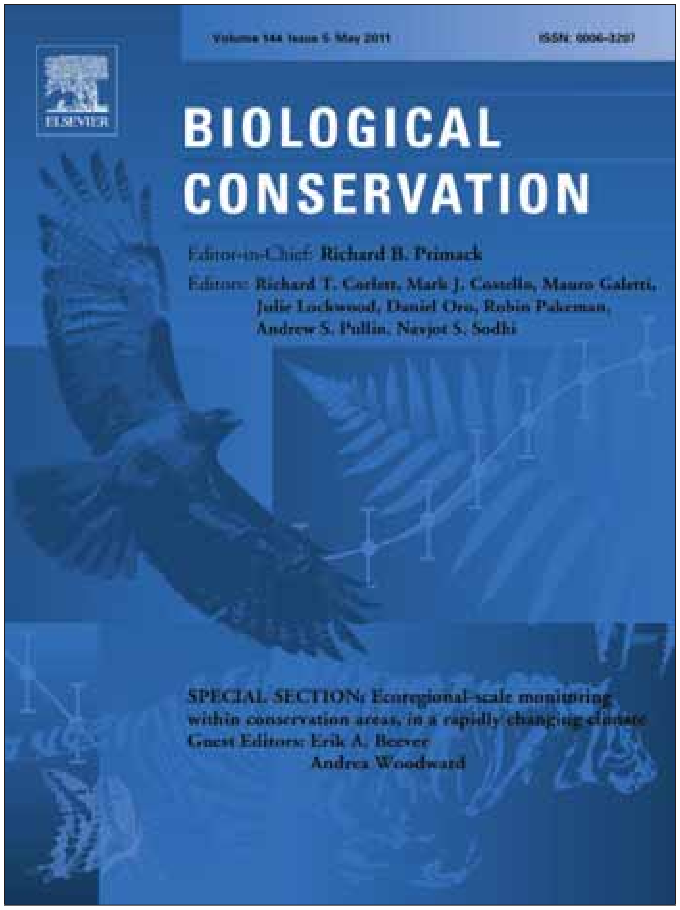
Volume 144 Issue 5 May 2011
ISSN 0006-3207
ELSEVIER
BIOLOGICAL CONSERVATION
Editor-in-Chief: Richard B. Primack
Editors: Richard T. Corlett, Mark J. Costello, Mauro Galetti, Julie Lockwood, Daniel Oro, Robin Pakeman, Andrew S. Pullin, Navjot S. Sodhi
SPECIAL SECTION: Ecoregional-scale monitoring within conservation areas, in a rapidly changing climate
Guest Editors: Erik A. Beever
Andrea Woodward

Biological Conservation 144 (2011) 1585–1594

Contents lists available at ScienceDirect

Biological Conservation

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

Incorporating temporality and biophysical vulnerability to quantify the human spatial footprint on ecosystems

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ARTICLE INFO

Article history:
Received 20 August 2010
Received in revised form 28 January 2011
Accepted 2 February 2011
Available online 4 March 2011

Keywords:
Biophysical vulnerability
Human impact
Landscape transformation
Land use intensity
Monitoring

ABSTRACT

Land use is a pervasive influence on most terrestrial ecosystems. Humans are converting natural ecosystems and appropriating an increasingly large portion of the net primary productivity of the Earth's ecosystems, leaving a rapidly expanding footprint on the environment and threatening the functioning of ecosystems and the ecological services they provide. Understanding the impacts of human activities on the environment from a local to a global scale requires an adequate representation of human modified landscapes and an explanation of the relationships between socioeconomic and biophysical factors. A first step towards this objective is the development of a quantitative measure of the spatial footprint of humans on landscapes, which can then be used as an analytical and monitoring tool for global change, biodiversity and ecosystem studies. Existing approaches have been based mainly on geographic proxies of human influence such as population density, land transformation, accessibility and infrastructure. In this paper, we developed a more comprehensive and spatially-explicit footprint index based on three dimensions: land use intensity, intervention time, and biophysical vulnerability, which we then applied to Colombia as a case study. We found the inclusion of the vulnerability index provided an effective means to address regional variability in biophysical responses to land use impacts. Accounting for the duration of human intervention provided new insights into the relative capacity of ecosystems to recover or be restored. From this knowledge, more appropriate land use policies can be developed.

1. Introduction

The conversion of natural habitat to other land covers through changes in human land use is a pervasive factor that has significantly altered most terrestrial ecosystems. This has left a growing human footprint on the environment that is threatening the functioning of global ecosystems and their ecological processes and services (Bondeau et al., 2007; Ellis and Ramankutty, 2008; Foley et al., 2005). Over much of the Earth's surface, human pressures have been progressively overriding natural processes for several thousand years, leading Crutzen (2002) to coin the term Anthropocene, further developed by Steffen et al. (2007), for this period where humankind has acquired a central role in local and global ecology. To provide for human needs, over 50% of the global usable land is already in pastoral or intensive agricultural uses, reducing the potential for the sustainable provision of many goods and services from natural ecosystems essential to support and fulfill the broad spectrum of human needs (Balmford et al., 2002; Tilman et al., 2002). While human impacts on ecosystems have been accumulating over hundreds if not thousands of years, the magnitude of these impacts has accelerated over recent decades due to the rapidly growing human population and associated resource consumption (Steffen et al., 2007; Vitousek et al., 1997).

Human activities that directly impact and change land cover and/or extract natural resources include agriculture, grazing, mineral extraction and urban development, and these are major drivers of the expanding human footprint on terrestrial ecosystems. Changes in land cover affect the functioning of ecological systems at multiple scales, with consequences ranging from regional and global climate change, to soil and hydrological degradation, increased biological extinctions and invasions (DeFries and Bounoua, 2004; Fearnside, 2000; Lambin et al., 2001; Laurance, 1999; Myers et al., 2000; Pielke et al., 2007). Vitousek et al., (1986) pointed to the rapidly increasing human appropriation of the Earth's net primary production (NPP), reducing the amount of energy available for all other species and influencing a range of ecosystem processes and services, including hydrological, carbon and energy flows. Haberl et al. (2007) calculated that current human land uses account for approximately 23.8% of the potential NPP, of which some 53% corresponds to direct harvest, 40% to changes induced by land

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doi:10.1016/j.biocon.2011.02.004

use, and the remaining 7% to human-induced fires. Ellis and Ramankutty (2008) estimated that globally only 22% of the land area is not subject to direct human occupation, and that unoccupied areas are located in the least productive ecosystems which account for only 11% of the total NPP. In the light of this imbalance, it is critical that we improve our knowledge of the extent and intensity of the human footprint.

Wackernagel and Rees (1996) first introduced the concept of the "ecological footprint" as a measure of the human impact of resource use and consumption on the environment. However, this concept lacks the spatial explicitness that would permit relating human demands to specific locations or ecosystems. This is important because the impact of the human footprint varies in response to the heterogeneity of the biophysical characteristics of ecosystems, the differences in land use and intensity, and the duration of intervention. This heterogeneity highlights the need for understanding the spatial dimension of the human footprint on terrestrial ecosystems to allow location-specific evaluation and monitoring of human impacts.

Hannah et al. (1995) developed a spatially-explicit disturbance classification index to assess the degree of human impact at the level of biomes and biogeographic provinces. More recently, Sanderson et al. (2002) developed a global map of the "human footprint" using population density, land transformation, accessibility and electrical power infrastructure as geographic proxies for human influence on the land and its resources. Such global approaches are however not well suited for regional-level analysis, as the coarse scale data fails to capture finer grain patterns. Woolmer et al. (2008) developed a re-scaled version of the "human footprint" for the Northern Appalachian/Acadian Ecoregion of North America. Their study revealed that although broad scale analysis of the Ecoregion corresponded with the global measures, the use of fine scale data highlighted the spatial complexity of the human footprint. Leu et al. (2008) modeled the spatial footprint across the western United States incorporating anthropogenic fragmentation, plant invasion risk, human fires and energy extraction sites. These measures were chosen to combine the actual area occupied by the anthropogenic features and the area influenced beyond this, such as invasive species and human-induced fires. They also evaluated the distribution of species that show affinity with human disturbed areas (termed synanthropic species) to test the model.

These approaches have mainly focused on the human footprint as an outcome of the socioeconomic stressors or variables associated with human activities such as population, infrastructure and land use (Turner et al., 2003). However, two additional components that play an important role in molding the extent and intensity of human impact have been overlooked: (i) the temporal dimension of the human impacts, and (ii) the biophysical vulnerability of the affected ecosystems. For example, savannas used for cattle grazing will maintain a closer physiognomic and functional resemblance to their unmodified state than pastures planted on former forested land and therefore the overall ecological impact should be less severe (Asner et al., 2004). A spatially-explicit measure of the human footprint which incorporates these components will provide policy makers and land managers with more detailed, spatially-explicit information on the extent of impacts and priority areas for intervention and policy reform. Such analyses will also assist in assessing the potential for destruction of carbon stores and the consequence for greenhouse gas release and land–atmosphere interactions (Bonan, 2008; McAlpine et al., 2009).

The aim of this paper is to improve the understanding of the human impacts on ecosystems, by constructing a comprehensive spatial footprint index. Our approach represents an important advance on previous studies by including the temporal and biophysical dimensions that permit a spatially and ecosystem explicit quantification of the human footprint index. First, we propose a conceptual framework for the construction of the spatial footprint index, and then we apply it to Colombia as a case study. Aside from constructing the spatial footprint index, we also assess variability in the footprint across different regions and ecosystems of Colombia.

1.1. Conceptual framework

The impact of the human footprint on terrestrial ecosystems results predominantly from the interaction of intrinsic factors from the land subject to use (e.g. soil, slope, rainfall, biodiversity) and of extrinsic factors from the types of land use (e.g. mechanization, fertilizer use, yields, nutrient extraction), and varies according to the spatial extent, the intensity, pattern, and duration of use. The footprint also changes with time as land use changes with the expansion and contraction of the societal demands for ecosystem services and natural resources such as food, fiber, and timber.

These considerations highlight the importance of taking into account the biophysical, socioeconomic and temporal contexts of human activities, in order to obtain a comprehensive approximation of the environmental impacts. We propose a framework to build a quantitative spatial and ecosystem specific human footprint indicator by addressing different variables grouped under three dimensions (Fig. 1): (i) land use intensity, (ii) intervention time, and (iii) biophysical vulnerability of the impacted ecosystems.

1.1.1. Land use type and intensity

This refers to the prevailing land use including management type. The type of land use is a basic factor, as it determines the level of habitat modification and resource extraction. Ecosystems respond differently to different types of land use as the level of environmental modification and the associated impact differs among land uses (DeFries et al., 2004).

The intensity of land use also needs to be addressed, because similar land use types with different intensities (mechanization, agrochemical use, water, nutrient extraction and urbanisation) produce different impacts. The intensity also depends on pressure factors (proxies) such as rural and urban population density, proximity to roads and settlements, energy supply (Geist and Lambin, 2002; Sanderson et al., 2002; Wright and Muller-Landau, 2006). These variables are important because they are related to biodiver-

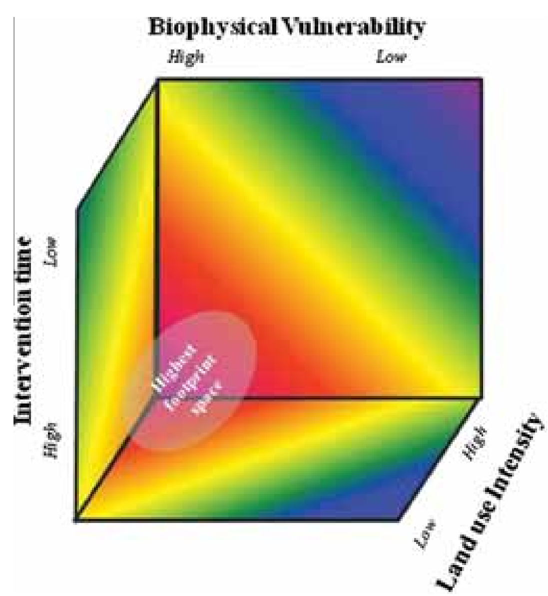

Fig. 1. Conceptual 3D diagram of the spatial footprint space constructed with the dimensions of land use intensity, intervention time, and biophysical vulnerability.

sity loss and invasion risk (e.g. due to land clearing, disturbance, roads); soil degradation and water availability (e.g. due to land clearing, mechanized farming, grazing); pollution (settlements, energy use, transportation roads); GHG emissions (urban areas, intensive agriculture, grazing, transportation). Other indicators of land use type and intensity include the degree of fragmentation (Fischer and Lindenmayer, 2007), and the reduction of biomass through land cover conversions such as from forest to pasture, cropping or urban land use.

1.1.2. Intervention time

The duration of time that the landscape has been subject to human disturbance determines: (i) how long land use has been continuously impacting an ecosystem, and (ii) the likely time lag of environmental response. Environmental impacts usually involve a time lag making biotic responses non-linear, as species and processes (extinction and invasion) may take years or decades to adjust to land use and land cover change, particularly if small patches of remnant vegetation allow temporary persistence of a species (Gardner et al., 2009; Hanski and Ovaskainen, 2002; Tilman et al., 1994). These lags may disguise the impact of human activity on landscapes and biota until a tipping point has been reached, after which irreversible changes may occur (Dupouey et al., 2002; Gardner et al., 2009).

1.1.3. Biophysical vulnerability

Ecosystems and landscapes respond differently to human disturbance depending on their biophysical characteristics such as the climatic conditions, topographic relief and soil types (Hobbs and McIntyre, 2005b; Turner et al., 2003). Hobbs and McIntyre (2005b) use the term "sensitivity to ecological dysfunction" which is associated with the concept of vulnerability. We use the concept of vulnerability following Turner et al. (2003) as the degree to which a system is likely to experience harm due to exposure to human land use.

We propose a measure of the biophysical vulnerability of the land through identifying "vulnerability factors" that are related to degradation processes such as erosion, hydrologic disruption and biologic extinction. Indicators of vulnerability include attributes such as slope (Salvati and Zitti, 2008), soil fertility (Jie et al., 2002), moisture deficit (drought stress) or excess, and number of endemic or restricted geographical range (e.g., less than 50,000 km^2) species (Abbitt et al., 2000; Purvis et al., 2000). Arid or extremely high rainfall areas, poor soil areas or steep sloping areas are more susceptible to degradation of soil and water resources supporting ecosystem productivity, and small range species more vulnerable to extinction by habitat transformation and disturbance. Species chosen are likely to vary between countries, but the majority of regions will contain a range of suitable indicator species.

Based on the above considerations, we propose a spatial footprint index F_{tot} composed of three sub-indices F_{int} (Land Use Intensity), F_{time}, (Intervention Time) and F_{vuln} (Biophysical Vulnerability) which together group 11 factors each weighted equally (Eqs. (1)-(3)). The spatial footprint index is generated for the entire terrestrial ecosystem area and is normalized to a scale between 0 (low) to 100 (high) (Eq. (4)).

$$F_{int} = \mathrm{LU} + \mathrm{PD} + \mathrm{DR} + \mathrm{DS} + \mathrm{FI} + \mathrm{BI} \quad (1)$$

$$F_{time} = \mathrm{TI} \quad (2)$$

$$F_{vuln} = \mathrm{SF} + \mathrm{SL} + \mathrm{MI} + \mathrm{ED} \quad (3)$$

$$F_{tot} = (F_{int} + F_{time} + F_{vuln}) * 100 / \sum (F_{int}\max + F_{time} \times \max + F_{vuln}\max) \quad (4)$$

where LU is land use type, PD is rural population density, DR is distance to roads, DS is distance to settlements, FI is fragmentation index of natural vegetation, BI is the biomass index relative to natural potential, TI is time since intervention in years (in case of clearing-recovery events, from last land clearing event), SF is soil fertility index, SL is slope, MI is moisture availability index, and ED is number of small (<50,000 km^2) range species.

2. Materials and methods

2.1. Study area

We used Colombia as a case study for applying the spatial footprint index. Colombia (1.1 million km^2) is located in the equatorial zone (10°N and 2°S) and comprises six major biogeographic regions: Andean (278,000 km^2), Inter-Andean (44,000 km^2), Caribbean (115,400 km^2), Pacific (74,600 km^2), Amazon (455,000 km^2), and Orinoco (169,200 km^2 (Fig. 2). Across these regions, there are large variations in altitude (0–5800 m), mean annual rainfall (300–10,000 mm), length of growing period (60–360 days year^{-1}) and geological substrate. A salient characteristic of Colombian geography is its high environmental variability relative to its geographic size, with Colombian ecosystems ranging from desert and tropical savannas, to very humid rainforests and tropical snow-covered mountains. This high environmental variability has resulted in high levels of endemism and species richness, making Colombia a mega-diverse country (Hernández et al., 1992; Myers et al., 2000). The Northern Andes in particular, is an area with one of the highest concentration of birds with small geographical ranges in the world and therefore highly susceptible to land clearing (Orme et al., 2005; Pimm et al., 2006). Also, IUCN estimates

Fig. 2. Study area map showing the major natural regions of Colombia.

show that Colombia has the highest number of threatened amphibian species (214), many of which are endemic (http://www.iucnredlist.org/initiatives/amphibians).

Over the past millennia, Colombia has undergone several historical periods of human landscape transformation, including pre-Columbian and Colonial periods, which have lead to a cumulative human footprint extending over much of its territory, especially the Andean and Caribbean regions (Etter et al., 2008). In 2008, the total population exceeded 44 million, a tenfold increase from 1900. Since the 1970s, Colombia has become an increasingly urban and industrialized country, with 75% of the population residing in urban areas, and over 100 cities with more than 50,000 inhabitants. With this transition, the rural population is stabilizing and the average national population growth rate fell below 2% in the late 1990s (Departamento Administrativo Nacional de Estadistica – DANE (National Statistics Department), 2008). The population has historically been and continues to be concentrated in the Andean and Caribbean regions which have a rural population density of approximately 33 persons per km^2, while the Pacific, Orinoco and Amazon regions have much lower densities ranging from 5 to 17 persons per km^2. Approximately 45% of the terrestrial ecosystems have been cleared (Etter et al., 2006).

The Colombian economy is mostly based on mining (oil, coal and nickel), export crops (coffee, flowers) and some industrial exports. The area devoted to cattle grazing is more than 85% of the agricultural area (Corporación Colombia Internacional (CCI), 2008). Low governance in frontier areas still facilitates the expansion of the agricultural frontier, often fueled by a pervasive export economy of illegal crops in remote rainforest areas (Coca – *Erythroxylum coca* – in the lowlands, and Opium – *Papaver somniferum*, in the highlands), which also causes social and political instability.

2.2. Data

The data used to calculate the spatial footprint for Colombia are grouped into the three dimensions identified in the conceptual framework with a total of six biophysical, one temporal and four socioeconomic variables (Table 1). The base datasets used for spatial analyses included the "present ecosystem" and "original ecosystem" maps of Colombia from Etter et al. (2008). Most of the data used in this study corresponded to the period 2000–2005. For the analysis, all datasets were unified to a common 1 km grid using the ArcGIS 9.3 software.

2.3. Calculations

All variables were re-scaled to an ordinal 0–5 scale indicating nil to very high footprint contribution based on the classes shown in Table 2. The values of all variables were added to generate a partial footprint index map, permitting the spatially explicit visualization of the contribution of each dimension to the overall footprint. Finally, the three maps were added and normalized to a 0–100 scale to produce the human footprint index map. The Biophysical Vulnerability Index (F_{vuln}) was applied only to those grid cells where land use and extended impacts of infrastructure had occurred as indicated by the Land Use Intensity Index (F_{int}) and the Intervention Time Index (F_{time}).

To analyze the spatial pattern of the footprint on native ecosystems, we performed a spatial pattern analysis using the Fragstats software (McGarigal et al., 2002), to quantify the number, mean size and the degree of connectedness of remnant native ecosystems defined in terms of the patch patterns of four broad footprint classes (0–20, 20–40, 40–60, >70).

To analyze the spatial distribution of the footprint index, the final map was overlaid with the map of natural regions as defined in Etter et al. (2006), the altitude map, the general ecosystem map, and general land use map (Etter et al., 2008) and a general conservation status map.

Finally, we performed a cross tabulation and comparison with Sanderson's global human footprint map (Sanderson et al., 2002). Because both maps were constructed with different data sources and variables, we used their standardized versions in a common 1 km grid, to calculate the Kappa statistic. We also subtracted the grid values of the two maps to calculate the spatially explicit differences and identify areas where our map showed higher or lower values.

3. Results

3.1. Footprint intensity scaling

The three indexes corresponding to the three footprint dimensions showed marked differences in their spatial patterns across the country, indicating a region-specific interaction (Fig. 3a–c). The highest overall values of the total footprint were located where the high values of the three maps coincide (Fig. 3d). The time of exposure to land use is particularly long in the Andean and Carib-

Table 1
Variables considered and sources used in the construction of the spatial footprint index for Colombia.

Dimension	Variable	Source	Spatial resolution or scale of data
Land use intensity	Present land use type (LU) [a]	Etter et al. (2006), IDEAM (2008)	1 km grid
	Rural pop. density Inhab/km^2 (PD)	DANE (2005)	1 km grid
	Distance to roads km (DR)	IGAC (2005)	1 km grid (originally 1:100 000)
	Distance to settlements km (DS)	IGAC (2005)	1 km grid (originally 1:100 000)
	Fragmentation index (prop. natural vegetation in 50 × 50 km) (FI)	Etter et al. (2006)	1 km grid
	Biomass index (relative to original ecosystem) (BI)	Anaya et al. (2009)	500 m resampled to 1 km grid
Intervention time	Number of years of intervention (TI)	Etter et al. (2008)	1 km grid
Biophysical vulnerability	Soil fertility class (SF)	IGAC (1983), Etter et al. (2006)	1 km grid
	Slope% (SP)	SRTM (Nasa)	90 m grid resampled to 1 km
	Moisture Availability index (MA)	IWMI (2009)	1 km grid
	Number of small range (<50,000 km^2) amphibian and mammal species (ED)	NatureServe (2009)	1 km grid

[a] Natural vegetation, Fallows and secondary vegetation, Forestry plantations, Heterogeneous agriculture, Perennial crops, Pastures in natural grasslands, Pastures in introduced pastures, Annual intensive agriculture, mining, urban.

Table 2
Scaling of the value ranges of each variable used in the analysis.

Contribution to footprint value	Variables of analysis										
	Land use	Time of intervention (years)	Rural population density Inhab (km^2)	Distance to roads (km)	Distance to settlements (km)	Fragment (% natural in 250 km^2)	Biomass (% from potential vegetation)	Relative fertility	Slope (%)	Moisture Availability index	No. of small range Amphibian and Mammal species
0	Natural	0	0	>20	>25	100	100	Very high	<1	35–40	0
1	FALLOWS AND SECONDARY VEG	<30	<2	>8	>15	<90	<90	Very high	<5	35–40	0–2
2	FOREST PLANT, HETEROG. AGRIC.	30–70	2–7	5–8	10–15	60–90	60–90	High	5–10	30–35, 40–42	2–5
3	PERRENIAL CROPS, PASTURES	70–150	7–15	3–5	6–10	30–60	30–60	Moderate	10–25	20–30, 42–48	5–10
4	ANNUAL INTENSIVE AGRIC.	150–300	15–35	1.5–3	3–6	10–30	10–30	Low	25–50	6–20, 48–58	10–15
5	URBAN, MINING	>300	>35	0–1.5	0–3	<10	<10	Very low	>50	<6, >58	>15

bean regions, where also the higher vulnerability values occur, therefore reinforcing the overall footprint.

The footprint map provided a detailed pattern of the variable impacts, with strong regional contrasts. For the half of the country that has been extensively transformed through land use, 70% of this area (35% of the total land area) has a footprint greater than 40. However, a similar area still has a low level of human impact with an index of less than 10 (Fig. 4). The higher footprint indices were concentrated in the Andean, inter-Andean (Catatumbo and Magdalena) and Caribbean regions where more than 50% of the area exhibits a footprint class >50. In the Andean region, the footprint was highest in the 1000–2500 m altitude range where most of the population and settlements are concentrated. In contrast, in the lowland and less populated Amazon and Orinoco regions, more than 80% of the land area had spatial footprint values below 20.

The patterns of the footprint map indicate that the historic human impacts have left a heterogeneous spatial pattern of remnant vegetation. The number of remnant patches was highest for the intermediate footprint (30–60) values (Fig. 5a), while the average patch area was highest in the lower footprint range (<20) located in the forests and savannas beyond the agricultural frontier (Fig. 5b). The connectedness of patches was highest in both the high (>70) and in the low (<20) footprint classes (Fig. 5c), reflecting that the intermediate footprint values (20–60) occur in a very fragmented and interspersed pattern.

3.2. Footprint at the ecosystem and management area levels

When analyzed against major ecosystem types, the Dry tropical forests, Sub-humid tropical forests and Tropical montane (Andean) forests had more than 50% of their area with footprint values greater than 50 (Table 3). The remnant Dry forests which accounted for only 10% of the original area, had over 80% of their area with values larger than 50. In contrast, the Humid tropical forests, Alluvial forests, Deserts and scrublands, and Savannas had more than 50% of their area with footprint values under 20.

As expected, the Indigenous and Afro-American reserves had >80% of their areas with footprint values <10. For the National Parks, approximately 60% had values <10, while surprisingly 35% of their area had spatial footprint values between 20 and 40, especially for conservation areas located in the Andean region. The remnant "natural lands" in the "National Forests" category that do not have a strict legal conservation status (Park or Reserve) but are located beyond the agricultural frontiers, still have 35% of their area in the 0–20 range. However, 35% of their area was in the 30–60 footprint index range. In contrast to the conservation areas and national forests, the mosaics of the cleared (agriculture) areas show predominant values in the 50–70 ranges (Fig. 6).

The footprint index classes across the major current land uses are as anticipated highest in urban and intensive agriculture areas, followed by mixed agriculture and grazing on introduced pastures. However, we found striking differences in cattle grazing land uses, with grazing on introduced pastures that occupy former forested lands having more than 50% of their current area with an index greater than 50, compared to cattle grazing in natural savanna grasslands that have 85% of their area with an index of less than 30.

3.3. Footprint index comparison

The cross tabulation between the Sanderson Map (Sanderson et al., 2002) and our spatial footprint map had a Kappa Index of 0.38, interpreted as a fair level of agreement (Altman, 1991). This indicates that there were important differences between the two maps resulting from the additional information on vulnerability and time of exposure used in our approach. These differences were evident in the spatial patterns of both maps as seen in Fig. 7a. This was further revealed in the spatially explicit comparison of the standardized versions of both maps (Fig. 7b), which portrayed an intricate pattern of areas with positive and negative differences between the two. Our map showed in general higher values in the Andean region, and in the recently colonized areas in the lowlands. The Amazon was the region showing the least differences.

4. Discussion

A major challenge for society, in view of the increasing demands of a growing human population, is to plan and accommodate these demands without extending the human footprint and destroying remaining terrestrial ecosystems (Ojima et al., 2007). The future expansion of agriculture and other land uses needs be carefully planned to avoid undesirable levels of human impact that could lead to further degradation of agricultural systems, remnant ecosystems and biodiversity. Steffen et al. (2007) stress that humanity needs to enter the "Earth stewards" phase of the Anthropocene, characterized by improved decision making and consciousness about the environmental impacts of society's demands. Quantifying and evaluating the impact of human activities on ecosystems in a spatially explicit way can provide an information base to guide such decisions and awareness.

4.1. Human footprint in Colombia

When comparing the spatial footprint index of our map with the Sanderson map, which is the only other exercise available for Colombia, several differences can be observed. Although some of

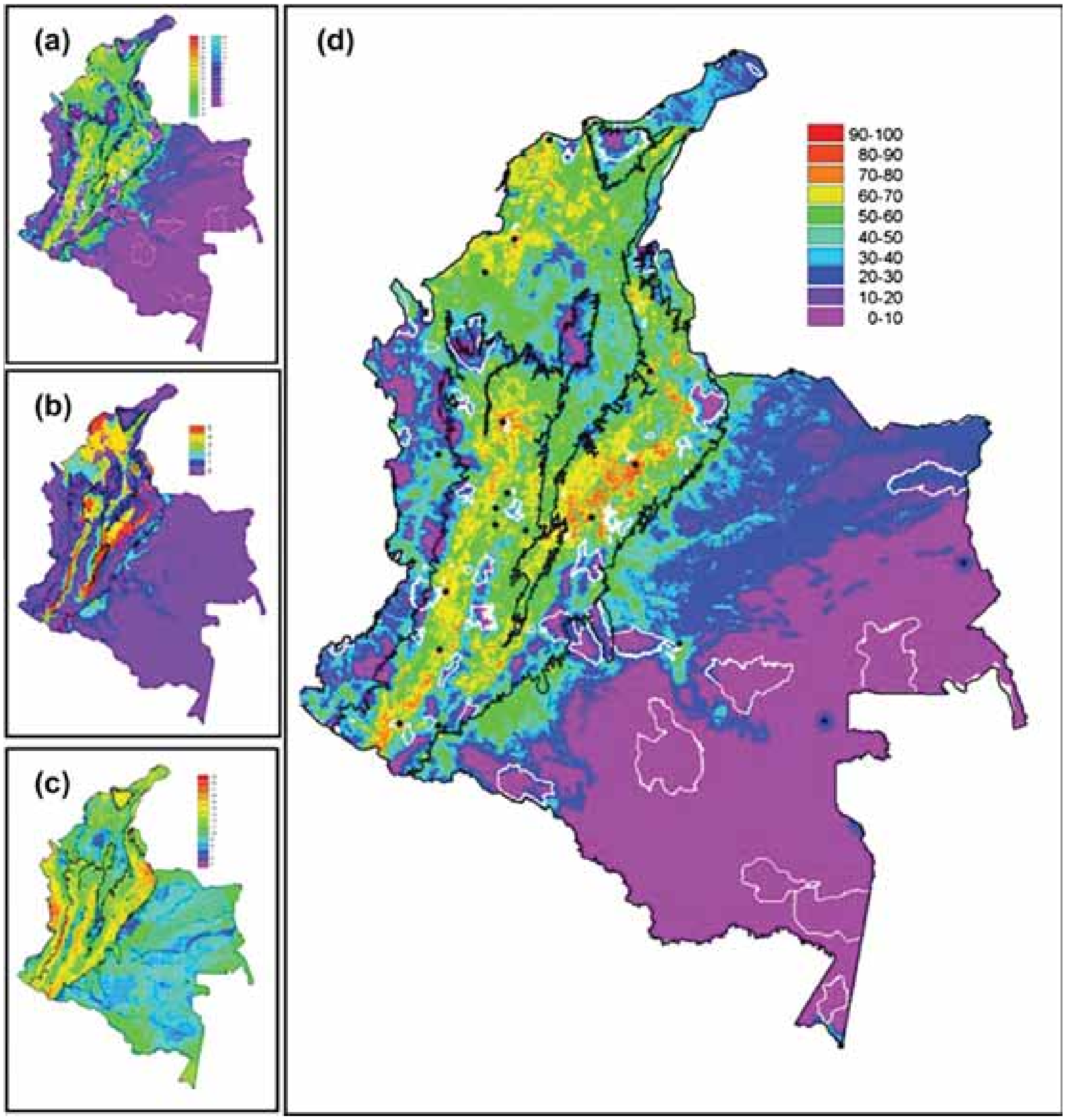

Fig. 3. The spatial footprint indexes and footprint map of Colombia. The Fig. shows the disaggregated footprint indexes for: (a) land use intensity, (b) intervention time and (c) biophysical vulnerability; and (d) the consolidated footprint index (black line – Andean region, white line – National Protected Areas, black dots – main cities).

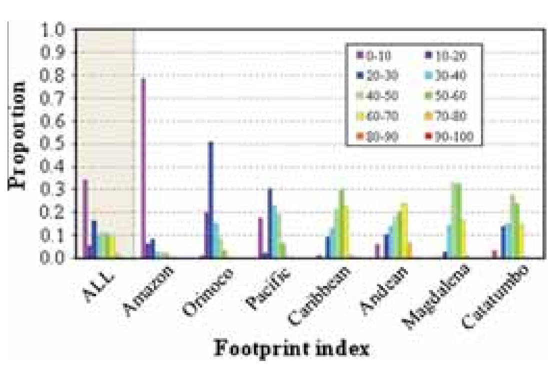

Fig. 4. Distribution of the footprint intensities for the entire country compared with the footprint for the regions.

the differences arise from the data of both studies corresponding to partly different timeframes in infrastructure and land use, most of these can be attributed to the use of the additional information on exposure time and biophysical vulnerability. For example, the Andean region that has been intensively used for longer time periods and also has higher associated vulnerability weightings, may explain the observed relative underestimation of the footprint in the Sanderson map. Areas showing differences in the Pacific region can be interpreted by the additional vulnerability measure too.

The results of our exercise are by nature limited by the date, scale and types of the variables used to calculate the index. The present extent of the human footprint in Colombia as seen through our approach can still be classed as moderate, considering that over 50% of the country still has low levels (<20) of impact. However, regions such as the Andes and Caribbean have less than 10% of their area in the lower footprint classes (<20). This is alarming considering that the Andean region has been identified as a priority area for the conservation of biological diversity (Orme et al., 2005), and for protection of hydrological flows, as it contains most of the upper watershed areas of the major rivers of the country. Importantly, a large part of the national footprint can be attributed

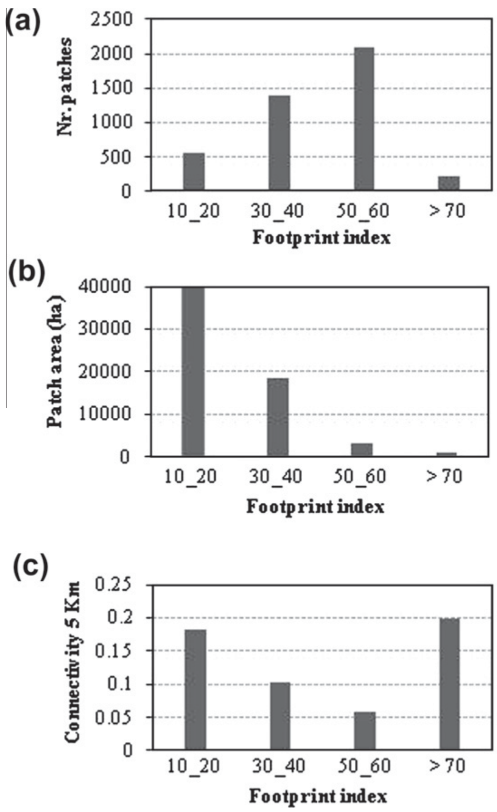

Fig. 5. Spatial patterns of the footprint classes for the natural remnant vegetation: (a) number of patches, (b) mean patch size, and (c) 5 km connectance index.

to extensive low productivity cattle grazing land uses (Etter et al., 2008). One option for future planning would be to increase the intensity of these land uses and thereby slow the spatial expansion of the human footprint (Balmford et al., 2005; Grau and Aide, 2008). Intensification also has other potential benefits such as the overall net effect globally of higher agricultural yields from intensification since the 1960s that have resulted in a reduction in greenhouse gas emissions (Burney et al., 2010).

4.2. Applications of the spatial human footprint

Our framework for assessing the human footprint identifies current environmental impact levels, and can also provide information on where future and cumulative environmental impacts are more likely to occur, by accounting for the time since intervention and biophysical vulnerability of the land. We are therefore provided with information on how the most vulnerable areas are geographically distributed and this can facilitate proactive management to control negative environmental impacts.

By considering the time frame and a measure of the vulnerability of the site in terms of biophysical factors, the approach presented in this paper shows several improvements compared to the previous proposals by Hannah et al. (1995) and Sanderson et al. (2002). In general, the footprint methodology we have presented reflects a more ecosystem specific response, permitting a more precise identification of the degree of human impact. It is therefore able to better guide land use planning decisions.

One obvious possible application of the spatial footprint mapping is its inclusion in prioritization of conservation and/or restoration planning. Ecosystem management in both natural areas and rural landscape mosaics needs to be informed by the level of human impact as this can influence the likelihood of success of investments. For instance, our approach helps quantify the variability between "ecosystem remnants" in fragmented rural landscapes by distinguishing the degree of "naturalness" of the individual remnants as a base for a more detailed field-based evaluation of their conservation functionality in terms of the human impact.

4.3. The next step

It should be stressed that footprint analyses such as ours, although becoming increasingly comprehensive, are an underestimate of the real impacts of society on the global environmental system due to the exclusion of several aspects concerning the atmospheric (local climate feedbacks, pollution), hydrologic (catchment dynamics) or biological (factors such as species mobility, dispersal and invasions) dimensions.

It is implicit in our study that a higher footprint index directly represents more severe impact on biodiversity and ecological processes. However, we need to emphasize that the processes of land use and land cover change and resource extraction are often complex, comprising trends that include land clearing, conversion, modification, intensification, and eventually also counteracting

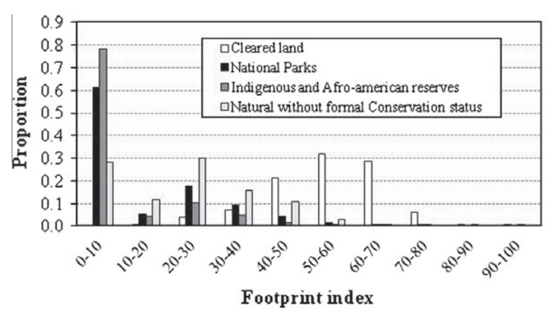

Fig. 6. Variation of the intensity of the footprint index in relation to the conservation status types.

Table 3
Proportion of the remnants from major ecosystems in the different footprint index classes.

Ecosystem	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100
Alluvial forests	0.36	0.12	0.22	0.09	0.10	0.06	0.03	0.01	0.00	0.00
Deserts and scrublands	0.00	0.00	0.45	**0.53**	0.02	0.00	0.00	0.00	0.00	0.00
Dry tropical forests	0.00	0.00	0.03	0.04	0.13	0.33	0.41	0.07	0.00	0.00
Highland "Páramo" vegetation	0.10	0.00	0.16	**0.36**	0.21	0.11	0.04	0.01	0.00	0.00
Humid tropical forests	0.66	0.05	0.09	0.06	0.08	0.05	0.01	0.00	0.00	0.00
Mangrove forests	0.06	0.03	0.39	0.29	0.11	0.08	0.04	0.01	0.00	0.00
Montane tropical forests	0.11	0.00	0.11	0.14	0.19	0.20	0.21	0.05	0.00	0.00
Savannas	0.07	0.18	0.50	0.14	0.07	0.03	0.01	0.00	0.00	0.00
Sub-humid tropical forests	0.06	0.00	0.06	0.10	0.31	0.39	0.07	0.00	0.00	0.00

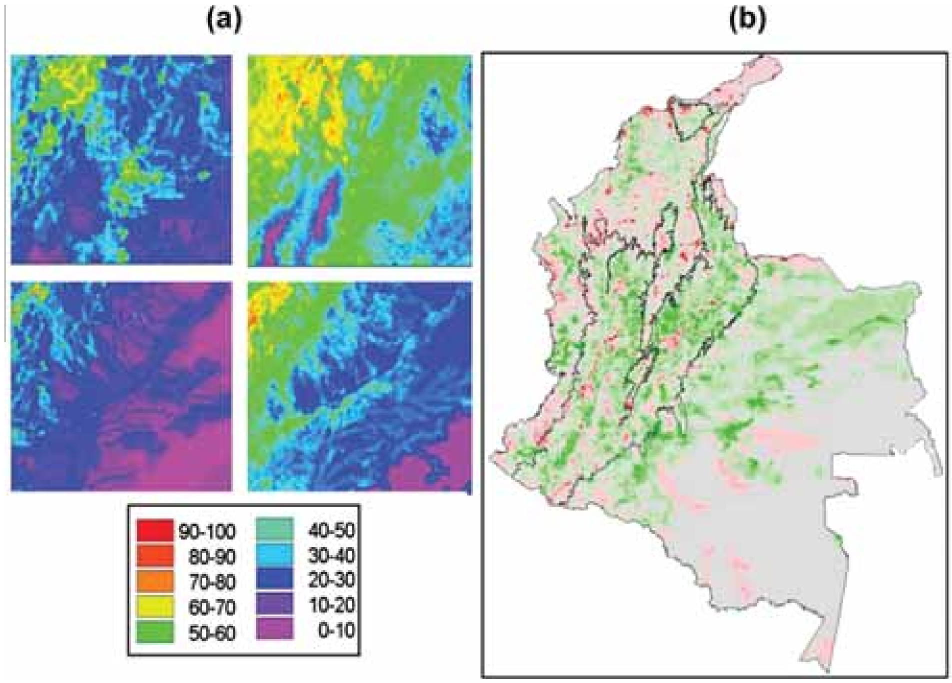

Fig. 7. Differences in spatial patterns of the human spatial footprint between the "Human footprint" (Sanderson et al., 2002) and this study as visualized in: (a) LEFT the Human Intensity Index of the Sanderson Map, and RIGHT the Footprint Index of this study; (b) spatially explicit comparison of the standardized maps used in comparison: RED Sanderson et al. (2002) slightly to strongly overestimates; GREEN Sanderson et al. (2002) slightly to strongly underestimates.

processes of land abandonment and forest regeneration (Bowen et al., 2007; Cramer et al., 2008; Grau and Aide, 2008). There are two major challenges to including such dynamics into our conceptual framework.

First, a complication of measuring temporal change is that over centuries land use may vary in intensity, with cycles of development and abandonment, and the partial recovery of damaged ecosystems (Cramer et al., 2008; Foster et al., 2003; Jones and Schmitz, 2009; Rudel et al., 2005). The "forest transition theory" describes such a scenario, which predicts that the cumulative impact of the human footprint can be at least partially reversed given the proper demographic and socioeconomic conditions (Rudel et al., 2005). Such circumstances of land use changes may lead to ecological transitions that counteract human impacts and restore biologically and ecologically complex systems (Balmford et al., 2005). A recent study by Jones and Schmitz (2009) provides insight into the effectiveness of the recovery from human transformation of various ecosystem types under several timeframes and management conditions.

Second, the accumulated impacts of the historical land uses (Dupouey et al., 2002) may lead to "novel ecosystems" (Hobbs et al., 2006; Lindenmayer et al., 2008), which may still fulfill some ecological functions but have an associated ecological cost for species that cannot adapt to change. Several examples of novel ecosystems exist in relation to introduced alien grasses. Such is the case of the Kikuyo (*Pennisetum clandestinum*) grasslands which have displaced extensive areas of native ecosystems in the sub-humid to humid Andean ranges in the 1500–3000 m altitude range (Etter et al., Unpublished), or the Buffel grass (*Cynodon dactylon*) grasslands in northern Australia (Friedel et al., 2006).

Extensions to our framework to incorporate temporal trends would provide an opportunity to more closely scrutinize processes that relate to the possible future outcomes for heavily impacted areas in relation to: (i) land abandonment and the recovery of damaged ecosystems (Jones and Schmitz, 2009), and (ii) the value and irreversibility of human-triggered novel ecosystems (Lindenmayer et al., 2008).

Urban areas concentrate half of the world population at present, which by 2030 is expected to rise to 70%, implying that the urban footprint will expand further. Urban areas already consume an estimated 80% of global energy, generate over 70% of all waste, and directly contribute to over 60% of greenhouse gas emissions. Because most consumed goods and energy are not locally produced, the urban footprint characteristically extends far beyond the area where the demands originate (e.g., Güneralp and Seto, 2008). It is imperative to find ways to approach the footprint of teleconnected impacts of urban land uses to calculate the urban footprint more accurately in a spatially explicit manner.

In light of regional and global climate change, we require a refined quantification of the human footprint to incorporate aspects of land use impacts on local and regional climate via direct or proxy data of land cover change such as the return of water vapor to the atmosphere, cloud formation, and wind speed alterations. Examples of such studies already exist in the Amazon (Roy and Avissar, 2002; Sampaio et al., 2007) and Australia (McAlpine et al., 2009; Pitman et al., 2004).

An important consideration for the mapping and prediction of the human footprint is the issue of scale and spatial resolution (Hobbs and McIntyre, 2005a). For assessments about the human impacts to be applicable in planning and decision making, spatially explicit and multi-scale approximations are needed. Local analyses cannot be addressed with the same variable categories as global or broad scale national analyses. We need to link specific attributes and processes affected by human ecosystem modification to each scale of analysis. For example, broad measures of land cover change that are useful to address impacts on the local–regional climate or species movements, may not be appropriate to analyze species viability or soil degradation.

An important and necessary next step will be to test the footprint index with biological and ecological field data in order to validate its applicability to land management and conservation. For this, we need to address the parameterization of the link between the footprint index and the biological responses to it, so that the footprint index can be translated to species and community specific indexes. This also requires access to knowledge of the original condition of local ecosystems in order to undertake comparative assessments.

5. Conclusions

The growing global environmental problems related to the high demands from the human population have resulted in the global system being pushed outside its resilience boundaries. Appropriate management actions to mitigate and control these problems need to rely increasingly on the adequate assessment and monitoring of the different levels of human impacts on ecosystems and resources. However, this requires a refined quantification and upscaling of the human footprint to incorporate spatial and temporal aspects of land use impacts from local and regional scales. To make the knowledge about such human impacts operational in a land use planning decision framework, these need to be considered in the context of the complex interactions between land use and the biophysical environment within which they arise. Use of the spatially explicit and multi-temporal framework we have provided to quantify the human spatial footprint is a promising way to achieve this goal. Such an approach will further help improve the dialog between science and decision makers, by allowing the comparison of alternative scenarios of future land use.

Acknowledgements

This research received funds from the Javeriana University Research Fund. We acknowledge valuable inputs from reviewers that helped improve the manuscript.

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