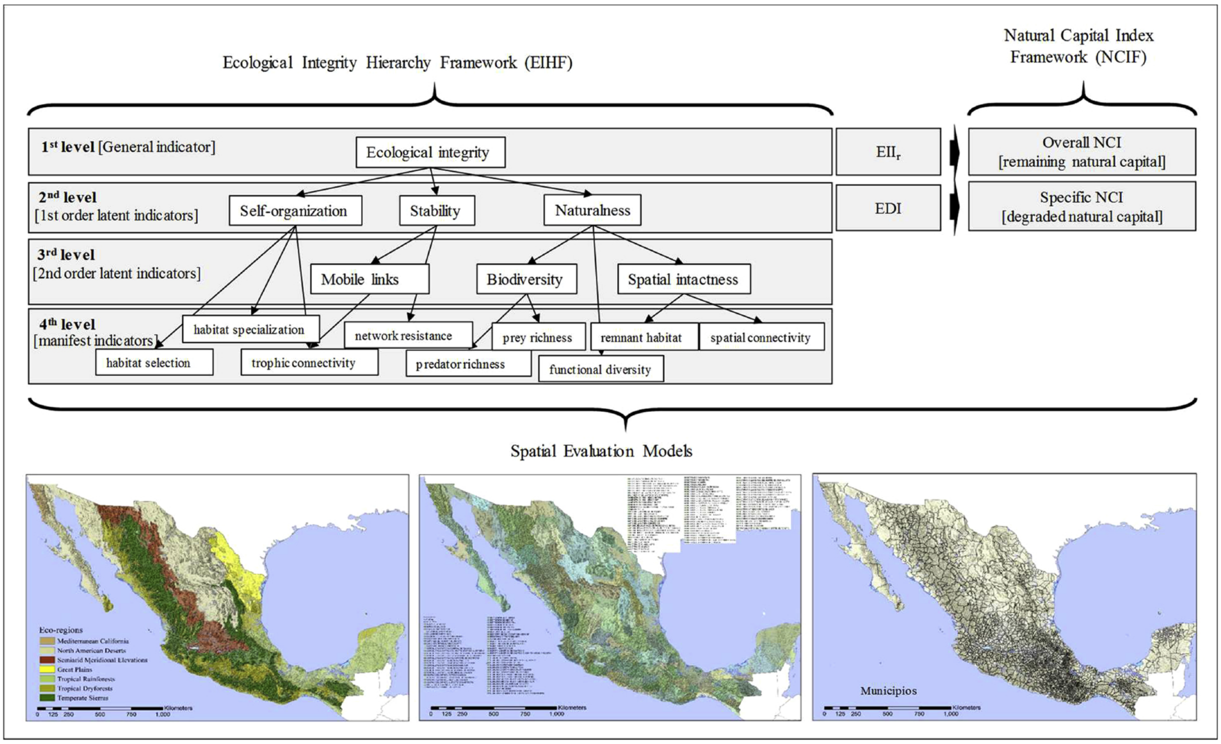

Fig. 1. The integration of the Ecological Integrity Hierarchy Framework (EIHF) and the Natural Capital Index Framework (NCIF) for evaluating NCI using three spatial regionalization models in Mexico.

selected for NCI evaluations. Here, ecosystem criteria for the definition of spatial evaluation models is hopefully better suited for decision-making purposes, as the eco-region model is used primarily here for simplicity and illustrative purposes, while two additional spatial region models (Environmental UAOT units and Administrative Units-Municipios) are used for comparative purposes (in fact, any spatial regional model can be used for NCI evaluations, as long as they make sense for decision making). The eco-regions spatial model is used here as the main directive as it offers the possibility of making hierarchical evaluations, and because at the simplest level of generalization allows for the communication of the evaluation findings in a simpler and concise way.

2.2. The ecological integrity hierarchy framework

As mentioned before, the ecological integrity hierarchy framework (EIHF) is a set of spatial ecological integrity indicators that evaluate the state or condition of ecosystems that sustain key ecological process (Mora, 2017b). Here, the ecosystem condition is portrayed as the capacity to sustain an ecologically relevant function; i.e., to maintain predator-prey interactions, while supporting the ecosystem capacity to sustain viable populations of apex predators. As such, *intact*, *stable* and *concurrent* conditions (which represent the best conditions for naturalness, stability and self-organization) represent the *critical capital* that is left for future generations.

Additionally, the rationale behind the EIHF tool relies in the possibility to perform an evaluation of the ecosystem condition at several levels of ecological complexity (Fig. 1). At the first hierarchy level, the overall state of the ecosystem´s integrity condition is evaluated through the general indicator of ecological integrity (EIC_i), which is also a quantitative measure of the ecosystem´s quality. At subsequent levels, the interaction of emergent properties; i.e., self-organization, stability and naturalness, defines a set of abstract indicators that allows the evaluation of the ecosystem´s degradation for sustaining the ecological process of interest. The interaction among abstract indicators identify the combination that most determines the loss of emergent properties, resulting in a specific ecological condition (EC). The interaction properties are then subsequently captured in three main indicators; i.e., the remnant ecological integrity index (EIC_i), the ecological degradation index (EDI_i) and the human transformation index (HTI_i) (Mora, 2017b).

In order to estimate the NCI from abstract indicators, the EC can be expressed as a quantitative integrated measure by weighting the amount of natural landscape that pertains to all ecological integrity conditions observed. Therefore, a combined EC score of all possible conditions in a remnant landscape is obtained as an additive index based on cumulative scores of all attributes. As an additive index, the resulting score is integrative, assuming that each state is compensatory and independent, so a reduction or absence of one state may be balanced by an increase in another (McElhinny, Gibbons, Brack, & Bauhus, 2005). Therefore, the overall ecological condition (EC_i); i.e. the sum of ecological integrity, ecological degradation and human transformed, for all landscape units *i* pertaining to a specific evaluation model is:

$$EC_i = [EIC_i + EDI_i + HTI_i]$$

Then, the ecological integrity condition (EIC_i) can be obtained as the mean EI value for all natural remnant areas in a spatial unit:

$$EIC_i = \frac{EIAN_i}{A_i}$$

Where EIC_i is the ecological integrity condition for the i_{th} spatial unit (e.g., ecoregion type); $EIAN_i$ refers to average ecological integrity value for all pixels (at 1 km^2) with EI $>$ 0; A_i being the total area (km^2) for the i_{th} spatial unit. The resultant EIC_i value represents the mean ecological value for a single unit, with a higher EIC_i close to 1.0 generally representing higher ecological integrity, and therefore, higher ecosystem quality.

The human transformation index (HTI_i) is the proportional area that has been transformed from natural to non-natural (TA_i), according to the total distribution area of each landscape unit (A_i); therefore:

Table 1
Ecosystem services unit values for different biomes within eco-regions. Unit values are translated from global unit ($/ha/yr) (Costanza et al., 2014; and Taylor et al. (2017) for Deserts).

Eco-region/Biome	Dry forest	Desert	Tropical forest	Temperate forest	Coastal Wetlands	Floodplains	Mangrove	Grass/Range lands
Mediterranean California		504		3,137				4,166
Temperate Sierras				3,137		25,681		4,166
North American Deserts		504		3,137	140,174		193,843	4,166
Great Plains							193,843	4,166
Dry Forests	4,901				140,174		193,843	
Tropical Rainforests			5,382				193,843	
Semiarid Meridional Elevations								4,166

$$HTI_i = \frac{TA_i}{A_i}$$

The ecological degradation index (EDI_i) is the difference between the actual EIC_i score and the potential EIC_p score if all remnant natural area was equal to the best ecological condition [1-HTI_i]. Therefore, EDI_i is calculated as:

$$EDI_i = [1 - (HTI_i + EIC_i)]$$

The EIC_i and EDI_i indicators were used for characterizing the quality of remnant natural resources, and later on, used for evaluating their natural capital.

2.3. The natural capital index framework

The Natural Capital Index (NCI) is one of the first high-level aggregated biodiversity indicators used internationally (Czúcz et al., 2012). The conceptual model simply establishes that given an indicator of ecological quality (EQ), the NCI can be estimated by calculating the remaining amount of ecosystem quantity (EA), therefore:

NCI = ecosystem quality * ecosystem quantity = EQ * EA

For an NCI evaluation using a regionalization spatial model that contains different landscape units, the NCI becomes:

$$NCI = \sum_{i=1}^{n} EQi * EAi$$

where EQ_i and EA_i correspond to the values of each landscape unit *i*.

As mentioned in the previous section, ecological integrity indicators were used as measures of ecological quality. Then, by using ecological integrity, the concept of NCI becomes dependent upon the assumption that biodiversity loss; i.e., the loss of predator-prey interactions and ecological integrity indicators associated with the EIHN, can be modeled as a spatial process driven by two main components. These components include habitat loss due to conversion of natural areas into agricultural fields or urban areas; and, degradation of the remaining habitat patches, caused by species loss, habitat loss, and fragmentation. Since the model of ecological integrity used here for the NCI evaluation directly accounts for the effects of habitat loss and fragmentation within the naturalness condition index, the overall ecological integrity index can be used directly as a measure of ecological quality resulting from human activities (Czúcz et al., 2012).

However, the overall concept of *quality* can be disaggregated further into three main components based upon the contributions of self-organization, stability and naturalness to the overall index. The interaction of these components into the remnant integrity condition, and the amount of ecosystems in a degraded state, offers an additional way to obtain an accurate estimation of the NCI, and value the areas with less ecological integrity within the evaluation of the NCI framework. Then a measure of degraded NCI (NCI_{deg}) can be obtained by:

NCI_{deg} = ecosystem quality degraded * ecosystem quantity = EQ_{deg} * EA_{deg}

And the NCI_{degi} for a landscape with differential i_{th} landscape units:

$$NCI_{degi} = \sum_{i=1}^{n} EQ_{degi} * EA_{degi}$$

Since the NCI relies on the average values for both EQ and EA; it becomes highly susceptible to the spatial landscape model used for evaluation. Here, the NCI evaluation is primarily based on the extent of each landscape unit portrayed in the spatial regional model. Then, by using an ecological criterion for NCI evaluation, the ecoregions regionalization serves for spatially evaluating the NCI and NCI_{deg}. The spatial regionalization model based on Eco-regions represents the variety of ecological conditions in the country, and serves to characterize the NCI at different spatial scales.

2.4. Valuing the natural capital

Values for the remnant natural capital in Mexico were obtained by translating the global value of ecosystem services (Costanza et al., 1992, 2014) for the dominant biomes of remnant ecological resources existing in Mexico. This scheme provided an updated estimate based upon ecosystem service values and land use change estimates between 1997 and 2011, which relates closely with the evaluation date of the EII framework (circa 2010). Although some other estimates of economic values for ecosystem services exists for Mexico (Lara-Pulido, Guevara-Sanginés, & Arias Martelo, 2018) they are not as comprehensive as the global estimates for covering all ecological units or biomes within eco-regions. For that reason, a combined scheme of biome types valued within eco-regions was used for economic evaluation purposes (Table 1).

Then, the economic value (EV) for each landscape unit (*i*) within Eco-regions can be estimated as:

$$EV_i = EV_{eco} * EQ_i * EI_i$$

Where EV_{eco} is the total ecosystem services value for the entire Eco-region unit (added values from Table 1); EQ_i is the amount of natural remnant landscape (ecosystem quantity); and EI_i is the ecological integrity for each landscape unit. Therefore, EV_i can be also expressed as:

$$EV_i = EV_{eco} * NCI_i$$

Where NCI_i is the natural capital index for each landscape unit. The total Natural Capital value for each Eco-region (NCV_{eco}) is then estimated as:

$$NCV_{eco} = \sum_{i=1}^{n} EV_i$$

3. Results

3.1. The global natural capital index for eco-regions in Mexico

The spatial distribution of the natural capital index (NCI), the associated spatial elements; i.e., ecosystem quality (EQ), and ecosystem

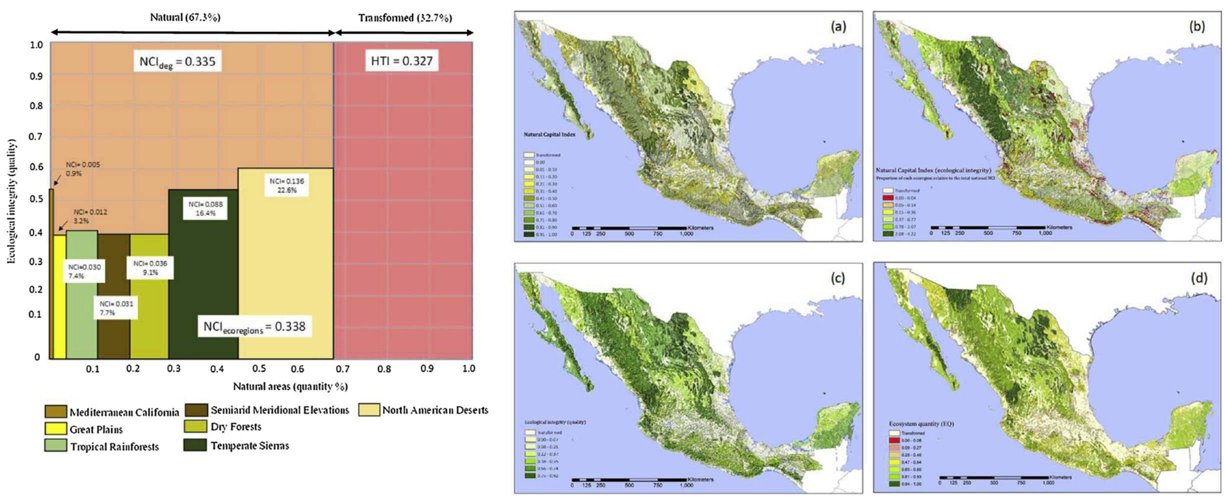

Fig. 2. Spatial distribution of (a) NCI calculated from eco-regions EQ and EA base upon ecological integrity and remnant natural areas; and (b) the contribution (percentage) of each ecoregion to the total (national) NCI. The NCI is calculated from (c) ecosystem quality (EQ = ecological integrity); and (d) ecosystem quantity (EA) for every polygon of each ecoregion. The global (nation-wide) NCI is ~34%, with ~67% of remnant natural areas, and ~33% of human transformed ecosystems.

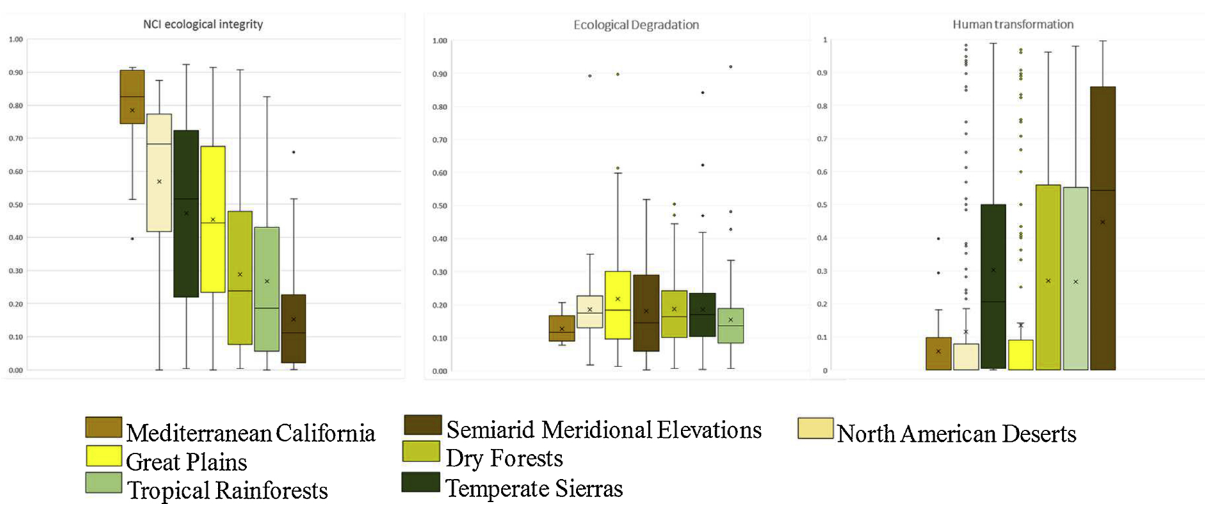

Fig. 3. Contribution of (a) NCI calculated from ecological integrity; (b) ecological degradation, and (c) of human transformed ecosystems; for each ecoregion in Mexico.

quantity (EA) for calculating the NCI using the ecoregions spatial model; and the contribution of each ecoregion spatial unit (polygon) to the global NCI is presented in Fig. 2. As calculated, the extent of the country that can be considered as "natural" is ~67%; while the amount of human transformed areas is ~33%, which gives a total estimate of NCI = 0.334; i.e., only ~33.4% of the national capital remains currently available (Fig. 2e). The NCI showed a characteristic spatial variation (Figs. 2a; 5 a) as a function of ecoregion size (EA) and ecoregion´s ecological integrity (EQ) (Fig. 2c–d).

As analyzed by eco-regions, the North American Deserts (NCI = 0.136; ~23%) and Temperate Sierras (NCI = 0.09; ~22%) account for more of the 40% of the remaining natural capital in the country (which also showed values of ecological integrity greater than 0.5); while the Dry Forest eco-region (NCI = 0.036; ~9%), Semiarid Meridional Elevations (NCI = 0.04; ~9%); Tropical Rainforests (NCI = 0.03; ~7%), Great Plains (NCI = 0.01; ~3%) and the Mediterranean California (NCI = 0.005; ~1%) account for the other half of the remaining natural capital in Mexico. These low natural capital areas also showed low ecological integrity values (EQ $<$ 0.5). The contribution of each eco-region to the national NCI seemed to be directly associated with eco-region size, but also from the amount of remnant natural ecosystems (natural areas quantity), and ecological integrity (Fig. 2e).

The NCI values varied considerably for all landscape units associated with each eco-region (Fig. 3a). Most of the large eco-regions; i.e., with greater extent ranged from an $NCI_{NADeserts} = 0.27 \pm 0.34$ to $NCI_{TempForest} = 0.37 \pm 0.3$; while the greatest $NCI_{MedCal} = 0.50 \pm 0.4$ is found in smaller size ecoregions, such as the Mediterranean California and the Great Plains ($NCI_{GreatPlains} = 0.18 \pm 0.23$) (Fig. 3a), indicating that while being small in extent, they practically maintain their ecological quality almost intact. On the other hand, several ecoregions with NCI values closer to zero were mainly observed in the Dry Forest, Tropical Rainforests and Semiarid Meridional Elevations; which in turn, showed the highest human landscape transformation, and consequently, lower values of NCI (Fig. 3a,b).

The relationship for NCI as a function of the amount of eco-regions transformed by humans (as measured by the HTI) showed an inverse trend; i.e., NCI directly decreases as the amount of human transformed landscape increases (Fig. 4a). Spatial units with a large extent (area) and high NCI can be observed for Temperate Sierras and North American Deserts. Large spatial units of the Great Plains ecoregion can be

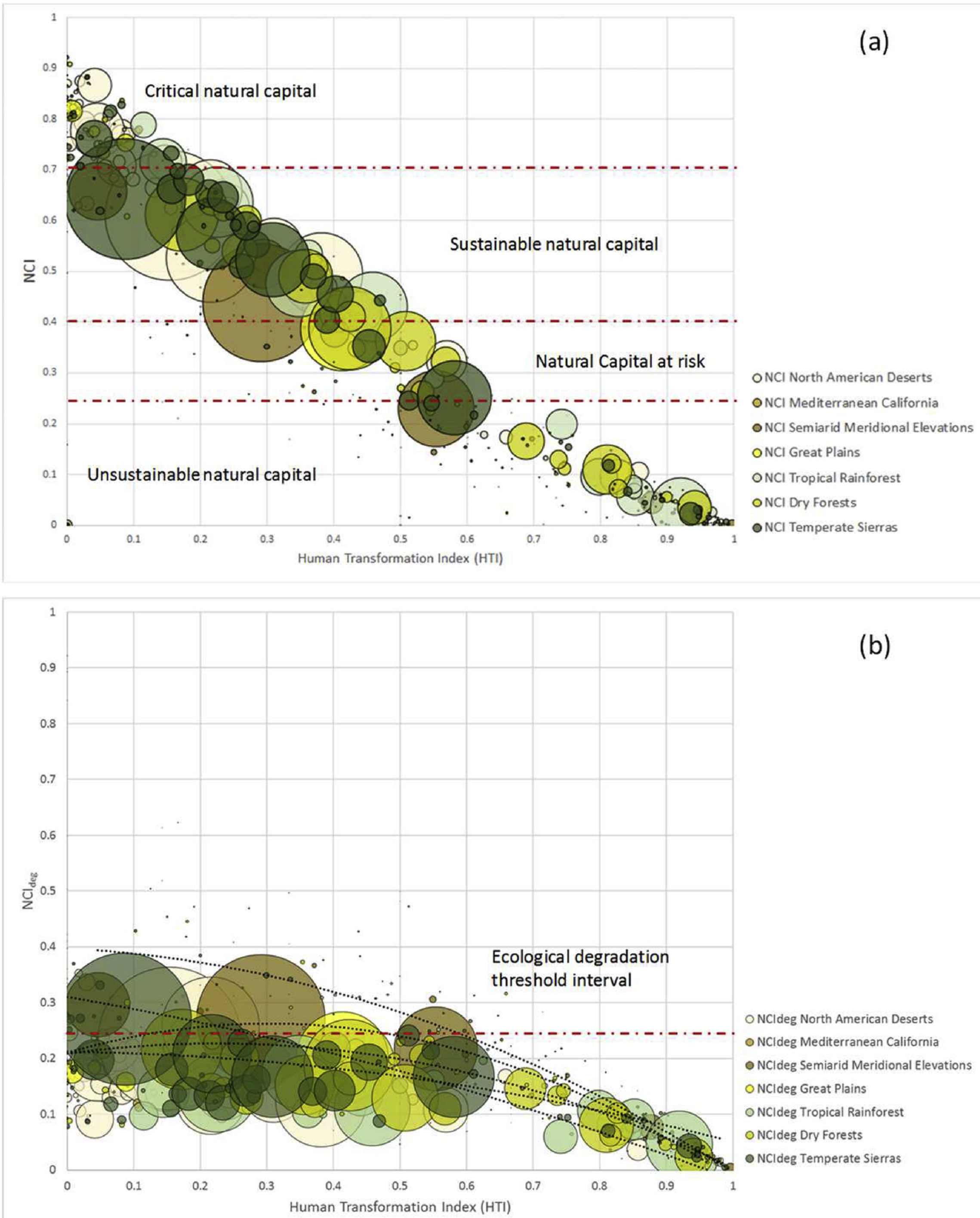

Fig. 4. (a) NCI and (b) NCI_{deg} as a function of human transformation index (HTI) for all eco-regions in Mexico. Bubble size is proportional to the area of each landscape unit pertaining to each eco-region. Fig. 4a shows the critical natural capital represented as the conditions where the ecosystem has an evolutionary legacy; i.e., maintaining the self-regulatory, self-organizing and stabilizing properties of ecological process (NCI > 0.7); sustainable natural capital for ecoregions are identified when ecosystem condition has not been degraded to the level that emergent properties can no longer sustain intact, stable and self-organizing properties (NCI ≥ 0.4 and NCI ≤ 0.7); and Natural Capital at risk is considered when evolutionary legacy is no longer sustained (NCI ≥ 0.25 and NCI ≤ 0.4) and unsustainable natural capital is identified when ecological degradation is at a maximum saturation point (NCI ≤ 0.25) of ecological degradation (Fig. 4b).

observed at moderate levels of NCI and HTI. Contrastingly, medium-sized landscape units, with corresponding low values of NCI (< 0.2) and considerable amounts of transformed landscape (HTI > 0.7) can be observed for Dry Forests, Tropical Rainforest and Semiarid Meridional Elevations (Fig. 4a). The relationship between NCI and HTI suggest a framework for identifying several levels of sustainability (Fig. 4a).

In addition, from the relationship between NCI and HTI several levels of sustainability for NCI loss are identified (Ullsten et al., 2004): (a) critical; (b) sustainable; (c) at risk; and (d) unsustainable (Fig. 4b). The sustainability evaluation for the additional spatial evaluation models used in this analysis are spatially consistent (Fig. 5g, h, and i). The status of sustainability for all spatial models of evaluation is presented in Fig. 7. The eco-region model identified a slightly different amount of

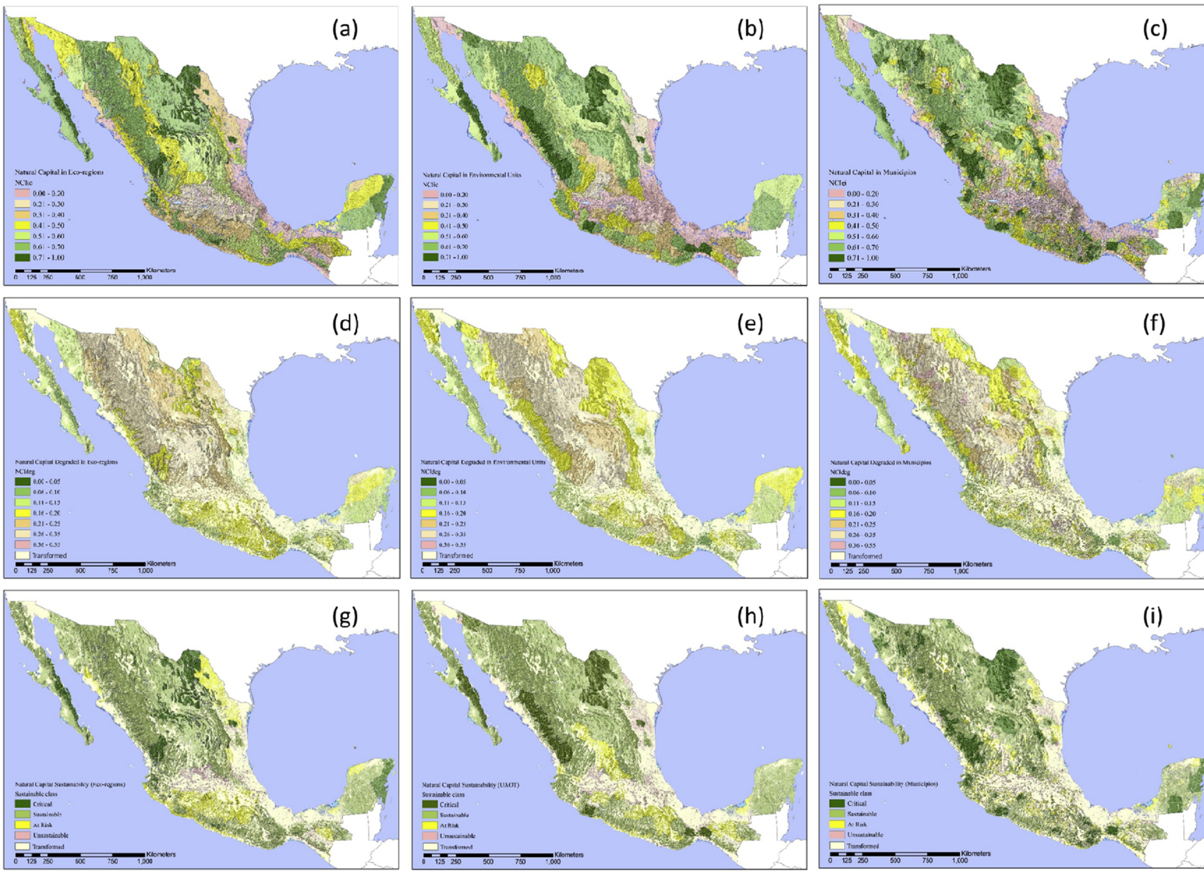

Fig. 5. (a,b,c) NCI ecological integrity; (d,e,f) NCI_{deg}; and (g,h,i) Natural Capital and sustainability for all landscape units of eco-regions; Environmental Units of Ecological Ordination (UAOT); and Administrative Units (Municipios) in Mexico.

critical natural capital (12.5%) from the other two spatial models (6.2% and 4.8%, for UAOT units and Municipios, respectively). Also, the amount of sustainable natural capital is greater in UAOT units (32%) and Municipios (31%), than in eco-regions (14%). The amount of unsustainable natural capital within eco-regions is greater (67%) than UAOT units (51%) and Municipios (44%).

3.2. Natural capital in eco-regions using the ecological degradation index

Ecological degradation was also considered as a part of the natural capital evaluation for México. The NCI_{deg} can be used also for estimating the amount of ecological capital that is degraded by human transformation and ecological integrity loss (Fig. 3). For Mexico, NCI_{deg} is ~33% (Fig. 2e), which is spatially distributed in several eco-regions (Fig. 5b). Overall, the eco-regions with the higher average values of ecological degradation (Fig. 3b) are the Semi-Arid Meridional Elevations, and the Great Plains, which also have been considerably transformed (Fig. 3c). Less levels of ecological degradation are also observed for forested eco-regions, except for Temperate Sierras, mostly because Tropical Rainforest and Dry Forest, have been highly transformed (Fig. 3c).

The relationship between NCI_{deg} and HTI is clearly non-linear (Fig. 4b), which indicates a limit saturation level of the maximum amount of degradation as a function of both, the ecological integrity level, and the amount of remaining non-transformed areas. However, the tipping point for indicating the maximum value of degradation possible, varies among ecoregions (Fig. 4b). In any case, the level of ecological degradation does not exceed more than 0.5, and when it reaches a maximum point (~0.3), it also steadily decreases as a function of ecological integrity and ecosystem quantity loss.

3.3. Natural Capital value for ecosystem services

The value of the Natural Capital for providing ecosystem services in each ecoregion is shown in Figs. 8 and 9. Higher unit values are concentrated in northern areas with Temperate Sierras with an estimate of $32- $55 billion/yr; North American Deserts, and some coastal wetlands and mangroves, and Tropical Rainforest in the south with an estimate of $55-$172 billion/yr and $16-$32 billion/yr, respectively (Fig. 8a). The highest economic potential for restoring natural capital degraded occurs in the Temperate Sierras, with an estimate of $10-$16 billion/yr, for most of the Eco-regions with degraded natural capital (Fig. 8b). Although the highest opportunity to add natural capital economic value is in Temperate Sierras and North American Deserts; there is also a great value for restoration in southern Coastal wetlands of the Gulf of Mexico (Fig. 8c).

The Tropical Rainforest eco-region holds the greatest total economic value ($332 billion/yr) with an average value of $2.1 billion/yr for each landscape unit; the average restoration value for each landscape unit is $600 million/yr; resulting in a $90 billion/yr total restoration value. The North American Desert eco-region is ranking second in importance according with the total current natural capital value ($183 billion/yr). The value of restoring degraded natural capital in deserts is in average is $330 million/yr for each landscape unit, offering a total potential value of $60 billion/yr, increasing the total potential value in $243 billion/yr. The Temperate Sierras hold a total current value of $73 billion/yr; where each landscape unit is worth in average $575 million/yr The total degraded value is $27 billion/yr; which can be increased up until $100 billion/yr after restoration (Table 2; Fig. 9).

Table 2
Current, degraded, and potential (after restoration) Natural Capital Value statistics for all landscape units of Eco-regions in Mexico.

Eco-region	Current value			Values NC degraded			Potential Value after restoration		
	Sum	Mean	Std	Sum	Mean	Std	Sum	Mean	Std
Mediterranean California	$808,690,898.00	$32,347,635.92	$86,276,019.05	$220,560,732.00	$8,822,429.28	$30,273,118.81	$1,029,251,780.00	$41,170,071.20	$115,842,409.99
Temperate Sierras	$57,854,102,949.39	$455,544,117.71	$2,367,027,578.51	$21,334,578,657.09	$167,988,808.32	$974,379,922.25	$79,188,696,407.60	$623,533,042.58	$3,337,823,148.06
North American Deserts	$56,441,758,434.59	$310,119,551.84	$2,180,456,969.17	$15,932,341,590.01	$87,540,338.41	$485,859,347.68	$72,374,104,159.82	$397,659,912.97	$2,650,057,788.69
Great Plains	$22,271,663,188.00	$136,635,970.48	$1,025,958,861.24	$11,788,334,986.00	$72,321,073.53	$614,175,334.22	$34,060,038,158.00	$208,957,289.31	$1,637,539,629.06
Dry Forests	$80,764,390,162.20	$511,167,026.34	$2,800,552,364.84	$31,279,266,570.16	$197,970,041.58	$797,977,969.11	$112,043,700,092.40	$709,137,342.36	$3,566,661,636.30
Tropical Rainforests	$224,959,714,156.73	$1,460,777,364.65	$9,255,968,133.03	$55,439,520,424.40	$359,996,885.87	$2,148,792,543.50	$280,399,261,232.20	$1,820,774,423.59	$11,223,411,320.63
Semiarid Meridional Elevations	$13,986,486,908.85	$177,044,138.09	$1,406,793,795.13	$8,623,671,375.90	$109,160,397.16	$867,822,824.28	$22,610,179,775.50	$286,204,807.28	$2,274,448,352.24
Total	**$457,086,806,697.77**			**$144,618,274,335.56**			**$601,705,231,605.51**		

4. Discussion

4.1. The Natural Capital Index at different scales

When the EIHF and the NCI frameworks are integrated, the state or condition of ecosystems becomes the most important indicator for evaluating the Natural Capital Index in a spatial context. Furthermore, by including ecological integrity as a measure of ecosystem quality, the NCI goes beyond the quantitative description of natural assets, and then inherently evaluates the role of maintaining biodiversity and important ecological processes in critical resources for every spatial evaluation model. Ecological integrity and ecological degradation offer the possibility to evaluate different forms to represent the Natural Capital and their sustainability.

As analyzed, the Natural Capital in Mexico, which is the amount of remnant natural landscape with ecological integrity, is ~0.33.4. The current NCI is a direct result of human landscape transformation, which has historically reached ~33%. While only 67% of the natural landscape remains untransformed, almost 33% has been also ecologically degraded. Then, the historical loss of NCI indicates an overall decrease of sustainability occurring for centuries, more importantly where historical landscape transformation has greatly occurred. However, as compared with other NCI values in other countries (Academy, 1999; Azqueta & Sotelsek, 2007; Czúcz et al., 2012), it seems that a considerable amount of natural capital remains in the country.

As observed, NCI also identified the remaining importance of the different co-regions for providing sustainable ecosystem services. The loss of NCI is greater in the Semiarid Meridional Elevations and the Dry Forests (in central Mexico); where historical human transformation has occurred for centuries due to the agriculture potential and expansion. In contrast; heavy human transformation of the tropical rainforests has occurred on relatively recent times due to development policies instituted in the 1960s to 1970s, before a national conservation initiative took place during the 1980s. In contrast, the remaining NCI is comparatively higher in other eco-regions, where low populated and less accessible areas still contribute greatly to the overall NCI. Then, for example, the Mediterranean California, North American Deserts, and Temperate Sierras maintain relatively high levels of NCI due to low population density and remoteness areas.

The amount of natural capital degradation also underscores the importance of identifying critical natural capital, and the value to restore degraded landscapes. When analyzed simultaneously, NCI and NCI_{deg} showed a direct relationship with the amount of anthropogenic transformation, measured with the HTI (Fig. 4). From this relationship, a critical natural capital that is irreplaceable to support ecological functions is identified, and is also part of the sustainable natural capital, and indicates the conditions where the ecosystem may have an evolutionary legacy; i.e., maintaining the self-regulatory, self-organizing and stabilizing properties of ecological processes such as predator-prey interactions. In addition, sustainable natural capital for eco-regions is also identified when the ecosystem condition has not been degraded to the level that emergent properties can no longer sustain intact, stable and self-organizing properties. Natural Capital at risk is considered when evolutionary legacy is no longer sustained; and unsustainable natural capital is identified when ecological integrity is at a maximum saturation point of ecological degradation (Fig. 4a and b).

With the present status of the NC in the country, the question that logically arises is, will 33% of the remaining natural capital support a sustainable development for future generations? Apparently it will not. The proportion of unsustainable NC for all ecoregions ranges from 36%–85% (NC = 64.8% ± 18.2%) (Fig. 6). The amount of critical habitat for all ecoregions range from 0% to 48% (NC = 13.3% ± 16.5%). The suitable natural capital that is at risk ranges from 4% to ~10% (NC = 6.3% ± 2.5%).

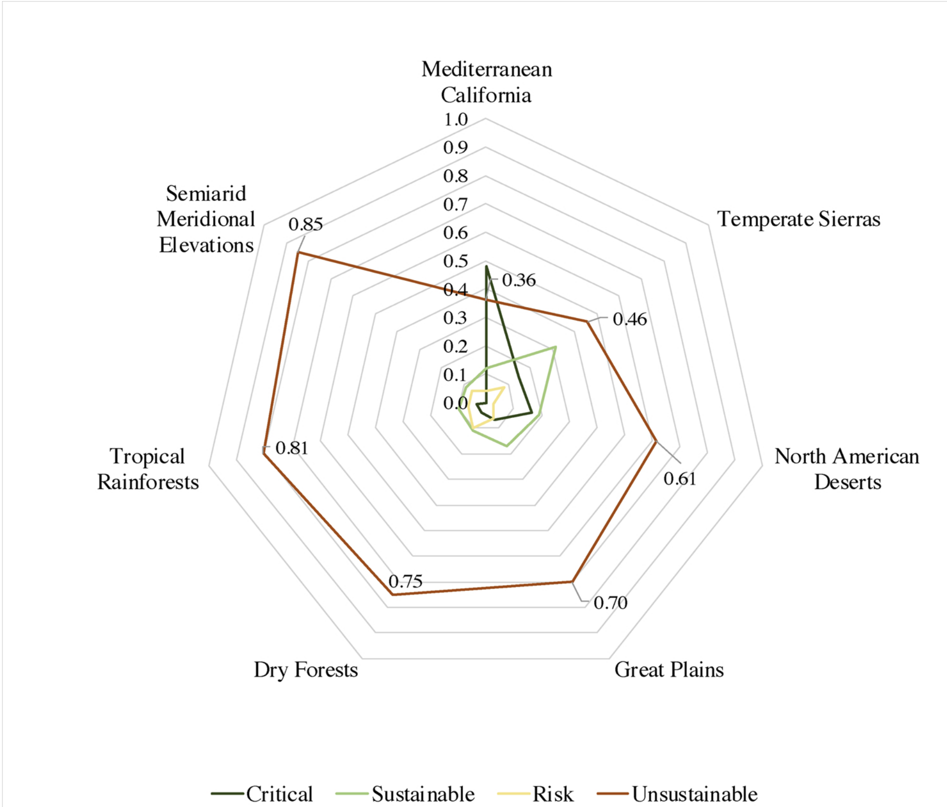

Fig. 6. Indicators of Natural Capital and sustainability for eco-regions in Mexico. The Sustainability categories are identified according with the threshold levels in Fig. 4. The values show the percentage of landscape units pertaining to each sustainable category for each ecoregion as presented in Fig. 5c.

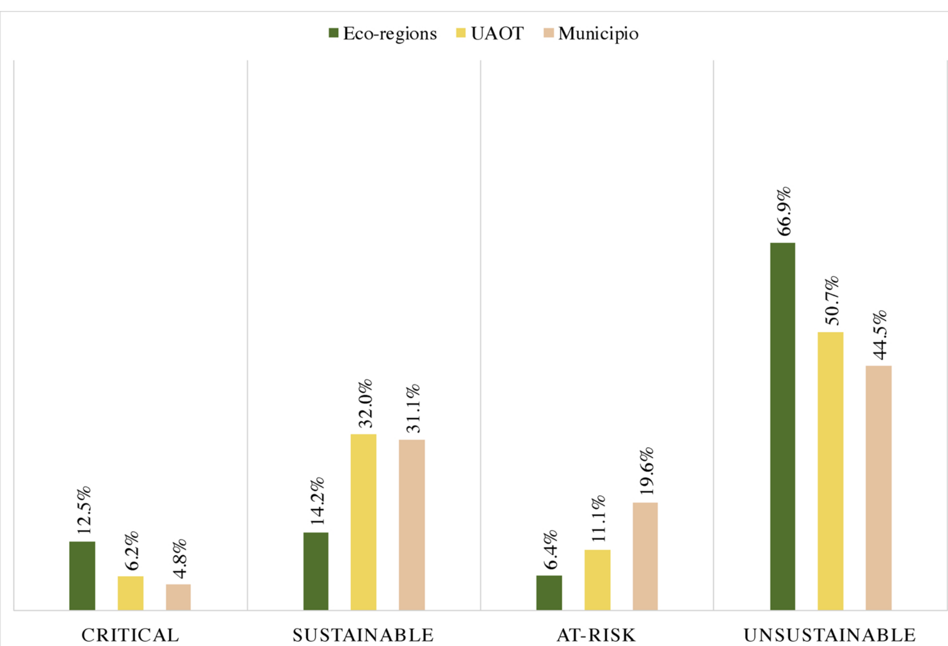

Fig. 7. Status of Natural Capital and sustainability for the different spatial evaluation models (eco-regions, UAOT and Municipios) in Mexico. The Sustainability categories are identified according with the threshold levels in Fig. 4. The values show the percentage of landscape units pertaining to each sustainable category for each evaluation model as presented in Fig. 5.

4.2. NCI as the basis for sustainable development

- 'Sustainability': humanity´s target goal of human-ecosystem equilibrium; …

- 'sustainable development' is the holistic approach and temporal process to reach sustainability. (Shaker, 2018)

As signatory of several international treaties, Mexico is committed to a "development that meets the needs of the present without compromising that ability of future generations to meet their own needs" (WCED – World Commission on Environment & Development, 1987: 43). However, as several new nation-level sustainability indicators have recently identified, the route of Mexico towards sustainability remains difficult. According to the sustainable assessment for the Americas, Mexico currently ranks very low in achieving sustainable development, mainly due to socio-economic factors conveying the importance of a resilient economy, improved domestic safety and security

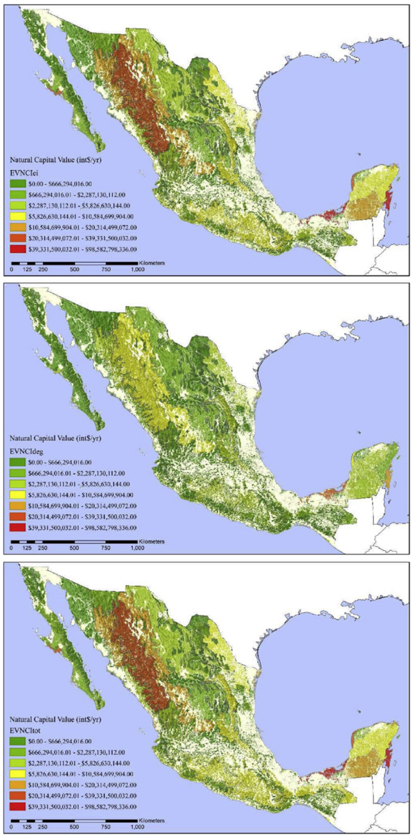

Fig. 8. The natural capital value for ecosystem services (a) Natural capital with degradation; (b) Natural capital degraded; and (c) Natural capital before degradation for eco-regions in Mexico. Economic value was estimated according with global ecosystem services units (Costanza et al., 2014)(see Section 3.3).

and decreased international conflict for reaching sustainability (Shaker, 2018). However, Mexico maintains globally a high socio-ecological status based upon concepts of socio-ecological resilience and pressure, both related to the sustainable development goals (Estoque & Murayama, 2014, 2017) which encourage the efforts for achieving sustainability. Furthermore, Mexico is one of the 32 countries with a stationary ecological footprint (Solarin & Bello, 2018), which demonstrate that even while suffering an ecological deficit, there exists a commitment for abating human consumption at expense of the country´s biocapacity. Although Mexico performs well in its potential for ecological suitability, the challenge for achieving a higher potential for prosperity relies on economic development, particularly social inclusion, and civic participation, without undermining natural capital (Fritz & Koch, 2014). Economic development is the mean to reach sustainability. Therefore, maintaining a sustainable and critical natural capital is pre-requisite for achieving a future sustainable development.

The sustainability assessment of Mexico based upon the ecological and economic value of the remaining natural capital should trigger a strategic ecological assessment for sustainable development. While a third of the country has been historically transformed, the current and most urgent environmental issue to reach sustainability is to abate and reverse ecological degradation. The loss of ecosystem´s capacities that constitute an evolutionary legacy is one of the most important handicaps for maintaining a course for achieving sustainable development. Nonetheless, the present use of Mexico´s Natural Capital has reached non sustainable levels. The amount of landscape units which have a considerable loss of natural capital; i.e., “the stock that possesses the capacity of giving rise to flows of goods and/or services” (Ekins, 2003), is more than 60% on average for all ecoregions. The amount of sustainable natural capital from Mexico is ~35%, but only ~13% is considered critical; i.e., with an evolutionary legacy property (Fig. 7). When the other two spatial evaluation models are analyzed, unsuitable natural capital varies from ~45% (Municipios) to ~ 51% (UAOT units). For all eco-regions, unsustainable natural capital greatly overpasses the amount of critical and sustainable NC. The Mediterranean California and Temperate Sierras are the eco-regions where critical and sustainable natural capital represent an important asset. However, sustainability is below the non-sustainable portion of landscape units in the country.

The path for sustainable development is also leading to the establishment of management goals and national policies that could increase the amount of sustainable and critical natural capital, but is undermined by the need for development. While necessary for economic growth, much of the future proposed development projects still underline the economic gain over maintaining ecological integrity. Thus,

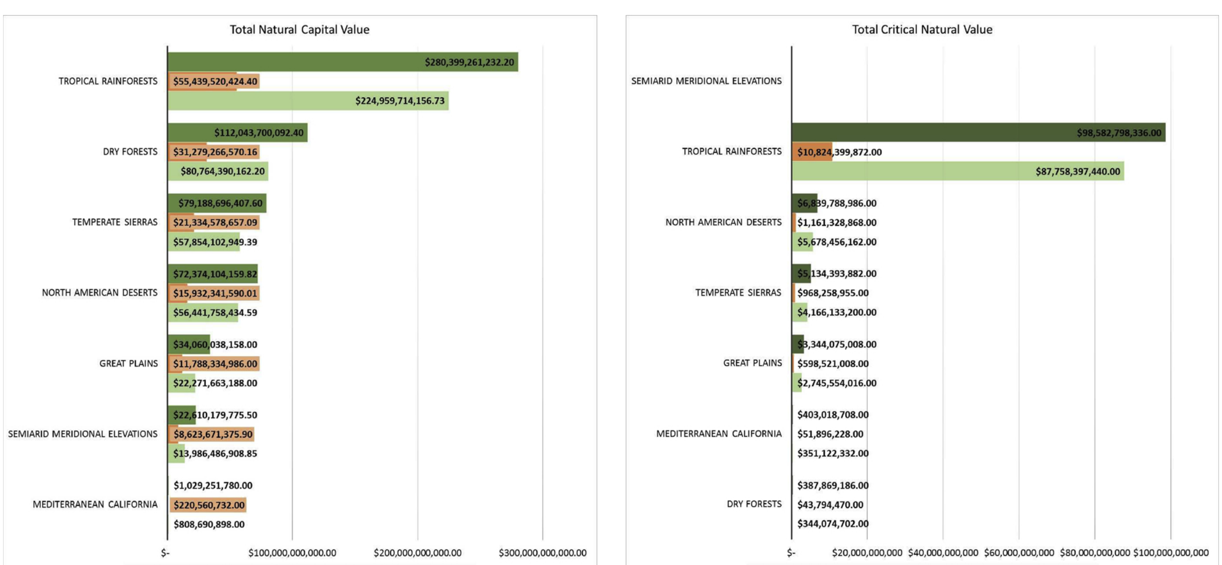

Fig. 9. The (a) total natural capital value ($/yr); and (b) total critical natural value for all landscape Eco-regions units (as to 2011 updated values) including: (a) Natural Capital with degradation; (b) Natural Capital degraded; and (c) Natural Capital after restoration for all eco-regions in Mexico. Economic value was estimated according with global ecosystem services unit values (Costanza et al., 2014)(see Section 3.3).

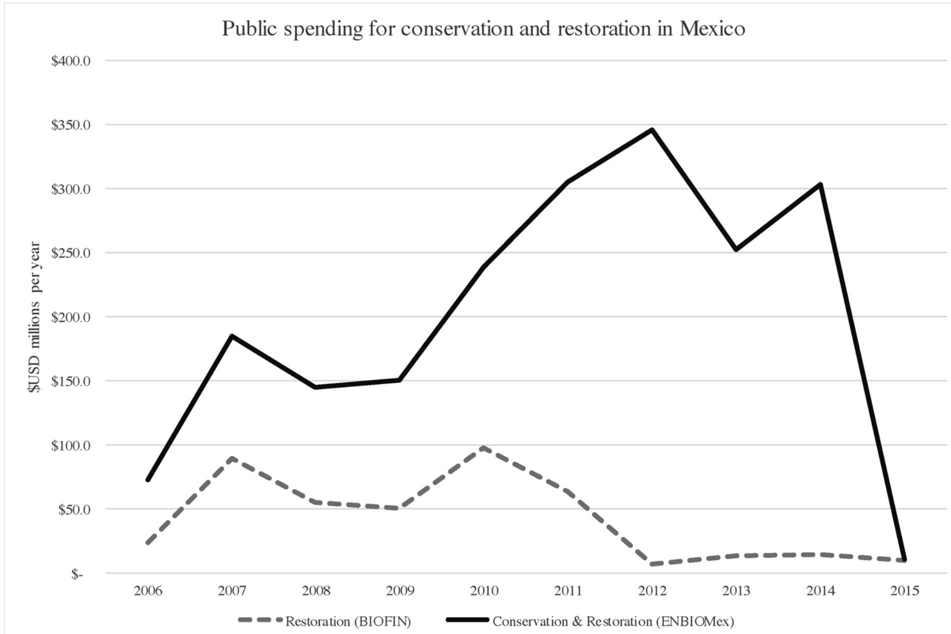

Fig. 10. Total public spending in Conservation and Restoration in Mexico. Data from Initiative Financing Biodiversity BIOFIN-PNUD, México.

ecological integrity is being lost by reducing natural environments, species interactions and spatial habitat connectivity, and as a consequence, producing some other adverse ecological effects such as trophic connectivity loss, and impairing necessary functional properties of wildlife such as mobile links. The loss of stability and self-organization in natural ecosystems have transformed the necessary landscape to maintain viability and ecological significance of biodiversity components. These include key ecological interactions such as predator-prey, which support irrepleaceble ecological processes with evolutionary significance. Restoration efforts can be then linked to ecosystem management goals for abating these effects in wild populations of big predators (e.g., Pumas and Jaguars), and reinforce species reintroductions, like the Mexican Gray Wolf. There is a great potential for analyzing the importance (ecological and economic) of reintroduction of locally extinct species or functional similar species in degraded environments, so we can revert the consequences of defaunation (Galetti & Dirzo, 2013).

One third of the country is prone to restoration efforts by reducing human impact pressures that modify ecological integrity. While national policies have been implemented so far to halt landscape transformation, ecological degradation now emerges as the most important management issue from habitat fragmentation and habitat loss, that results from the implementation of low-impact development plans like tourism, urbanization and communication infrastructure. However, the economic investment for restoration efforts to increase natural capital is meager, with a declining trend after 2012 (Fig. 10); although is anticipated that a cost between USD$6.3 to USD$43.5 billion is needed to restore 8.4 million hectares by 2020, in order to meet the Bonn Challenge (PNUD, 2018a, 2018b).

4.3. Natural Capital value for ecosystem services

While NC has reached non sustainable levels, the economic value of the remnant NC is still considerable. The total estimated value of current natural capital in Mexico is ~ USD$457.1 billion/yr, which is ~76% of the total potential value; i.e., the value after restoration. For comparison, the value of the current natural capital is ~435 times greater than the national GDP ($1.051 billion in 2010). However, the cost of maintaining the degradation of the natural capital is ~ USD $144.6 billion/yr (138 times greater than national GDP in 2010); which represents ~24% of the total natural capital before degradation. The potential value of the natural capital after restoration would be ~ USD $602 billion/yr; which is in comparison, 0.48% of the global value (USD$124.8 trillion/yr), and ~0.8% of the global GDP (USD$75.2 trillion/yr) (as compared with figures reported in Costanza et al., 2014). Previous estimates of total economic value of terrestrial ecosystems in Mexico (~USD$831.8 billion/yr) and degraded lands (~USD$745.2 billion/yr) based upon demand for Net Primary Production (Sutton, Anderson, Costanza, & Kubiszewski, 2016) are greater than the value of natural capital evaluated as a functional property to sustain predator-prey interactions. However, the amount of degraded lands is highly underestimated by Sutton et al. (2016), where only 10.4% of ecological degradation is reported. Nevertheless, the importance of the NCI_{deg} for increasing the total NCI economic value is undeniable. A Strategic Environmental Assessment (SEA) for the country ought to integrate restoration goals for a sustainable use of natural resources in the country.

In contrast, the total current value for critical natural capital is USD $101.05 billion/yr; which is only 22% of the total current natural capital. The value of degraded critical capital is USD$13.6 billion/yr; which could increase the total value of the critical natural capital up to USD$114.7 billion/yr; which is only 19% of the current potential value of critical natural capital after restoration. These figures characterize the economic value for the natural capital considered as a legacy for future generations (Table 3). Strategic goals for increasing the amount of critical natural capital are needed in order to provide sustainability for future generations.

Critical natural capital (CNC) and sustainable natural capital are important factors for environmental sustainability and national development, and they should be considered as main indicators for policy decisions and development planning. Critical NC conveys an evolutionary legacy; i.e., maintaining the self-regulatory, self-organizing and stabilizing properties of ecological process, and therefore becomes a critical concept for SEA. At the current status of the natural capital, the amount of critical capital is only 12%, with 22% of the total value of current capital. Sustainable natural capital conveys all forms of natural resource management and use that support economic and social development, with a potential value of USD$601.7 billion/yr for providing ecosystem services. Different forms of sustainable capital also identify areas where significant ecological degradation may occur. The

Table 3
Current, degraded, and potential (after restoration) Critical Natural Capital value statistics for all landscape units of Eco-regions in Mexico.

Eco-region	Current value			Values NC degraded			Potential Value after restoration		
	Sum	Mean	Std	Sum	Mean	Std	Sum	Mean	Std
Mediterranean California	$351,122,332.00	$29,260,194.33	$47,567,617.85	$51,896,228.00	$4,324,685.67	$7,169,570.55	$403,018,708.00	$33,584,892.33	$54,726,056.03
Temperate Sierras	$4,166,133,200.00	$181,136,226.09	$603,925,496.84	$968,258,955.00	$42,098,215.43	$156,913,204.14	$5,134,393,882.00	$223,234,516.61	$760,570,120.61
North American Deserts	$5,678,456,162.00	$189,281,872.07	$283,697,945.46	$1,161,328,868.00	$38,710,962.27	$61,974,389.38	$6,839,788,986.00	$227,992,966.20	$344,850,283.07
Great Plains	$2,745,554,016.00	$249,595,819.64	$466,069,241.77	$598,521,008.00	$54,411,000.73	$100,811,252.95	$3,344,075,008.00	$304,006,818.91	$566,841,106.14
Dry Forests	$344,074,702.00	$57,345,783.67	$43,121,214.60	$43,794,470.00	$7,299,078.33	$4,927,251.22	$387,869,186.00	$64,644,864.33	$47,522,741.59
Tropical Rainforests	$87,758,397,440.00			$10,824,399,872.00			$98,582,798,336.00		
Semiarid Meridional Elevations	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total	**$101,043,737,852.00**			**$13,648,199,401.00**			**$114,691,944,106.00**		

loss of natural capital by degradation represents 33% of the total sustainable capital, with a cost of USD$144.6 billion/yr. This loss can be then used as a reference for evaluating human impacts within ecosystems.

Additionally, it seems that the importance of the current sustainable natural capital would be better valued as a function of differential benefits of ecosystem services. To date, economic value for providing ecosystems services in Mexico has not been included in national accounting systems, primarily because there is a lack of an evaluation scheme that represent the complexity of ecological conditions, and secondly, because the evaluation of ecosystem services is still incomplete. A review of 106 studies that estimate economic value for any given environmental good and services in Mexico, identified that regulation services are the most valuable, even when policy decisions still favor land use change for provisioning services. However, this situation will not change until the market recognize the value of preserving regulation services (Lara-Pulido et al., 2018). This is particularly important when valuing different ecosystems like wetlands and other terrestrial ecosystems. Wetlands are even more valuable in providing provisioning and regulating services than arable land (Lara-Pulido et al., 2018), although as identified here, tropical rainforests maintain the highest total economic value for terrestrial ecosystems; while large extents are still lost every year due to land use changes. Nevertheless, an economic scheme of compensatory mechanisms for impairing or halting incentives for land use change do not exist for all ecosystems, although Mexico is a successful case of payment for ecosystem services schemes (PES). Since 2003, the Mexican government compensates forest ownership by paying an economic retribution that is closer to opportunity costs (i.e., crops). Although useful for deterring deforestation, in most cases it does not equal the necessary costs to invest in technology to increase productivity, and is insufficient (for example, the payment for 2017 was $30-$55 USD/ha/yr for hydrological services) to meet the minimum needed to overpass the provisioning service from croplands ($144 USD/ha/yr). As determined by the EIHF indicators, land use change resulting in habitat loss and fragmentation is the main cause for ecological degradation. A program that pays for hydrological services in forest ecosystems, while significantly reducing expected land cover loss, does not generate significant poverty alleviation. The PES is more a “win-neutral” than “win-win” strategy for environment and development (Alix-Garcia, Sims, Yanez-Pagans, & Shapiro, 2015). The total cost of maintaining ecological degradation is another way of valuing the mechanisms that maintain poverty among the rural population.

Finally, the current natural capital can be properly valued as a function of several ecosystem services if better schemes for valuing ecosystems can be developed. The information regarding ecosystems services values have not been published for some Mexican biomes, particularly for desert ecosystems, although new estimates have been provided for the Chihuahuan bioregion, which is the largest desert in North America (Taylor, Davis, Abad, McClung, & Moran, 2017). However, the Chihuahuan desert faces several threats that will degrade ecosystem integrity and later on negatively impact ecosystem services values, including energy development and overuse of natural resources, as mining and oil, gas and wind energy production are becoming main directives of regional development and public policies. Forest ecosystems (both tropical and temperate) are highly diverse in terms of ecological conditions and ecological processes that should be maintained for ecological legacy. Still, the value of maintaining ecological processes such as pollination, seed dispersal, biomedicine and bioenergy and others derived from biotic interactions is full of important information gaps. The most valued goods and services for several ecosystems are recreation, water and food resources, while many important ecosystem services remain unnoticed and are not considered for a total economic value (Perez-Verdin et al., 2016).

It seems that the ecosystem service science in Mexico is still incomplete for providing a comprehensive national scheme of ecosystem values, where most of the natural capital value remains unknown for different ecosystem services. Although the scheme used here for valuing ecosystem services at global scale may seem too general, it offers a comprehensive view for making an adequate spatial (although general) representation of all biomes occurring in Mexico. Nevertheless, the total economic value obtained with this scheme may still be underestimated, but helps to dimension the importance of the remnant natural capital. However, by presenting this valuing exercise, will hope to encourage better initiatives for fostering ecosystem services science in Mexico.

5. Conclusion

The current status of the amount and value of the natural capital in Mexico is not sustainable for an ecological and evolutionary legacy. Only 33% of the total natural capital is currently sustainable, and only 12% is currently considered as a critical capital. Furthermore, the critical natural capital as a form of legacy with evolutionary properties may not sustain future generations. Therefore, a need for reviewing plans and decision-making that includes evolutionary legacy criteria calls for a deep review of the status of the current natural capital that can allow for the establishment of sustainable goals in natural resource management. This necessarily needs to be included in all Environmental Impact Assessments (EIA) and Strategic Environmental Assessments (SEA) in the country. Furthermore, EIA and SEA ought to include fine-scale NCI implementations for local and regional policy development and ecological evaluation purposes. The evaluation of ecological integrity at different scales becomes then a key and very helpful tool for ecological and valuing monitoring efforts of the remaining natural capital, as has been presented here.

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Appendix A

Table A1
Description of the metrics used as manifest ecological integrity indicators in Mexico (Mora, 2017b).

Ecological metric	Formula	Description and interpretation	References
Functional diversity	$FD = \frac{FG}{\sqrt{S}}$	Functional diversity (FD) is a concept used to describe the variety of functional characters, complexity of food webs and functional groups present in a community. As used here, functional diversity indicates the number of species groups that perform different functions within ecosystem, or show similar responses to the environment. For predator-prey interactions all 239 mammal species were categorized in seventeen functional groups. The FD spatial indicator represents the spatial variation of the relationship between the number of functional groups, and the number of species within groups.	(Mason, Mouillot, Lee, & Wilson, 2005); (Gitay & Noble, 1997).
Predator and prey diversity	Number of species (S)	Predator and prey diversity is expressed as species richness (S). Prey richness is an indicator of the number of preys present from the species´ pool (239 mammal species identified in the interaction networks). Predator richness is the number of predators present as described by the stack-SDMs.	
Ecological (habitat) specialization	$SSI = \left[\left(\frac{H}{h}\right) - 1\right]^{\frac{1}{2}}$ $CSSI = \sum SSI/S$	Ecological specialization is a measure of the variety of ecological conditions (habitats) where species occur. Here, the term specialization is a manifestation of the tendency of species to occur in different landscapes composed of different species. As a spatial indicator, provides a similarity measure of the geographic co-occurrence of local species, as compared to large-scale occurrence data (SSI). The level of ecological specialization for predators and prey as they occur in the landscape was calculated as a compound of the specialization index for all species occurring in a location (CSSI).	(Vimal & Devictor, 2015) (Devictor et al., 2010; Julliard, Clavel, Devictor, Jiguet, & Couvet, 2006)
Habitat selection		The habitat selection indicator integrates a measure of the species' ability to select all available habitats as a function of their spatial distribution. As such, is an indirect measure of the prevalence of species in the habitat. This indicator is calculated as the average proportion of habitats occupied by all species described in the interaction networks.	
Remnant habitat	Amount of remnant habitat	The amount of remnant habitat is associated with the spatial requirements of species which allows a viable population to persist as a meta-population. Remnant habitat is defined here as the proportion (within species´ home range) of viable habitat that is not transformed from its natural condition. Therefore, the amount of remnant habitat is an inverse indication of habitat loss.	(Hendriks, Willers, Lenders, & Leuven, 2009); (Riitters et al., 2002)
Habitat connectivity	Probability of habitat adjacency	Habitat connectivity is calculated as the probability of having similar adjacent habitat types within the home-range for all species in the interaction network. Therefore, along with the amount of remnant habitat, it is an indication of habitat fragmentation for top predators.	(Riitters et al., 2002)

(continued on next page)

Table A1 (*continued*)

Ecological metric	Formula	Description and interpretation	References
Trophic connectivity	Probability of habitat adjacency (for apex predators)	Trophic connectivity is the mobility among different habitats for mobile (in this case trophic) links. Mobile links here are organisms that spread the predator function (apex predators). Trophic connectivity is defined here as the probability that a top predator can visit similar adjacent habitats and perform its ecological role within their surrounding landscape. Trophic connectivity is associated with predator's mobility by analyzing the spatial heterogeneity within its home range. The trophic connectivity is calculated as the probability of adjacency of similar habitats for apex predators, based on the model developed for evaluating habitat fragmentation at landscape scale.	(Lundberg & Moberg, 2003). (Riitters et al., 2002)
Network resistance	$C = \frac{L}{S^2}$	Here, network resistance (within a species' interaction network) is an indicator that shows the capacity of the trophic network to resist changes due to species loss by measuring species connectivity (C) as an indirect measure of resistance (resistance increases as connectivity increases). Therefore, connectivity integrates the information about number of species (S), and number of interactions or links (L) within an interaction network	(Dunne, Williams, & Martinez, 2002)

Table A2
Description of the latent (emergent) ecological integrity indicators obtained with a Structural Equation Model of ecological integrity (Mora, 2017a).

Latent indicator	Description and interpretation
Stability (1st order indicator)	Stability is an emergent condition that describes the consistency and permanence in predator-prey interactions. As a spatial indicator, stability varies from unstable to stable conditions. Therefore, stability is described here at three levels: (1) unstable, (2) precarious; and (3) stable. An unstable condition shows a lack of key elements in maintaining species interactions as a result of trophic downgrading or biotic homogenization (by losing specialist or generalist species) and the disruption of habitat occupation mechanisms (such as habitat selection), all of which may produce potential non-desirable effects, such as the loss of horizontal biodiversity (functional diversity) and possible "cascade" effects (Duffy, 2002; Duffy et al., 2007). A precarious condition describes the ecosystem´s tendency towards a stable condition, by implementing the mechanisms of ecological memory that allow recovering unity and cohesion. Finally, a stable condition describes a state of organization in ecosystems, in which all structural (habitat functions such as connectivity and spatial integrity) and functional elements (interaction networks for predators and preys) remain unchanged due to perturbations and human impact.
Self-organization (1st order indicator)	Self-organization is an indication of an ecosystem's ability to self-regulate and self-maintain the organization of several components and their occurrence in the landscape (interaction networks and habitat use). For trophic relationships, it assumes the presence of key components for species interactions (e.g., apex predators, meso-predators and preys), which are, in turn, organized hierarchically as interaction networks. As a latent variable, self-organization describes ecosystem condition at three levels: (1) divergent; (2) convergent; and (3) concurrent conditions. A divergent condition shows that human impact has removed some or all possible elements for habitat use and distribution (e.g., top predators or prey connectivity) in such a way that the ecosystem reflects a loss of the functional balance of trophic connectivity and ecological memory. A convergent condition is present when some of the elements that sustain a species interaction are lost, but they remain in neighboring habitats, allowing their recuperation or re-colonization (depending upon habitat connectivity, ecological memory and mobile links) once the human impact decreases or is removed. A concurrent condition shows that all elements that allow a balance between convergence and divergence processes are maintained throughout evolutionary and ecological processes (e.g., the presence of apex predators regulates prey patterns in addition to other bottom-up effects).
Naturalness (1st order indicator)	As another latent variable, naturalness, qualifies the human ecological impact in a gradient from intact to impacted. As a qualitative indicator, it can be described at three levels: (1) intact, (2) deteriorated and (3) impacted. An impacted condition reflects a strong modification of ecological processes and species interactions due to a heavy human presence (i.e., thru the loss of species and interactions as well as their habitat transformation). A deteriorated condition reflects certain level of human footprint, but mechanisms of self-regulation and self-organization allow the ecosystem to recover without human influence. An intact condition reflects a null (or almost imperceptible) human impact on species interactions and their habitat; i.e., assumes that enough suitable habitats are available to sustain viable populations. The main components for naturalness integrate the modifications of prey and predator diversity indicators, as well as functional diversity, measured as the number of functional groups. Naturalness is also an indication of spatial intactness (i.e., the inverse of habitat fragmentation) in the landscape when the human impact on habitats is considered.
Mobile links (2nd order indicator)	Trophic mobile links are a measure of the buffer capacity and opportunity for reorganization after environmental impacts (Lundberg & Moberg, 2003). Therefore, the functional role of predators in maintaining landscape functional unity is accounted by the mobile link indicator. As developed here, trophic links increase positively with landscape heterogeneity and trophic (habitat) connectivity. Apex predators, as process linkers, also play a role in stability since stable conditions are directly affected by mobile links. Mobile links can be associated with some other properties, including predation risk (as trait-mediated effects), and control effects in prey and meso-predators (as density-mediated effects), and the landscape of fear (Coleman & Hill, 2014; Estes et al., 2011).
Biodiversity (2nd order indicator)	Biodiversity represents the richness in the pool of species (i.e., 239 mammal species) identified within interaction networks for extant top predators (Puma *concolor, Panthera onca, Ursus americanus, Leopardus pardalis, Leopardus wiedii, Canis latrans, Puma yagouaroundi* and *Lynx rufus*). The spatial indicators associated with biodiversity integrate the measures of prey and predators' richness, and their spatial distribution in the landscape.
Spatial (habitat) intactness (2nd order indicator)	Spatial intactness is an attribute of the natural remnant landscape. As a measure of the amount of natural remnant habitat and connectivity, is an inverse measure of habitat fragmentation. As such, it combines the measures of habitat (remnant) amount and habitat connectivity.

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