Land Use Policy 99 (2020) 104874

Contents lists available at ScienceDirect

Land Use Policy

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

Assessing restoration priorities for high-risk ecosystems: An application of the IUCN red list of ecosystems

Andrés Etter[a,*], Angela Andrade[b], Cara R. Nelson[c], Juliana Cortés[a], Kelly Saavedra[a]

[a] Department of Ecology and Territory, Pontificia Universidad Javeriana, Bogotá, Colombia
[b] Conservación Internacional-Colombia, Bogotá, Colombia
[c] Department of Ecosystem and Conservation Sciences, Franke College of Forestry and 9 Conservation, University of Montana, Missoula, Montana, United States

ARTICLE INFO

Keywords:
Ecosystems at risk
Environmental degradation
Prioritization
Land use trade-offs

ABSTRACT

Land clearing and ecosystem degradation are primary causes of loss of biodiversity and ecosystem services worldwide, putting at risk sustainable options for Earth and humankind. According to recent global estimates, degraded lands already account for at least 1 and up to 6 billion ha. Given high rates of habitat degradation and loss of biodiversity in human-dominated landscapes with high levels of ecosystem transformation, conventional approaches to conservation such as setting aside lands in protected areas, are not enough; in combination with ecosystem protection, ecological restoration is essential to ensure the conservation of biodiversity and delivery of ecosystem services. Despite recognition of the role of ecological restoration, the planning of restoration at the landscape scale remains a major challenge. Specifically, more studies are needed on developing restoration plans that maximize conservation and provisioning of ecosystem services, while minimizing competition with high-productivity land uses. We use Colombia, one of the world's mega-diversity countries in which ca. 25 % of ecosystems are listed as critically endangered (CR), as a test case for exploring the potential advantages of including the Red List of Ecosystems, a newly developed tool for assessing conservation value, in restoration planning. We identified restoration priorities focused on both high-risk ecosystems and low-productivity lands, to maximize conservation value and minimize land-use conflicts. This approach allowed us to identify over 6 M ha of priority areas for restoration, targeting the restoration of 31 (75 %) of the country's endangered ecosystems. Eight of the Regional Administrative Environmental Planning Areas (CARs) had greater than 20 % of their area identified as restoration priorities. We roughly estimated that the cost of restoring the prioritized areas with restoration through natural regeneration, using payment for ecosystem services (PES), would equal less than 50 % of the annual budget of the CARs. Our results are in sharp contrast (only 12 % agreement) with the priorities identified under the current National Restoration Strategy of Colombia, and highlight the potential contribution of the Red List of Ecosystems in refining and improving restoration planning strategies at both national and sub-national levels.

1. Introduction

Land clearing and ecosystem transformation and degradation associated with an increasing demand for land, especially for agriculture, are major causes of the decline in biodiversity and the linked ecosystem services worldwide, putting at risk options for humankind to have a sustainable future on Earth (Foley et al., 2005; Cardinale et al., 2012). Currently, there are an estimated one to six billion hectares of degraded lands across the globe (Gibbs and Salmon, 2015) that cost more than 230 billion USD per year, an equivalent of 0.4 % of global GDP (Nkonya et al., 2016). This level of land degradation (Millenium Ecosystem Assessment, 2005), has created an unprecedented need for ecosystem restoration —the process of assisting in the repair of lands that have been degraded, damaged, or destroyed (SER (Society for Ecological Restoration), 2004; Gann et al., 2019). There is currently widespread agreement on the need for ecosystem restoration (Alexander et al., 2011; Aronson and Alexander, 2013) and ambitious global restoration targets have been created (e.g., Bonn Challenge and UN Convention on Biological Diversity Aiche Targets), with a growing number of countries engaging in strategic prioritization of areas for ecological restoration (IUCN, 2019b). However, restoration prioritization is often done without adequate consideration of biodiversity or at-risk ecosystems (but see, Martinez-Harms et al., 2017; Bland et al., 2019). Thus, there is a critical need to integrate restoration and conservation planning in

* Corresponding author: Tr. 4 Nr 42-00, piso 8, Pontificia Universidad Javeriana, Bogotá, Colombia.
E-mail address: aetter@javeriana.edu.co (A. Etter).

https://doi.org/10.1016/j.landusepol.2020.104874
Received 29 November 2019; Received in revised form 8 June 2020; Accepted 22 June 2020

large-scale initiatives, especially in recognized biodiversity hotspots, such as the tropical Andean countries - Colombia, Venezuela, Ecuador, Peru and Bolivia, given their disproportionate importance to global species protection and conservation.

Although conservation initiatives have historically been based on ecosystem protection as the main strategy, there is increasing recognition that ecological restoration is equally as critical for effective conservation, given continued high rates of ecosystem transformation across the globe (Gann et al., 2019; Possingham et al., 2015). Increasingly large proportions of highly endangered ecosystems exist outside of protected areas (Watson et al., 2016), embedded within a matrix of human dominated lands. Therefore, restoration is critical to protect threatened ecosystems outside of protected areas but also to restore connectivity among remnant patches. Additionally, many protected areas are subject to human pressures and degradation, and have begun to resemble their surrounding modified environments (Laurance et al., 2014); therefore, many sites even within the borders of protected areas require ecological restoration. Thus, effectively reversing habitat degradation and ensuring the conservation of biodiversity and availability of supported ecosystem services in face of global change, requires the integration of conservation and restoration assessments and activities into land use planning (Possingham et al., 2015; Wiens and Hobbs, 2015).

Restoration as a tool for conserving biodiversity will become even more important in face of increasing ecosystem degradation and climate change (Lomax, 2015), and the consequent increase in number and extent of endangered ecosystems outside of protected areas. For instance, currently, half of remaining tropical forests have been degraded to some degree, and this trend is likely to advance especially in South America and Africa because these regions harbor most of the currently unexploited land in the topics; therefore, the pressure to clear land for agriculture in the future will increase in these areas (Laurance et al., 2014). At the same time vast expanses of tropical lowland forests of Latin America have been cleared for low-productivity and high-impact cattle grazing (Wassenaar et al., 2007; McAlpine et al., 2009). These large underproductive areas represent important opportunities for ecosystem restoration that could be implemented with sustainable development initiatives.

To address the huge restoration imperative, the UN Convention on Biological Diversity (CBD) included strategic targets in its 2011 – 2020 strategic plan, and IUCN launched the Global Partnership on Forest and Landscape Restoration (GPFLR) in 2003, later followed by the Bonn Challenge (2011) and the New York Declaration on Forests (2014). Although the GPFLR produced a map of potential forest landscape restoration opportunities at the global scale, it was primarily meant to serve as a communication tool and not as a priority setting framework. Thus, there is an immediate need to prioritize areas for restoration using systematic planning protocols (Moilanen et al., 2009; Wilson et al., 2011; Strassburg et al., 2019). Prioritizing areas for restoration, however, is a complex task. For this reason, multi-criteria decision approaches are useful for identifying best alternatives based on a large number of natural and social factors, including decision-makers' needs (Department for Communities and Local Government, 2009).

In multi-criteria decision approaches for restoration planning, it is critical to include information on ecosystem risk, including large-scale processes and the dynamic nature of ecological systems (Ehrenfed, 2000). With increasing availability of spatially explicit datasets on biodiversity, ecosystem function and threats, these variables can be included in the process of identifying priority restoration or conservation areas. One such dataset is the Red List of Ecosystems (RLE), a new standard promoted by the IUCN in 2012 (Keith et al., 2013), that allows the categorization of ecosystems by risk category, and the identification of where ecosystems have been lost, or are being threatened. The RLE is already available for several countries (IUCN, 2019a). For instance, a recent RLE assessment for Colombia (Etter et al., 2017) indicates that the most threatened ecosystems are not well represented or protected in the country's National Protected Areas (NPA) system, while expansion of land-use for agriculture is causing ongoing loss of some of the last remaining remnants of threatened and endangered ecosystems. The RLE assessments have the potential to greatly improve biodiversity considerations in restoration planning. For example, Martinez-Harms et al. (2017) demonstrate the importance of including the Red List of Ecosystems (RLE) in assessments of both degradation due to wildfire and priorities for forest restoration in Chile, and Bland et al. (2019) summarize applications of the RLE to inform restoration priorities across countries such as Australia, France, Finland, and South Africa.

Because restoration activities occur in the context of socio-ecological systems, it is important to include in any restoration prioritization simultaneous consideration of predicted restorative benefits and social and economic costs and benefits (Wilson et al., 2011; Possingham et al., 2015). One way to maximize cost efficiencies is to prioritize areas for restoration that have high ecological value and limited value for other land uses, such as agriculture. Land-use and infrastructure maps permit the identification of underproductive agricultural lands (Evans et al., 2017; Zuluaga and Etter, 2018), and land degradation issues often associated with them (FAO, 2017), and thereby allow restoration to be prioritized on areas that will only minimally compete with agricultural uses. Another way to maximize efficiencies is to identify areas for restoration that both are ecological priorities and are relatively inexpensive to restore (Strassburg et al., 2019). Towards this end, it is important to consider the extent to which restoration can occur through natural regeneration versus active planting (Crouzeilles et al., 2017). For this reason, it is important to consider distance to intact sites, through the use of land cover maps (Hansen, 2013; Song et al., 2018), in restoration prioritization. Taken together, these considerations will help identify areas where continued agricultural use is appropriate, as well as areas where ecological restoration should be prioritized for recuperation and conservation of species, ecosystems and ecological services, minimizing competition with productive land uses in their vicinity (Wiens and Hobbs, 2015).

The purpose of this study was to identify priority areas for restoration based on degree of ecosystem endangerment (determined by the Red List of Ecosystems (RLE) (Etter et al., 2017) and cost effectiveness, using Colombia as a study case. We applied a multi-criteria analysis, based on maps of potential ecosystems (models of the original extent of natural ecosystems), land use and other geographical data. We then analyzed how the selected priority areas represent the array of critically endangered ecosystems and how they overlap the Regional Administrative Environmental Planning Areas (CARs). Our study adds to a growing body of literature on methods for prioritizing ecosystems for ecosystem conservation and management (e.g., Polasky et al., 2008; Orsi et al., 2011; Pennington et al., 2017; e.g., Strassburg et al., 2019; Oyafuso et al., 2020) and, although we focus on Colombia, is relevant to the many countries and programs around the world that are working on land-use planning for ecological restoration.

2. Materials and methods

2.1. Study area

This study was conducted in Colombia, a country located in northwestern South America, occupying over 1.1 million km^2. With 81 types of general ecosystems, ranging from desert and tropical savannas to humid rainforests and tropical snow-covered mountains, Colombia possesses an outstandingly diverse mix of geographic, climatic, biological and ecosystem components (Etter et al., 2017). Because of this variability, Colombia is one of the world's top mega-diversity countries, harboring around 10 % of the planet´s biodiversity in less than 1% of its surface, and containing high levels of endemism (Hernández et al., 1992; Myers et al., 2000; Orme et al., 2005). Worldwide, it ranks first in bird and orchid species richness and second in richness of plants, butterflies, freshwater fishes and amphibians (IAvH, 2017).

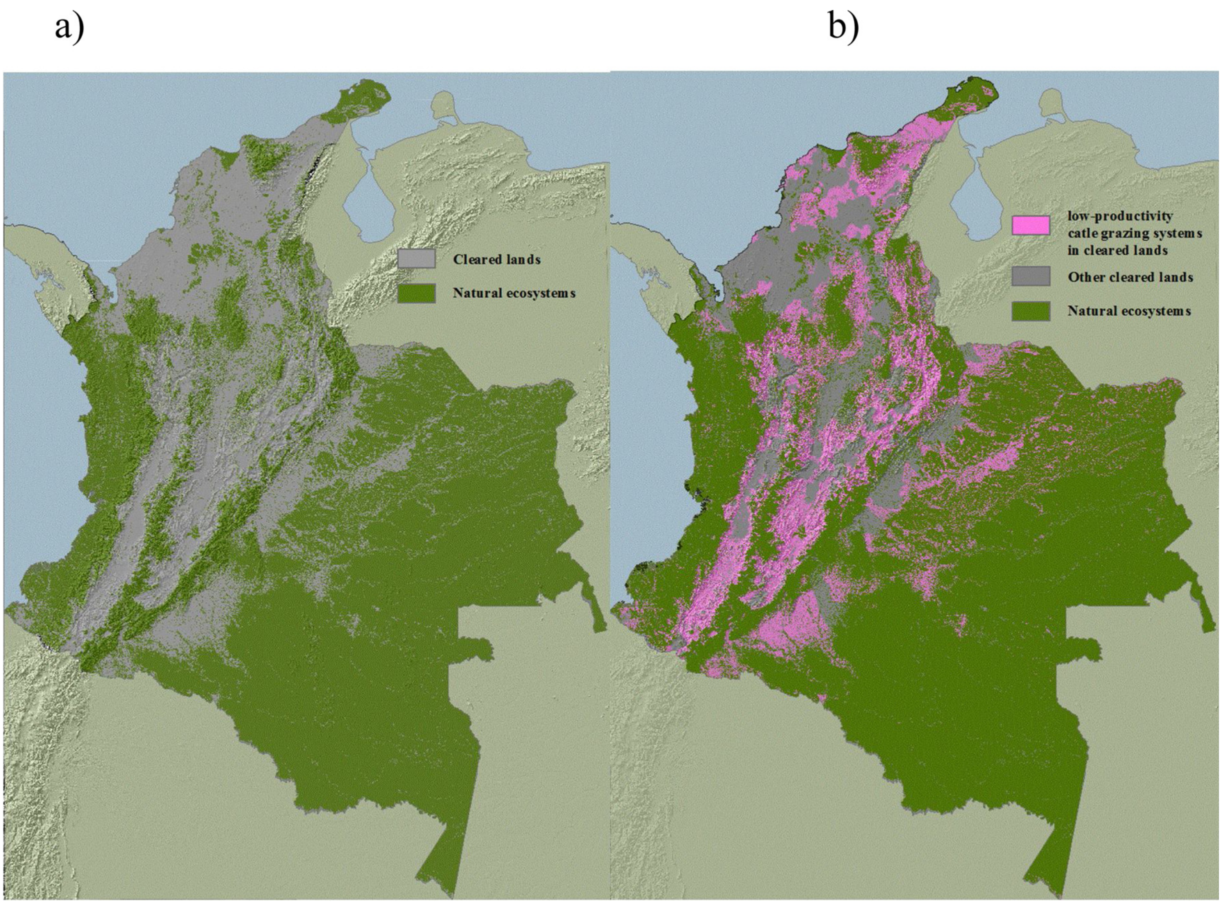

Fig. 1. Location of the study area showing: a) cleared lands (grey) and remnants of natural ecosystems (forests, savannas, Páramos, wetlands) (green) (Etter et al., 2017); and b) areas of cleared lands (pink) within the agricultural frontier that correspond to low-productivity grazing systems (Zuluaga and Etter, 2018).

However, especially during the past 50 years, native ecosystems in Colombia have been substantially transformed by deforestation and land-use change (Etter et al., 2008). Since 1990, more than 6 million ha of forests have been cleared (more than 200,000 ha.yr-1), mainly due to illegal crops, cattle ranching, mining and infrastructure development (Etter et al., 2006), and this land clearing in Colombia has occurred in the absence of land-use planning. Currently there are more than 38 million ha (34 % of the country) of transformed ecosystems within the agricultural frontier (all lands cleared for agriculture) (Fig. 1a). Although in recent years Colombia has taken steps to improve the representation of natural ecosystems in protected areas (SINAP, 2017) and to restore degraded lands from agricultural development and mining activities (Vanegas Pinzón et al., 2015; Ramírez et al., 2016), these efforts still fall short of fulfilling the needs for biodiversity protection and restoration for many ecosystems and species (Murcia et al., 2016).

Around 80 % of the agricultural frontier is used for cattle grazing, which largely occurs in biophysically vulnerable areas, causing environmental degradation, and on lands with low productivity (Zuluaga and Etter, 2018). These low-productivity cattle grazing systems cover over 10 million hectares, equivalent to more than 25 % of the agricultural frontier, and are mostly located in the center and north of the country (Andean and Caribbean regions) (Fig. 1b). They represent an important opportunity to develop integrated land-use and conservation plans where ecological restoration and improved land-use models could make a significant contribution to enhancing environmental and socioeconomic quality.

2.2. *Analytical framework*

We created a multicriteria framework (Department for Communities and Local Government, 2009) to evaluate restoration need based on degree of ecosystem endangerment and cost effectiveness of restoration. Specifically, we used the RLE evaluation for Colombia (Etter et al., 2017) to select areas that would help recover biodiversity and ecosystem services for the most endangered (CR and EN) ecosystem types. To determine cost effectiveness, we included proxies related to the cost of land, including current land productivity (Zuluaga and Etter, 2018), soil degradation, and accessibility, as well as data related to the potential for natural regeneration, including availability of local propagules, based on the existence of native ecosystems in the vicinity and riparian connectivity (Fig. 2).

2.3. *Data*

We assembled a spatial dataset to apply the multicriteria framework (Fig. 2) from available and constructed data sources (Table 1). All maps were transformed to a common raster format of 100 m resolution.

2.4. *Analysis*

2.4.1. *Multi-criteria analysis*

The multi-criteria analysis (MCA) followed a simple step-by-step process (Fig. 2). For all spatial variables (Table 1), a priority map was created by classifying each raster map by a variable score (Table 2), using the *Map reclassify Toolbox* from Arc-GIS10.1. The MCA was performed using the maps of all variables combined and the *Weighted Sum tool of the Spatial Analyst* “Overlay Toolbox” in ArcGIS 10.2. Our

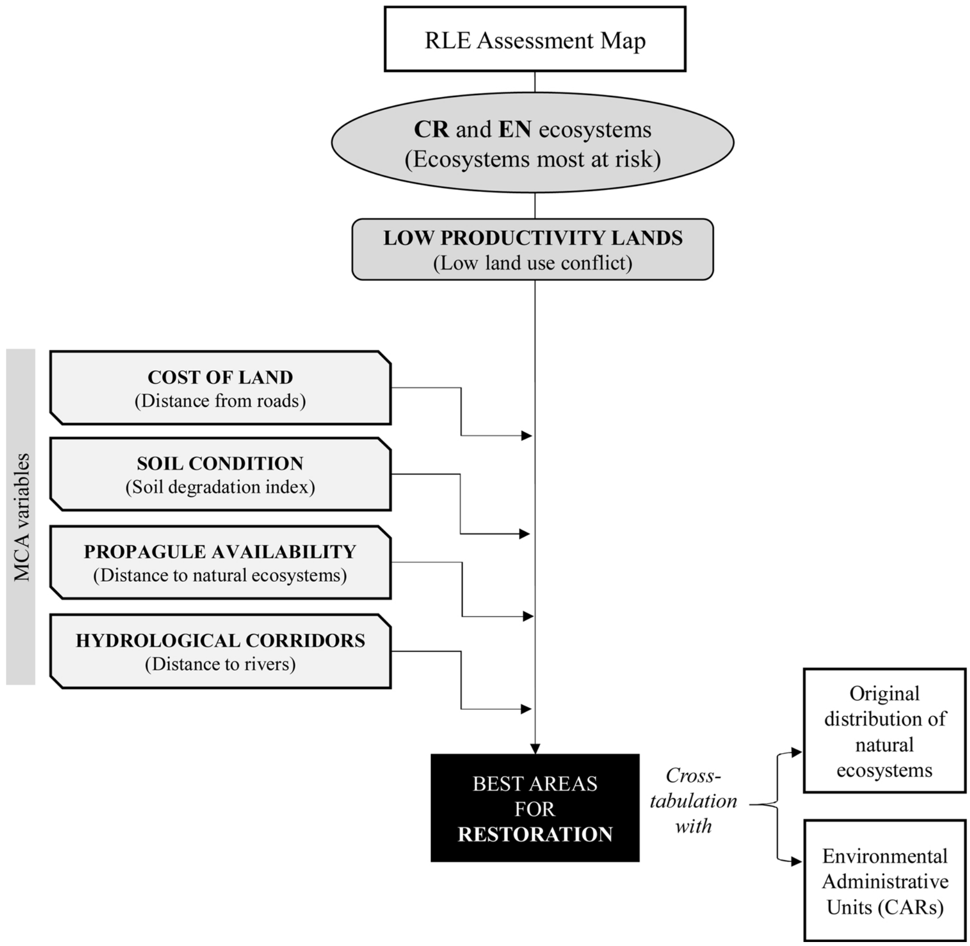

Fig. 2. Methodological flowchart of the application of the multi-criteria analysis (MCA) to identify restoration priority areas.

selection started from the prerequisite of targeting the ecosystems that are most at risk (CR and EN) and that are located in areas where the land is categorized as low productivity (Fig. 2). Because we aim at restoring lands based on natural regeneration, within the former we priortized sites using four additional criteria (Table 2, Fig. 2). We gave highest importance (highest weight) to cost of land acquisition/treatment (Polasky et al., 2008) (areas located far from roads were prioritized), then to soil condition (Chazdon, 2003; Orsi et al., 2011) (areas with low soil degradation were prioritized) and propagule availability (Thomlinson et al., 1996) (areas close to natural vegetation were prioritized), and finally to hydrological corridors (Orsi et al., 2011) (areas close to rivers were prioritized).

The obtained map was classified into three priority classes: low, medium and high applying the Jenks natural breaks classification in ArcGIS10.2, which reduces variance within classes and maximizes variance among classes.

2.4.2. Priority areas in relation to ecosystems and environmental administrative areas

The priority map was then overlaid on the potential ecosystem map, and the Regional environmental administrative and planning areas (CARs), (Table 1), to identify the level of representation of different specific endangered ecosystems in the selected restoration priority classes, and the extent of their overlap with the CARs administrative units.

3. Results

We calculated that of the 18 million hectares of cleared ecosystems that are classified as critically endangered (CR) or endangered (EN), over one third of (5.9 million ha) overlap with low-productivity cattle ranching land (Table 3). This is about 17 % of all cleared lands of the country.

Of these low-productivity lands overlapping endangered ecosystems

Table 1
Data used for analysis.

Data	Source	Reference
Location of CR and EN ecosystems (degree of risk to the ecosystem)	Red List of Ecosystems	Etter et al. (2017)
Location of cleared ecosystems	Potential Ecosystem Map	Etter et al. (2017)
Land productivity level	Grazing land use map	Zuluaga and Etter (2018)
Distance to roads	Road map	IGAC (2017a)
Distance to waterways	Drainage map	IGAC (2017a)
Distance to natural ecosystems	Ecosystem transformation map	Etter et al. (2017)
Soil degradation categories	Erosion and soil degradation map	IDEAM (2015)
Administrative planning areas	Regional environmental administrative and planning areas (CARs) map	IGAC (2017b)

Table 2
Scoring matrix of the MCA showing for each variable the scaling and the weighting factor.

Variable \ Score	1	2	3	4	5	Weighting Factor
Distance to road (km)	< 0.5	0.5 – 1	1 – 2	2 – 5	> 5	0.35
Soil degradation (category)				Moderate	Low	0.25
Distance to natural ecosystems (km)	> 10	5 – 10	2 – 5	1 – 2	< 1	0.25
Distance to water (km)	> 5	2 – 5	1 – 2	0.5 – 1	< 1	0.15

Table 3
Area of cleared areas of critically endangered (CR) and endangered (EN) ecosystems within the agricultural frontier, and the subset coinciding with low-productivity cattle grazing areas.

	Total	Low productivity	
	(ha)	(ha)	(proportion)
CR	14,684,375	4,591,225	0.31
EN	3,429,431	1,360,338	0.40
Total	18,113,806	5,951,563	0.33

Table 4
Area (ha) of CR and EN ecosystems categorized as low, medium, and high priority for restoration.

	Low	Medium	High	Total
CR	2,100,488	1,875,519	615,219	4,591,225
EN	683,013	556,794	120,531	1,360,338
Total	2,783,500	2,432,313	735,750	5,951,563

over 4.5 million hectares (77 %) are categorized as critically endangered (CR), and over 1.3 million hectares (23 %) where categorized as endangered (EN) (Table 3, Fig. 3). The majority of these areas are located in the Caribbean region and the inter-Andean dry valleys. Within these remnant ecosystems, the area of CR and EN ecosystems is highly reduced.

3.1. Restoration priority areas

Of the nearly 6 million hectares of priority areas identified for restoration, 0.8 million ha were categorized as high priority, corresponding to 12.5 % of the low-productivity cattle lands and 2.2 % of all cleared ecosystems of the country. Of these high-priority areas, 83 % are in CR ecosystems (Table 4). The analysis also classified 2.4 and 2.7 million hectares in the medium and lower priority restoration classes respectively, also mostly of CR ecosystem types (76.3 %).

The total area of all three priority classes combined account for: 16.3 % of the current agricultural frontier, 31.2 % of all cleared ecosystems classified as CR, and 40.2 % of all cleared ecosystems classified as EN, and all located in underproductive land use.

The majority of the areas prioritized for restoration coincide with the Tropical Dry Forest biome of the Caribbean, and the Chicamocha, upper Magdalena and Patía Valleys in the Andes (Fig. 4). Additional important restoration areas are located in the rainforests of the piedmont in the Llanos, and the area surrounding the San Lucas mountain range. Also, these prioritized areas are mostly located in the lowlands

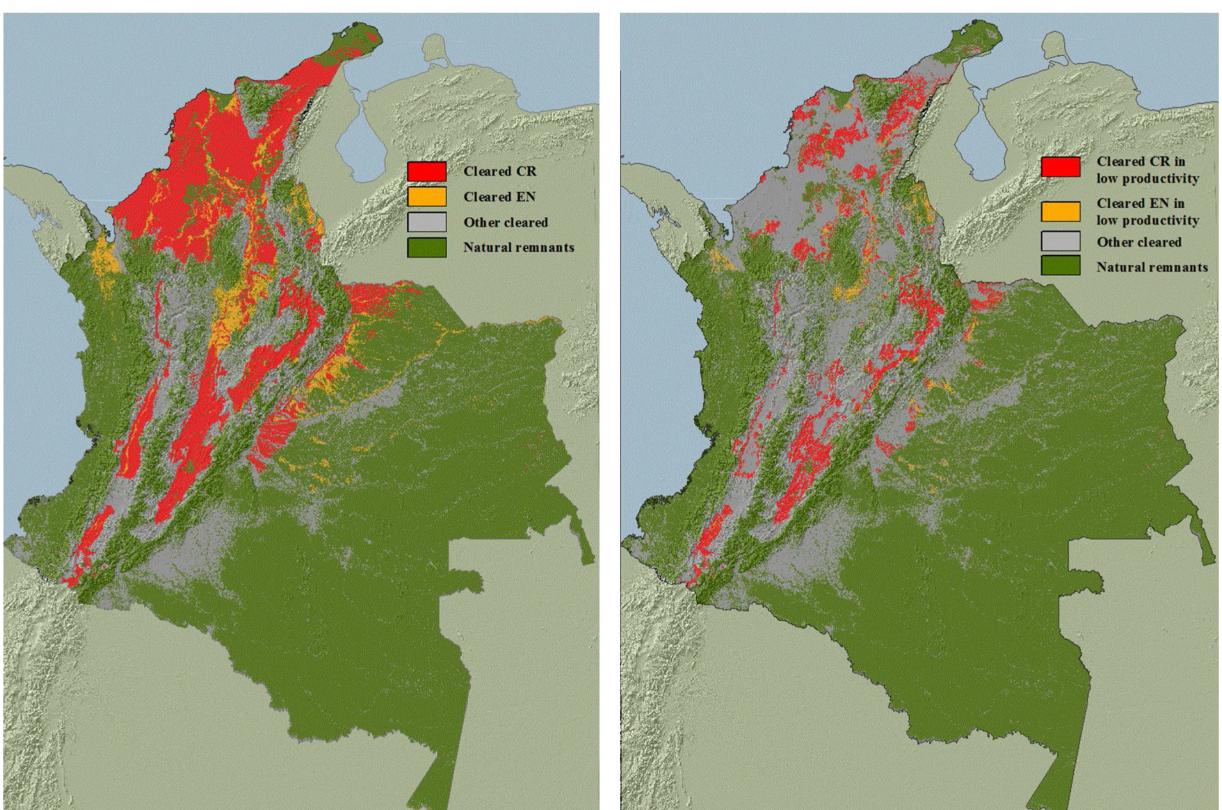

Fig. 3. Map of transformed ecosystems categorized as critically endangered (CR, red) and endangered (EN, orange) in a) all areas, and b) low-productivity cattle grazing areas.

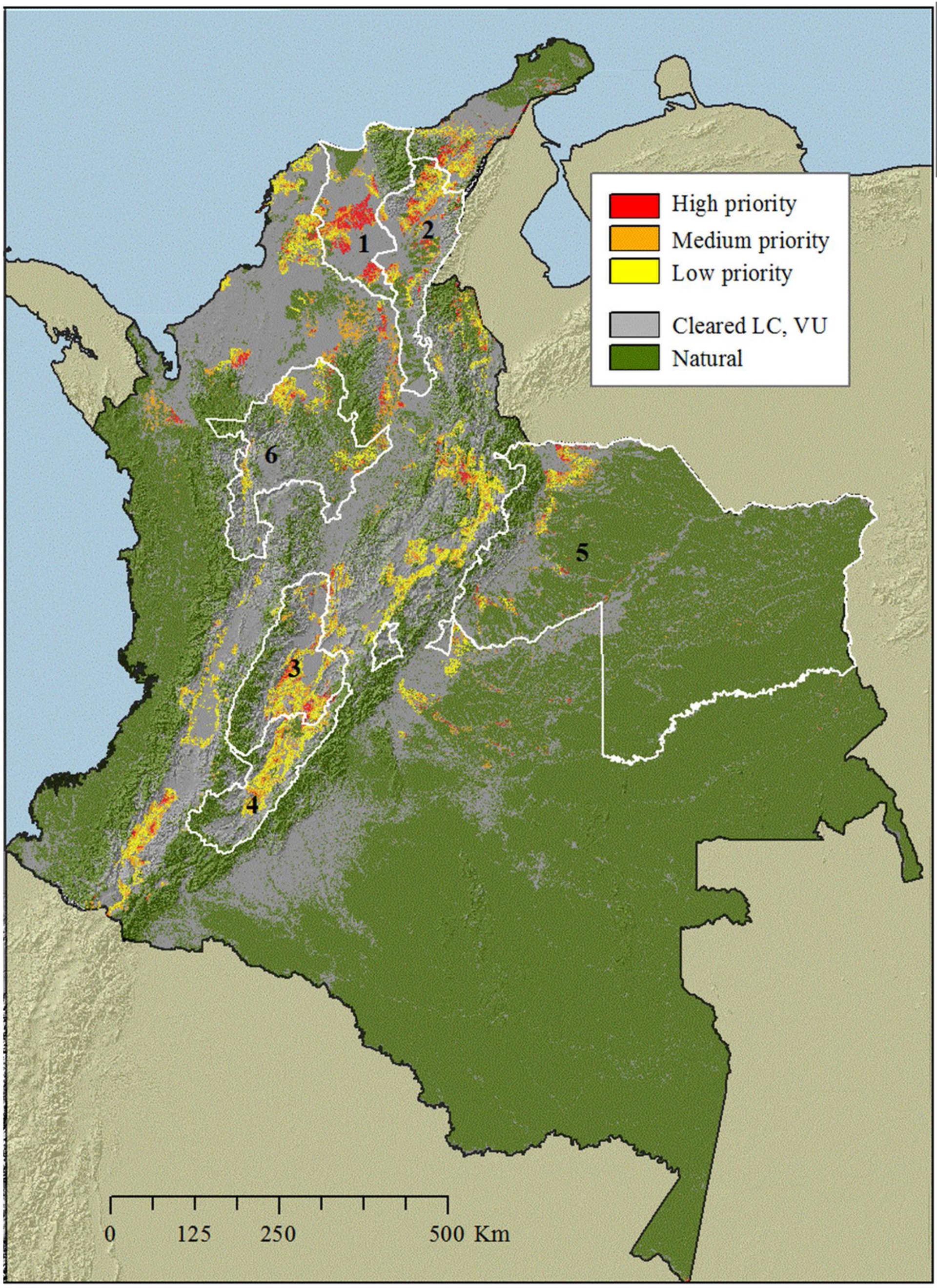

Fig. 4. Map of restoration priority classes and the six Regional Administrative Environmental Planning Areas (CARs) that had the largest area categorized as restoration priority areas (see Table 6): Corpamag (1), CorpoCesar (2), Cortolima (3), Corporación del Alto Magdalena (4), Corpoinoquia (5) and Corantioquia (6).

below 500 m of altitude (60 %). In terms of the natural regions of Colombia, 40 % of prioritized areas fall in the Andean, 34 % in the Caribbean, 11 % in the Magdalena and 10 % in the Orinoco regions (Fig. 5).

3.2. Restoration priorities and the regional administrative environmental planning areas (CARs)

The area prioritized for restoration varied greatly among the Regional Administrative Environmental Planning Areas (CARs) (Table 5). Eight of these areas have more than 20 % of their area categorized as priority for restoration.

The CARs with the highest area to be restored are Cortolima, Corpamag, Cam, CorpoCesar, Corpoinoquia and Corantioquia (Fig. 4), each with more than 400,000 ha identified as priorities for restoration.

3.3. Ecosystem composition of restoration priority areas

Of the 37 ecosystem types that were classified as CR and EN in the Colombian RLE assessment, 31 (17 CR and 14 EN) of these ecosystem types (83 %) were identified in our priority areas for restoration. However, just 10 of these ecosystem types account for 73 % of all identified priority areas for restoration (Table 6).

The four ecosystems with the largest area classified as high-priority restoration are the critically endangered tropical dry forests found in the Caribbean and inter-Andean valleys, and the rainforests of the Orinoco Piedmont, which together account to more than half of the high-priority restoration areas.

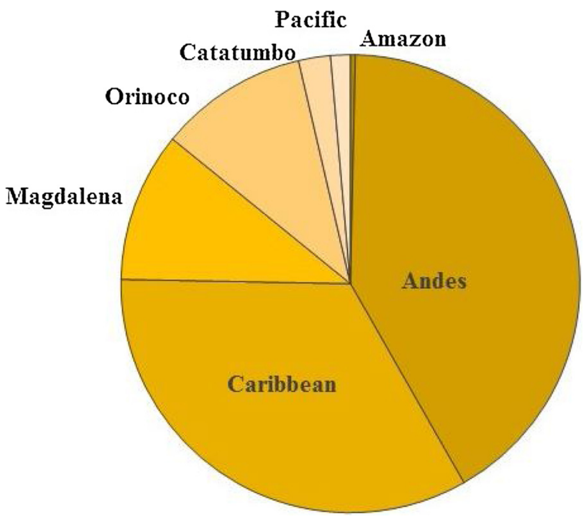

Fig. 5. Proportion of priority areas by regions.

Table 5
Regional Administrative Environmental Planning Areas (CARs), with area (ha) classified as high-, medium, and low-priority restoration, and proportion of each jurisdiction classified as restoration priority by our study.

Jurisdiction Name	Low (ha)	Medium (ha)	High (ha)	Total (ha)	Proportion of Jurisdiction
Cortolima	244,094	247,506	57,119	548,719	0.23
Corpamag	76,425	174,944	215,125	466,494	0.2
Cam	300,019	142,406	18,388	460,813	0.25
Corpocesar	158,669	210,356	87,375	456,400	0.2
Corporinoquia	147,594	215,000	56,431	419,025	0.02
Corantioquia	215,250	165,100	30,538	410,888	0.12
Corpoguajira	123,394	145,563	69,138	338,094	0.16
Corpoboyaca	237,575	85,500	3213	326,288	0.2
Csb	26,669	245,394	42,625	314,688	0.16
Car	184,956	111,838	9250	306,044	0.18
Cas	116,163	139,481	28,713	284,356	0.11
Cormacarena	115,288	107,819	31,619	254,725	0.03
Cardique	138,250	79,444	21,338	239,031	0.37
Crc	125,831	86,456	14,694	226,981	0.07
Corponariño	107,600	78,650	8419	194,669	0.06
Corponor	94,581	66,069	20,725	181,375	0.08
Cvc	111,875	52,806	1400	166,081	0.08
Cvs	42,081	47,419	20,894	110,394	0.04
Codechoco	644	62,644	13,506	76,794	0.02
Cra	57,331	10,563	469	68,363	0.21
Cdmb	34,388	24,138	3256	61,781	0.13
Carsucre	28,219	19,381	3288	50,888	0.1
Corpochivor	38,519	2325	0	40,844	0.13
Corpomojana	9594	26,956	1994	38,544	0.07
Epa	24,969	6056	1031	32,056	0.54
Sda	21,319	844	0	22,163	0.14
Corpocaldas	17,056	5019	56	22,131	0.03
Carder	11,144	1525	0	12,669	0.04
Dagma	8663	3944	0	12,606	0.22
Corpoguavio	10,463	1575	0	12,038	0.03

4. Discussion

Society is facing a major challenge: human transformation of the land and induced climate change are putting many ecosystems at risk of collapse (Keith et al., 2013). In response to this and recognizing the powerful role that ecosystem restoration can play in reversing ecosystem degradation, the UN declared 2021 – 2030 the "Decade on Ecosystem Restoration". However, a substantial challenge to promoting and implementing restoration projects and programs is that conservation and restoration initiatives often compete and conflict with areas used for agriculture and cattle ranching, leading to important tradeoffs (Tanentzap et al., 2015). Finding locations where the relative costs and conflicts are low and the benefits of restoration are high is essential (Orsi et al., 2011; Wiens and Hobbs, 2015). In this study, we used Colombia as an example of how to integrate multiple criteria to select areas for ecological restoration that maximize conservation of endangered ecosystems, potential for natural regeneration, and connectivity, and also minimize the conflict with competing land uses.

Colombia is an excellent example of a country in which conservation through protected areas is not enough to protect biodiversity and the services it provides. Although the country still possesses around 60 % of its native land cover area, 37 (45 %) of its ecosystem types have been categorized as critically endangered (CR) or endangered (EN) (Etter et al., 2017). Our finding that close to six million ha currently used for low-productivity agriculture and ranching occur in ecosystem types that are listed as CR or EN, suggests a tremendous opportunity for restoration. These low-productivity lands, mostly consisting of large farms with extensive land uses and low population density, contribute little to the economy and welfare of Colombians and, therefore, there may be more buy-in from stakeholders for ecological restoration than there would be in highly productive sites. In this way, our analysis identified important restoration sites that would help recover highest risk ecosystems with the least interference with high-productivity land uses. These results highlight that the RLE is a powerful tool to inform conservation and restoration actions because it identifies ecosystems most likely to enter a state of collapse (Keith et al., 2013), the locations where high-risk ecosystems have been most degraded, as well as their current land use conditions and threats, to inform decision making in planning at national and subnational levels.

4.1. *Colombia´s restoration plan*

Recognizing the threats that environmental degradation is imposing on biodiversity and services provided by its ecosystems, Colombia´s government recently adopted an ambitious 20-year National Restoration Plan (NRP) (Vanegas Pinzón et al., 2015), with the aspiration that it would become an integral part of the land-use planning process. As part of this process, the Ministry of Environment conducted a national prioritization analysis based on land use conflict, 100 m buffers to natural areas, legal buffers to rivers and water bodies, and burned areas. The Plan categorizes areas based on three approaches to ecosystem repair, restoration in cleared areas, rehabilitation in low degraded areas and recuperation in severely degraded areas (Vanegas Pinzón et al., 2015) – but lacks a clear statement of the objectives sought by the restoration process. The NRP selected over 24 million Ha (Vanegas Pinzón et al., 2015) as priorities for restoration, which accounts for an unrealistic two thirds of the agricultural frontier of the country, with vague references to land-use type and productivity. Of the areas selected, 90 % are in the "moderate" priority category. Having virtually all selected areas in the "moderate priority" class is not particularly useful for decision makers, as there is no guidance on what areas are most important within the large bulk of the moderate priority class (See Fig. 6).

When compared to our study, only 12 % of the selected areas in the NRP coincide with those of our study (Table7). Of these, over half (1,450,000 ha) fall in our "low priority" class. Of all the areas prioritized by our study (5,951,563 ha), only 3% (197,000 ha) coincide with the NRP's "very high" and "high" priority areas, which were selected in the NRP based mainly on proximity to river corridors. The spatial mismatch of the NRP with our study also is high (Fig. 6). This lack of spatial coincidence is notable in the Caribbean, Patía, Chicamocha and Llanos regions. The NRP selected areas mostly target large areas of ecosystems not categorized as endangered by the RLE, in the Andean, Amazon and Orinoco regions. However, the ecosystems selected by our study coincide with some of the conservation priorities included in a previous study by Pizano et al. (2016) for the Tropical Dry Forest Biome. Differences in results between our study and the NRP

Table 6
The 10 CR and EN ecosystems with the largest area (Ha) prioritized for restoration.

Ecosystem	RLE category	Restoration priority				Proportion restor/cleared
		Low	Medium	High	Total	
Tropical dry forest of the rolling plains	CR	545,131	453,925	258,119	1,257,175	0.37
Tropical dry forest of the hills	CR	513,294	459,606	133,675	1,106,575	0.62
Tropical dry forest of the plains	CR	427,281	278,225	82,506	788,013	0.26
Tropical rainforest of the Orinoco piedmont	CR	131,900	139,569	35,988	307,456	0.26
Tropical rainforest of the Magdalena rolling plains	EN	74,638	102,419	24,750	201,806	0.23
Tropical Andean subhumid forest	EN	82,769	92,081	22,381	197,231	0.31
Alluvial forests in humid biome	EN	84,594	146,981	21,625	253,200	0.21
Tropical rainforest of the Catatumbo plains	CR	12,381	24,225	19,638	56,244	0.12
Tropical Andean dry open forests and scrub	CR	127,400	100,406	19,206	247,013	0.77
Tropical rainforest of the Orinoco plains	EN	94	38,350	16,681	55,125	0.38

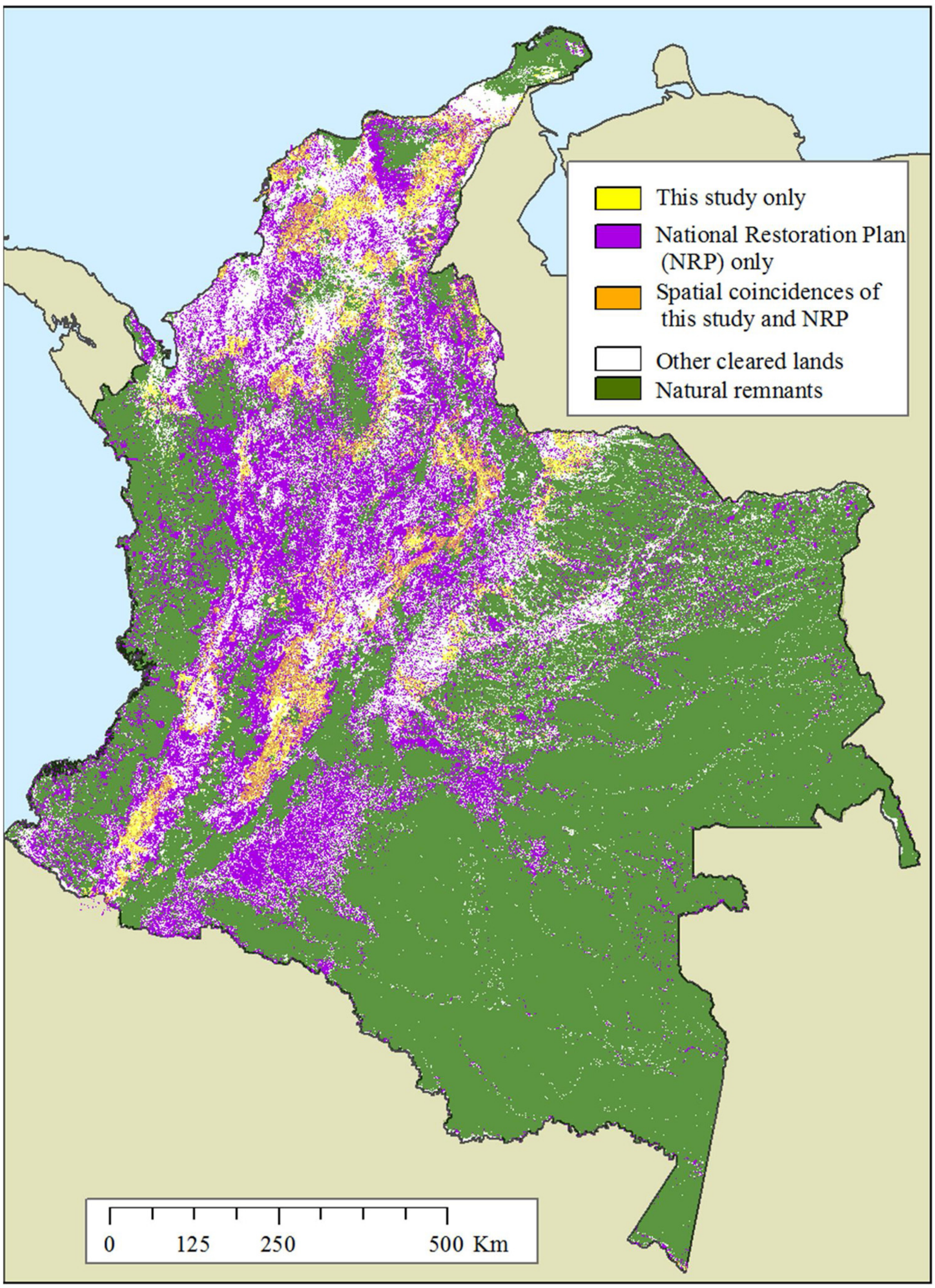

Fig. 6. Spatial comparison between the areas selected by National Restoration Plan (NRP) and our study. Coincidences between both studies are shown in orange. Large areas (purple) selected by the NRP show no coincidence with our critical ecosystems prioritization.

Table 7
Area (Ha.) shared by our study and the National Restoration Plan.

This Study	National Restoration Plan			
	Very High	High	Moderate	Low
Not selected	177,031	936,613	19,379,944	621,050
Low	9794	89,844	1,280,106	67,675
Medium	8163	68,288	1,067,769	22,638
High	1994	**19,325**	**300,581**	2206

prioritization are primarily due to the fact that the NRP did not consider four important aspects: ecosystems at risk, the productivity of agricultural lands, the potential synergy with natural remnants, and feasibility of low-cost natural regeneration approaches. This highlights the importance of incorporating ecosystem risk assessments into restoration prioritization and building capacity for and promoting the use of integrative planning processes that evaluate biodiversity and land-use tradeoffs. Our results should be useful for refining Colombia's National Restoration Strategy and improving biodiversity conservation in Colombia's restoration agenda.

4.2. Restoration approach

Within current global restoration initiatives, a variety of ecosystem management approaches are being promoted for ecosystem repair, ranging from improved management of forest plantations to active ecological restoration (Brancalion et al., 2019; Gann et al., 2019), depending on land management goals. Management activities in areas where biodiversity protection is the primary goal, such as in endangered ecosystems, should aim for the highest level of ecological restoration achievable (Gann et al., 2019). In these areas, recovery of species composition and ecosystem structure, functionality, and integrity over as large an area as possible is essential, may be more important than enhancing ecosystem goods and services such as C-storage or water regulation, given that often there are tradeoffs between biodiversity protection and carbon storage (Veldman et al., 2015). In other areas, there may be opportunities to implement restorative activities based on the Nature Based Solutions (NBS) framework (Cohen-Shacham et al., 2019), in which restoration and sustainable land use practices address other societal challenges effectively and adaptively, which is in line with the proposed land sharing strategy introduced by Phalan et al. (2011). Clearly restoration has the potential to target other services besides biodiversity conservation, by concentrating on particular forest/land restoration such as riparian areas, buffer zones around residual forest patches, corridors between forest areas, or eroding areas on steep hills (Lamb et al., 2005), helping to achieve goals such as improving water quality, reducing sedimentation and increasing C uptake (Holl and Aide, 2011).

4.3. Cost of passive restoration

When repairing ecosystems, managers have a choice of actively planting vegetation or relying on natural regeneration (Brancalion et al., 2019; Gann et al., 2019). A global analysis of forest restoration projects in the tropics (Crouzeilles et al., 2017), showed that natural regeneration and successional regrowth processes is in many cases the best solution for restoring biodiversity and ecosystem function and services. These approaches have also been found to have the lowest costs (Brancalion et al., 2019). Because of this, restoration planning, especially where the goals are conservation oriented, should explicitly identify proximity to natural remnants, accessibility and degree of human disturbance threats, which all impact the success of natural vegetation regeneration. Where natural regeneration is possible, the main expenses for restoration is the cost of the land, although there of course are additional costs for fencing and other management activities needed to protect against external threats.

Based on our findings of 6 MHa of areas prioritized for restoration, we estimate the cost of land purchase for passive restoration in Colombia to be between \$1.8 − 7.0 billion USD, assuming a purchase cost of USD 300 to USD 1200/ha (higher end for low-accessibility lands). If only the critically endangered (CR) ecosystems identified in this study are considered, which cover 0.75 MHa, the cost would range between \$250 − 900 million USD.

Another possible approach is a restoration action plan with Payment for Ecosystem Services (PES), where landowners are paid for passive restoration to safeguard successional regeneration forests. If we assume a land rent for low-productivity extensive grazing land to be in the order of 40 USD/ha.yr^{-1} (Zuluaga, 2019), the total cost for restoration of all priority areas in our study based on natural regeneration processes only, would be reduced to an annual cost of around \$240 million USD, or \$30 million USD for the prioritized CR ecosystems only. Given that the annual investment of the CARs for conservation and restoration can be estimated at \$20 − 30 million USD, restoring the prioritized areas would use less than 50 % of their annual budget. A potential important hurdle to implementing such a payment scheme for ecosystem services delivered by restoration initiatives with farmers, however, are the transaction costs of assuring that resources reach the farmers and monitoring of the process, in low-accessibility areas without banking infrastructure, an aspect that has been widely discussed in REDD and REDD + projects (Pistorius, 2012; Rendón-Thompson et al., 2013).

4.4. Limitations and further analysis needs

In this study, we emphasized identification of areas that can serve to restore ecosystems at risk and interfere as little as possible with productive land uses. However, prioritized areas need to be further assessed, applying a combined approach with cost-effectivity analyses where biological and socioeconomic trade-offs can be assessed, such as those by Strassburg et al. (2019); Pennington et al. (2017) and Polasky et al. (2008). In addition, although we included key variables, such as RLE, land productivity, and distance to remnant patches, other potentially important factors were not easily incorporated into our study, given that it was implemented at the national scale. For instance, we were unable to include important local variables, such as land-tenure context, land use history and cultural characteristics of land owners (McLain et al., 2019). The local stakeholder context is critical, especially in areas with complex land-tenure systems such as those found in Colombia and other countries and regions that are dominated by small farms. Also, political conflict and stakeholder mapping should be important in fine tuning the process of restoration planning.

Second, since our prioritization weighted areas by multiple factors not just degree of ecosystem threat, it left out some of the most endangered ecosystems, such as the Tropical Andean High-plain Forests and the Andean Wetlands (Etter et al., 2017), because they are situated in highly transformed and high-cost lands, leading to high land-use conflicts and costs. Nevertheless, these ecosystems need to be considered in a wider scope restoration strategy. Additionally, because we had a filter for proximity to intact patches, areas far from remnant patches that could potentially be important for restorative activities —such as mixed production intensification and conservation strategies based on land sharing, which would compensate the production lost in the proposed restoration areas —were not categorized as priorities (e.g. Alves-Pinto et al., 2017). Also, locations within the agricultural matrix far from natural areas, with highly fragmented and small remnants of native vegetation, might also be priorities for management activities, as they can significantly contribute to the conservation of biodiversity and ecosystem services (Wintle et al., 2019).

Finally, all such prioritization exercises face two major challenges that may jeopardize the vision of limiting the environmental impacts of agriculture put forward by Tanentzap et al. (2015): the need to win political support for policy change; and the need to geographically adjust the implementation of policy, as successful land allocation to restoration depends on features of the surrounding landscape, such as habitat connectivity and land-use specificity. A strong planning process with coherent goals is urgent, especially in countries such as Colombia with a poor history of land-use planning, and weak enforcement capacity of government restrictions on public and private land uses.

5. Conclusions

The extent to which we succeed in achieving ambitious global targets of environmental recuperation depends, in large part, on our effectiveness in prioritizing areas for restoration. Because of tradeoffs between biological conservation, ecological integrity, and ecosystem goods and services, stakeholders and planners must develop planning frameworks that adequately consider the multiple objectives of restoration. Here, we show the application of a new tool, the Red Lists of Ecosystems, to improve prioritization of restoration using Colombia as a study case. The large amount of land in Colombia used for low-productivity agriculture, offers substantial opportunities for restoring the environment and, when coupled with areas that have high potential for natural regeneration, the costs of restoration may be reduced. Like many countries, Colombia´s natural heritage has been heavily impacted and urgent action is required to create a more sustainable future. Our findings can be used in Colombia and elsewhere to improve existing efforts to identify areas that can help recover the natural heritage and associated values.

Acknowledgements

We acknowledge funding by the MAVA Foundation, the MOORE Foundation, the International Union for the Conservation of Nature (IUCN), Conservación Internacional - Colombia, and the Pontificia Universidad Javeriana research fund (PPTA 5395).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.landusepol.2020.104874.

References

Alexander, S., et al., 2011. Opportunities and challenges for ecological restoration within REDD+. Restor. Ecol. 19 (6), 683–689. https://doi.org/10.1111/j.1526-100X.2011.00822.x.
Alves-Pinto, H.N., et al., 2017. Reconciling rural development and ecological restoration: strategies and policy recommendations for the Brazilian Atlantic Forest. Land Use Policy 60, 419–426. https://doi.org/10.1016/j.landusepol.2016.08.004. Elsevier Ltd.
Aronson, J., Alexander, S., 2013. Ecosystem restoration is now a global priority: time to roll up our sleeves. Restor. Ecol. 21 (3), 293–296. https://doi.org/10.1111/rec.12011.
Bland, L.M., et al., 2019. Impacts of the IUCN red list of ecosystems on conservation policy and practice. Conserv. Lett. (June), 1–8. https://doi.org/10.1111/conl.12666.
Brancalion, P.H.S., et al., 2019. What makes ecosystem restoration expensive? A systematic cost assessment of projects in Brazil'. Biol. Conserv. 240 (September), 108274. https://doi.org/10.1016/j.biocon.2019.108274. Elsevier.
Cardinale, B.J., et al., 2012. Biodiversity loss and its impact on humanity. Nature 489 (7415). https://doi.org/10.1038/nature11373. pp. 326–326.
Chazdon, R.L., 2003. Tropical forest recovery: legacies of human impact and natural disturbances. Perspect. Plant Ecol. Evol. Syst. 6, 51–71.
Cohen-Shacham, E., et al., 2019. Core principles for successfully implementing and upscaling nature-based solutions. Environ. Sci. Policy 98 (April), 20–29. https://doi.org/10.1016/j.envsci.2019.04.014. Elsevier.
Crouzeilles, R., et al., 2017. Ecological restoration success is higher for natural regeneration than for active restoration in tropical forests. Sci. Adv. 3 (11), 1–8. https://doi.org/10.1126/sciadv.1701345.
Department for Communities and Local Government, 2009. Multi-criteria Analysis: a Manual. Available at:. Communities and Local Government Publications, London. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/7612/1132618.pdf.
Ehrenfed, J.G., 2000. Defining the limits of the need for reahstic goals. Restor. Ecol. 8 (I), 2–9. https://doi.org/10.1046/j.1526-100x.2000.80002.x.
Etter, A., et al., 2006. Regional patterns of agricultural land use and deforestation in Colombia. Agric. Ecosyst. Environ. 114 (2–3), 369–386.
Etter, A., McAlpine, C.A., Possingham, H.P., 2008. Historical patterns and drivers of landscape change in Colombia since 1500: a regionalized spatial approach. Ann. Assoc. Am. Geogr. 98 (1), 2–23. https://doi.org/10.1080/00045600701733911.
Etter, A., et al., 2017. Risk Assessment of Colombian Continental Ecosystems an Application of the Red List of Ecosystems Methodology (v. 2.0). Bogotá D.C., Colombia. Available at:. https://iucnrle.org/blog/colombia-red-list-of-ecosystems-version-2.0/.
Evans, L.J., Goossens, B., Asner, G.P., 2017. Underproductive agriculture aids connectivity in tropical forests'. For. Ecol. Manage. 401, 159–165. https://doi.org/10.1016/j.foreco.2017.07.015.
FAO, 2017. The Future of Food and Agriculture: Trends and Challenges, the Future of Food and Agriculture: Trends and Challenges. FAO, Rome doi: ISBN 978-92-5-109551-109555.
Foley, Ja, et al., 2005. Global consequences of land use. Science 309 (5734), 570–574. https://doi.org/10.1126/science.1111772.
Gann, G.D., et al., 2019. 2019. International Principles and Standards for the Practice of Ecological Restoration, second edition. https://doi.org/10.1111/rec.13035. *Restoration Ecology*, (Special Issue).
Gibbs, H.K., Salmon, J.M., 2015. Mapping the world's degraded lands. Appl. Geogr. 57, 12–21. https://doi.org/10.1016/j.apgeog.2014.11.024. Elsevier Ltd.
Hansen, M.C., 2013. High-Resolution Global Maps of 850. https://doi.org/10.1126/science.1244693.
Hernández, J., et al., 1992. In: Halffter, G. (Ed.), Estado de la biodiversidad en Colombia (State of biodiversity in Colombia), La diversidad biológica de Iberoamérica (Biodiversity in Iberoamerica). CYTED, Mexico, DF.
Holl, K.D., Aide, T.M., 2011. When and where to actively restore ecosystems? For. Ecol. Manage. 261 (10), 1558–1563. https://doi.org/10.1016/j.foreco.2010.07.004. Elsevier B.V.
IAvH, 2017. Biodiversidad en cifras: ¿Cuántas especies hay en Colombia? SIB-Colombia, (Instituto Alexander von Humboldt), Bogotá. Available at: https://sibcolombia.net/actualidad/biodiversidad-en-cifras/ (Accessed: 20 August 2007).
IDEAM, 2015. EROSIÓN en Colombia 2015. Bogota DC. Available at:. http://documentacion.ideam.gov.co/openbiblio/bvirtual/023648/Sintesis.pdf.
Instituto Geográfico Agustin Codazzi - IGAC, 2017a. Mapa de Corpotraciones Autónomas Regionales (CARs), SIGOT (Sistema de Información Geográfica para la planeación y el ordenamiento territorial). Available at: https://sigot.igac.gov.co/ (Accessed: 20 August 2010). .
Instituto Geográfico Agustin Codazzi - IGAC, 2017b. Mapa de Corpotraciones Autónomas Regionales (CARs), SIGOT (Sistema de Información Geográfica para la planeación y el ordenamiento territorial).
IUCN, 2019a. Red List of Ecosystems - Assessments. Available at: https://iucnrle.org/assessments/ (Accessed: 15 November 2019). .
IUCN, 2019b. Restoration Opportunities Methodology Assessment (ROAM). Available at: https://www.iucn.org/theme/forests/our-work/forest-landscape-restoration/restoration-opportunities-assessment-methodology-roam (Accessed: 16 November 2019). .
Keith, D.A., et al., 2013. Scientific foundations for an IUCN red list of ecosystems. PLoS One 8 (5). https://doi.org/10.1371/journal.pone.0062111.
Lamb, D., Eskirne, P., Parrotta, J.A., 2005. Restoration of degraded tropical forest landscapes. Science 310 (5754), 1628–1632. https://doi.org/10.1126/science.1111773.
Laurance, W.F., Sayer, J., Cassman, K.G., 2014. Agricultural expansion and its impacts on tropical nature'. Trends Ecol. Evol. 29 (2), 107–116. https://doi.org/10.1016/j.tree.2013.12.001. Elsevier Ltd.
Lomax, G., 2015. The Value of Land Restoration as a Response to Climate Change, Land Restoration: Reclaiming Landscapes for a Sustainable Future. Elsevier Inc.. https://doi.org/10.1016/B978-0-12-801231-4.00019-7.
Martinez-Harms, M.J., et al., 2017. After Chile' s fires, reforest private land. Science 356 (6334), 147–148.
McAlpine, C.A., et al., 2009. Increasing world consumption of beef as a driver of regional and global change: a call for policy action based on evidence from Queensland (Australia), Colombia and Brazil. Glob. Environ. Chang. Part A 19, 21–33.
McLain, R., et al., 2019. Integrating Tenure and Governance Into Assessments of Forest Landscape Restoration Opportunities, Integrating Tenure and Governance Into Assessments of Forest Landscape Restoration Opportunities. 190. Bogor.. https://doi.org/10.17528/cifor/007132.
Millenium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Desertification Synthesis. Washington, DC. Available at:. https://www.millenniumassessment.org/documents/document.356.aspx.pdf.
Moilanen, A., Wilson, K.A., Possingham, H.P., 2009. Spatial Conservation Prioritisation: Quantitative Methods and Computational Tools. Oxford University Press, Oxford, UK.
Murcia, C., et al., 2016. Challenges and prospects for scaling-up ecological restoration to meet international commitments: colombia as a case study. Conserv. Lett. 9 (3). https://doi.org/10.1111/conl.12199.
Myers, N., et al., 2000. Biodiversity hotspots for conservation priorities. Nature 403, 853–858. https://doi.org/10.1038/35002501. Available at: http://www.nature.com/nature/journal/v403/n6772/suppinfo/403853a0.html.
Nkonya, E., et al., 2016. Global cost of land degradation. In: Ephraim, Nkonya, Mirzabaev, A., von Braun, J. (Eds.), Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development. Springer International Publishing, New York, pp. 117–165. https://doi.org/10.1007/978-3-319-19168-3_6.
Orme, C.D.L., et al., 2005. Global hotspots of species richness are not congruent with endemism or threat. Nature 436 (7053), 1016–1019. https://doi.org/10.1038/

nature03850. Available at:.

Orsi, F., Geneletti, D., Newton, A.C., 2011. Towards a common set of criteria and indicators to identify forest restoration priorities: an expert panel-based approach. Ecol. Indic. 11 (2), 337–347. https://doi.org/10.1016/j.ecolind.2010.06.001.

Oyafuso, Z.S., Leung, P.S., Franklin, E.C., 2020. Understanding biological and socio-economic tradeoffs of marine reserve planning via a flexible integer linear programming approach. Biol. Conserv. 241 (March), 108319. https://doi.org/10.1016/j.biocon.2019.108319. Elsevier.

Pennington, D.N., et al., 2017. Cost-effective land use planning: optimizing land use and land management patterns to maximize social benefits. Ecol. Econ. 139 (January), 75–90. https://doi.org/10.1016/j.ecolecon.2017.04.024. Elsevier B.V.

Phalan, B., et al., 2011. Reconciling food production and biodiversity conservation: land sharing and land sparing compared. Science 333 (September), 1289–1292.

Pistorius, T., 2012. From RED to REDD+: the evolution of a forest-based mitigation approach for developing countries. Curr. Opin. Environ. Sustain. 4 (6), 638–645. https://doi.org/10.1016/j.cosust.2012.07.002. Elsevier B.V.

Pizano, C., et al., 2016. El bosque seco tropical en Colombia - Distribución y estado de conservación. In: Gómez, M.F. (Ed.), Biodiversidad 2015. Estado y tendencias de la biodiversidad continental de Colombia. Instituto Alexander von Humboldt, Bogota DC, Colombia p. 150.

Polasky, S., et al., 2008. Where to put things? Spatial land management to sustain biodiversity and economic returns. Biol. Conserv. 141 (6), 1505–1524. https://doi.org/10.1016/j.biocon.2008.03.022.

Possingham, H.P., Bode, M., Klein, C.J., 2015. Optimal conservation outcomes require both restoration and protection. PLoS Biol. 13 (1), 1–15. https://doi.org/10.1371/journal.pbio.1002052.

Ramírez, W., et al., 2016. Restauración ecológica: Los retos para Colombia. In: Gómez, M.F. (Ed.), Biodiversidad 2016. Estado y tendencias de la biodiversidad continental de Colombia. Instituto Alexander von Humboldt, Bogota DC, Colombia, pp. 38–39. Available at: http://www.humboldt.org.co/es/test/item/1089-biodiversidad2016-estado-y-tendencias-biodiversidad-continental-colombia.

Rendón-Thompson, O.R., et al., 2013. Reducing emissions from deforestation and forest degradation (REDD+): transaction costs of six peruvian projects. Ecol. Soc. 18 (1). https://doi.org/10.5751/ES-05239-180117.

SER (Society for Ecological Restoration), 2004. The SER International Primer on Ecological Restoration. Tucson, AZ. Available at:. www.ser.org.

SINAP, 2017. National Parks System Maps, Parques Nacionales De Colombia. Available at: http://www.parquesnacionales.gov.co/portal/es/parques-nacionales/ (Accessed: 1 December 2017). .

Song, X.P., et al., 2018. Global land change from 1982 to 2016. Nature 560 (7720), 639–643. https://doi.org/10.1038/s41586-018-0411-9. Springer US.

Strassburg, B.B.N., et al., 2019. Strategic approaches to restoring ecosystems can triple conservation gains and halve costs. Nat. Ecol. Evol. 3 (1), 62–70. https://doi.org/10.1038/s41559-018-0743-8.

Tanentzap, A.J., et al., 2015. Resolving conflicts between agriculture and the natural environment. PLoS Biol. 13 (9), 1–13. https://doi.org/10.1371/journal.pbio.1002242.

Thomlinson, J.R., et al., 1996. Land-Use Dynamics in a Post-Agricultural Puerto Rican Landscape (1936-1988). Biotropica 28 (4), 525. https://doi.org/10.2307/2389094.

Vanegas Pinzón, S., et al., 2015. Plan Nacional de Restauración: restauración ecológica, rehabilitación y recuperación de áreas disturbadas. Ministerio del Ambiente y Desarrollo Sostenible, Bogotá, Colombia.

Veldman, J.W., et al., 2015. Where tree planting and forest expansion are bad for biodiversity and ecosystem services. BioScience 65 (10), 1011–1018. https://doi.org/10.1093/biosci/biv118.

Wassenaar, T., et al., 2007. Projecting land use changes in the Neotropics: the geography of pasture expansion into forest'. Glob. Environ. Chang. Part A 17 (1), 86–104. Available at: http://www.sciencedirect.com/science/article/B6VFV-4K1G55Y-1/2/0fe0e8695e0da30296d55887e6ff918e.

Watson, J.E.M., et al., 2016. Persistent disparities between recent rates of habitat conversion and protection and implications for future global conservation targets. Conserv. Lett. 9 (6), 413–421. https://doi.org/10.1111/conl.12295.

Wiens, J.A., Hobbs, R.J., 2015. Integrating conservation and restoration in a changing world. BioScience 65 (3), 302–312. https://doi.org/10.1093/biosci/biu235.

Wilson, K.A., et al., 2011. Optimal restoration: accounting for space, time and uncertainty. J. Appl. Ecol. 48 (3), 715–725. https://doi.org/10.1111/j.1365-2664.2011.01975.x.

Wintle, B.A., et al., 2019. Global synthesis of conservation studies reveals the importance of small habitat patches for biodiversity. Proc. Natl. Acad. Sci. U.S.A. 116 (3), 909–914. https://doi.org/10.1073/pnas.1813051115.

Zuluaga, A.F., 2019. Modeling Scenarios of Environmental Transformation of Cattle Ranching in Colombia: an Approach to the National, Regional and Local Levels. Available at:. Pontificia Universidad Javeriana. https://www.javeriana.edu.co/biblos/bibliotecas.

Zuluaga, A.F., Etter, A., 2018. Áreas aptas para la actividad ganadera en Colombia. In: Moreno, L.A., Rueda, C., Andrade, G.I. (Eds.), Biodiversidad 2017. Estado y tendencias de la biodiversidad continental de Colombia, 1st edn. Instituto de Investigación de Recursos Biológicos Alexander von Humboldt, Bogotá, D. C., Colombia, pp. 53–54. Available at: http://hdl.handle.net/20.500.11761/34619.