A rapid approach for informing the prioritization of degraded agricultural lands for ecological recovery: A case study for Colombia

Janelle Sylvester, Jefferson Valencia Gomez, Louis V. Verchot*, Ngonidzashe Chirinda, Miguel Antonio Romero Sanchez, Marcela Quintero, Augusto Castro-Nuñez.

*Corresponding Author

International Center for Tropical Agriculture, KM 17 Recta Cali-Palmira, CP 763537, Apartado Aéreo 6713, Cali, Colombia

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Abstract

Turning national restoration commitments into action involves systematic spatial planning and prioritization of areas for investment. To achieve restoration at the landscape level, efforts must focus on recovering productivity and ecosystem services on degraded agricultural lands to meet not only environmental objectives, but socioeconomic objectives as well, which can be accomplished through the establishment of sustainable land use systems (SLUS). As financial resources for restoration are limited, identifying areas where resources can be used efficiently to achieve particular restoration objectives is critical. This study presents a rapid approach to identifying and prioritizing degraded agricultural lands for low-cost ecological recovery. Using publicly available remote sensing datasets at the national level, we apply the proposed methodology to Colombia, where we identify opportunities for cost effective interventions on productive lands with moderate to light degradation, based on biophysical indicators of soil degradation. In tandem, we identify areas experiencing underutilization, where SLUS can be used to sustainably intensify production, and overutilization, where SLUS can be used to mitigate soil degradation. We identify and map over 10.3 million ha of land with potential for ecological recovery. We find that the Caribbean region proportionally has a high prevalence of moderately degraded agricultural and agroforestry soils, while the Andean region has a high proportion of moderately degraded production forestry soils. Our results aid in the identification and prioritization of areas where multifunctional SLUS, such as agroforestry, agroecology or climate-smart agriculture, can be developed to restore productivity and ecosystem services to degraded agricultural lands.

Key words: Sustainable land management; sustainable land use systems (SLUS); agroecological restoration; land degradation; GIS, low-cost ecological recovery

Highlights:

- We can identify priority areas for restoration using publicly available data
- We mapped 10.3 M ha to prioritize interventions for restoration
- Soil erosion is widespread in agricultural land of the Orinoquia and Caribbean regions
- Soil erosion is widespread in forestry lands of the Andes region

- Many lands are overutilized, so degradation is worsening

Introduction

The restoration of degraded land is critical for meeting global aspirations of achieving Sustainable Development Goals (SDG) including no poverty, zero hunger, climate action, and life on land (Houghton, Byers, & Nassikas, 2015; Wheeler et al., 2016). To address concerns over biodiversity conservation, food security and sustainable rural livelihoods, attention must be given to the restoration of degraded agricultural lands, as unsustainable agricultural practices that result in soil degradation and loss of productivity, continue to drive agricultural expansion — and consequently deforestation — in the tropics (Epple, García Rangel, Jenkins, & Guth, 2016; Gliessman & Tittonell, 2015; Hosonuma et al., 2012). Successful restoration initiatives at the regional and national scales require an integrated landscape approach that incorporates a mixture of interventions used to achieve a variety of diverse objectives such as recovering ecosystem services, improving agricultural productivity, safeguarding rural livelihoods, and establishing social and ecological resilience (Maginnis & Jackson, 2003; Mansourian & Parotta, 2018; Reed, Van Vianen, Deakin, Barlow, & Sunderland, 2016; Sabogal, Besacier, & McGuire, 2015; Sayer et al., 2013; Van Dexter & Visseren-Hamakers, 2018). In Colombia, the government has committed to restoring 1 million ha of degraded land by 2020 under the Initiative 20x20 (WRI, 2018). Yet, given the limited available resources and time remaining to meet this target, achieving national restoration goals will require the prioritization of areas where cost-effective restoration interventions can be implemented rapidly (Murcia et al., 2016; Van Dexter & Visseren-Hamakers, 2018).

An estimated 25 percent of agricultural land worldwide is moderately to severely degraded (Tittonell, 2014; Bai et al., 2011). According to the assessment of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), land degradation impacts the well-being of over 3.2 billion people and costs more than 10% of annual global gross product from the loss of ecosystem services and biodiversity (IPBES, 2018). In Colombia, land degradation is widespread and over 40% of the land is degraded (Etter et al., 2008, 2010), which has been caused by a diversity of drivers including inappropriate land use for agricultural activities (MADS, 2019). Ecosystems experiencing the greatest impacts have traditionally been Andean forests and dry tropical forests, but recently deforestation rates have increased in the lowland forests of the Amazon and the Pacific regions (Clerici et al., 2019; Sánchez-Cuervo, et al., 2012).

Among the drivers of land degradation are what the Colombian government calls conflicts in land use, which are related to inappropriate use of agricultural lands, including the overuse and underuse of productive lands. Conflicts in land use arise when there is a discrepancy between the current use of the natural environment and the recommended use that is in accordance with the environmental potentials and restrictions of the land based on evaluation of ecological, cultural, social, and economic factors (IGAC, 2012). The underuse of productive lands may indirectly cause degradation through overexploitation of other lands to meet societal food, feed and fiber needs. Approximately 28 percent of land in Colombia experiences either overutilization or underutilization, mainly in the Andean and Caribbean regions (DNP, 2015). The extent of over- or underutilization of land, in Colombia, has been evaluated and mapped by the Geographic Institute Agustín Codazzi. The authors of IGAC (2012) determined that overutilization of agricultural land occurs when the intensity of current use exceeds the recommended usage intensity of the land resulting in degradation of soil resources, which is most commonly evident as water erosion. Underutilization occurs in agricultural lands when the current land use corresponds to a lower level of utilization intensity compared to the optimal usability or usage capacity of the soil, which leads to problems in the food supply, social dissatisfaction, over-use of fragile ecosystems and ultimately expansion of the agricultural frontier.

Colombia has over 60 years of experience with restoration of a broad range of ecosystems (Murcia et al., 2016). In 2015, the government published a National Restoration Plan (NRP) that outlines a 20-year framework designed to mitigate land degradation through the ecological restoration, rehabilitation and recovery of degraded areas (MADS, 2015). The framework consists of three levels of action: (1) Ecological *restoration* with the aim of restoring an ecosystem as nearly as possible to pre-disturbance conditions with respect to species composition, ecosystem structure and ecological processes. The restored ecosystem should be self-sustaining. (2) Ecological *rehabilitation* with the aim of restoring degraded areas to functional ecosystems that are self-sustaining, preserve some species, and provide some ecosystem services. The restored ecosystems may be considerably different from the pre-disturbance ecosystems. (3) Ecological *recovery* where focus is on recovering some ecosystem services of social interest in systems that are actively managed and that are not self-sustaining (MADS, 2015). Approaches to ecological recovery place emphasis on improving degraded agricultural lands through the adoption of sustainable land-use systems (SLUS) such as agroforestry and silvopastoral systems and through adaptive management techniques such as utilization of saline-tolerant plants and reduced-tillage cropping systems (Liniger, Mekdaschi Studer, Moll, & Zander, 2017). SLUS should enhance ecosystem functions (*e*.*g*. soil conservation, soil stabilization and pest control), recover biodiversity and ecosystem services, improve efficiency of land use, sustain agricultural productivity and support smallholder livelihoods (Van Dexter & Visseren-Hamakers, 2018).

Colombia's national restoration plan requires socioeconomic and political planning that can be aided by identifying and prioritizing land for cost-efficient restoration. Past restoration projects in Colombia have been driven mainly by external resources as limited government resources have been inadequate to address the extensive degradation challenge (Coppus et al., 2019; Murcia et al., 2016). Therefore, there is a need to develop a standardized land degradation assessment framework that can be used in the spatial planning and implementation of restoration efforts to ensure financial and human resources are allocated efficiently. The severity of land degradation is directly related to restoration costs; and the more degraded a landscape becomes, the higher the cost will be to achieve particular restoration outcomes (Chazdon, 2008; FAO & Global Mechanism of the UNCCD, 2015; Sabogal et al., 2015). Thus, given the growing demand for agricultural products, land degradation assessment tools should be used to prioritize degrading agricultural lands for ecological recovery so that land degradation is halted and abated before progressing to a state of severe degradation, which will be associated with high restoration costs.

The objective of this study is to develop a methodology that uses publicly available geospatial data on soil and land use variables to rapidly identify and prioritize degraded agricultural areas for low-cost ecological recovery — following the terminology established in Colombia's NRP. This methodology is based on assessing lands and prioritizing areas for intervention using three criteria: i.) soil degradation from erosion; ii.) soil degradation from salinization; and iii.) inappropriate use of lands. Assessing inappropriate use of lands was based on identifying areas suitable for agriculture that are currently underutilized or overutilized according to remote sensing data acquired from government sources. Using Colombia as a case study, we apply this methodology to identify degrading agricultural and production forestry lands that can be prioritized at the national level for ecological recovery through agroecological approaches and establishment of SLUS. We identified areas of light to moderate degradation experiencing under- or overutilization with the assumption that achieving ecological recovery objectives in these areas could require less intensive and less costly interventions compared to areas of more severe degradation and would halt the negative trajectory toward more severe degradation. By establishing SLUS in these areas, land degradation can be mitigated, agricultural productivity can be sustainably intensified in areas of underuse, and soils can be safeguarded against more severe degradation. Finally, we frame our results in the context of the government's NRP to demonstrate how this methodology can be used as a tool to help inform national restoration planning.

Materials and Methods

Data selection

This analysis focused on agricultural lands. An exhaustive search of national web platforms was conducted to identify geospatial datasets that could be used in GIS analyses for the identification of degrading agricultural areas where low-cost ecological recovery interventions could be implemented. Data collection was limited to publicly available datasets at the national scale produced by Colombian government agencies.

Geospatial datasets (1:100,000) were obtained for land suitability, conflicts in land usage and variables of soil degradation (see Table 1 for detailed descriptions of each selected dataset). The land suitability map was used to select areas considered most suited for either agriculture, agroforestry or production forestry. We used the conflicts in land use dataset from Colombia's Geographic Institute Agustín Codazzi to identify areas experiencing underutilization or overutilization. This dataset identifies areas of under- or over-utilization by determining and comparing the i) potential use of soils in areas suitable for agricultural and forestry production, and ii) the existing land cover and land use in the area (IGAC, 2012). We evaluated soil degradation using maps on soil erosion and soil salinization. Areas with slight to moderate soil degradation were identified as areas where low-cost ecological recovery interventions could be implemented. As all soils exhibit at least a very light degree of salinization, the levels of "very light", "light" and "moderate" soil salinization were selected. We selected corresponding levels of soil erosion, which consist of "no evidence of erosion", "light erosion" and "moderate erosion." We retained areas with "no evidence of erosion" in our analyses because, when intersecting the selected variables, areas without evident erosion can still be identified as degraded due to degrees of soil salinization and under- or overutilization.

Analysis

Selected geospatial datasets were analyzed in ArcGIS Pro 2.4.0. (ESRI, 2013). For each dataset, the selected attribute subcategories (listed in Table 1) were extracted to generate maps containing only the desired variables (e.g. map of very light, light and moderate soil salinization). These maps were then intersected using high-performance tools (*Pairwise Intersect* and *Pairwise Dissolve*), which have internal parallel processing algorithms useful for executing geospatial analyses with cartography of large file sizes (e.g. for the entire Colombian territory) and complex geometry. The results were subsequently disaggregated based on biogeographic regions, departments (states) and their corresponding municipalities.

When planning restoration on a national level, it is critical to consider restoration agendas set by the government. Therefore, we cross-referenced the preliminary areas identified using the aforementioned methodology with the areas identified in Colombia's NRP for ecological restoration, rehabilitation or recovery in order to select zones that were generated by both approaches. This final step enabled us to focus efforts and develop further analysis on areas of high national importance.

Results

We identified over 10.3 million ha as having potential for ecological recovery in Colombia, which we define as areas with a combination of moderate or less soil erosion and salinization, sub-optimal agricultural land-use suitability, and overutilization/underutilization. Of the identified degraded lands, land suitable for production forestry presented the largest area, followed by agriculture and agroforestry, respectively (Table 2; Figure 3). The Andean region had the largest resulting degraded area of land (6.6 million ha), followed by the Caribbean (1.6 million ha), Amazon (1.2 million ha), Orinoquia (557,485 ha) and Pacific (298,722 ha) regions.

Table 2 shows that of the resulting areas the greatest percentage of land with moderate to light erosion was found in the Andean region in areas most suited for production forestry. The greatest percentage of land suitable for agriculture with moderate to light erosion was found in the Caribbean region, followed by the Andean and Orinoquia regions. Overall, very light salinization was more widespread than light and moderate salinization levels (Figure 1). The highest proportion of land with moderate salinization was found in the Caribbean region on agricultural soils (Table 3). Furthermore, lands suited for production forestry in the Andean region presented the highest proportion of very light salinity.

Using results in Table 4, we classified areas by priority for intervention from a biophysical perspective, and we gave high priority to soils with low levels of degradation classified as NE-VLS (orange), intermediate priority to soils with intermediate degradation in the categories NE-LS, LE-LS and LE-VLS (yellow) and lower priority to moderately degraded soils with NE-MS, LE-MS, ME-MS, ME-LS and ME-VLS (purple). The basis for this classification is the level of effort required to restore soils, which follows the order NE<LE<ME for erosion and VLS<LS<MS for salinity. Following this approach, we find that 724,634 ha are high priority for recovery (Table 4, orange), 3,396,494 ha are moderate priority (Table 4, yellow) and 6,137895 ha are low priority for investment in ecological recovery and establishment of SLUS (Table 4, purple). Figure 2 displays the spatial distribution of degradation levels in the potential ecological recovery areas according to the combinations of soil erosion and salinization levels shown in Table 4 with colors corresponding to those used in Table 4.

The distribution of degrading and degraded lands in Figure 2 shows that areas of moderate to light degradation were largely found in clusters throughout the Andean and Caribbean regions. This raises the prospects that the logistical efforts and costs associated with recovering these large, clustered areas may be expected to be lower than costs in more isolated or remote areas with degradation. Lands suitable for production forestry were concentrated in the Andes, particularly on sloping lands. Lands suitable for agriculture were concentrated in the Caribbean and Orinoquia regions, and the valleys of the Andean region (Figure 3). Overutilization was widespread on both production forestry and agricultural lands, and underutilization was limited to the western portions of Orinoquia (Figure 3).

Results in Table 5 and Figure 4 suggest that large areas in the Andean and Caribbean regions could be prioritized for interventions that sustainably intensify agricultural production in underutilized areas and mitigate degradation in areas of overutilization. The Orinoquia region also presents a relatively high proportion of land that is suitable for agriculture but is presently underutilized. Overutilization appears to be more widespread in areas suitable for production forestry, particularly in the Andean region. Overall, of the lands identified for potential ecological recovery, 8.7 million ha are overutilized and 1.5 million ha are underutilized (Figure 3).

Discussion

Achieving restoration objectives at national and regional levels requires systematic spatial planning and prioritization of areas for investment, which in turn requires approaches for rapid and effective land evaluation. Estimates of land degradation vary widely and are complicated by the fact that most estimates are not derived from direct measurement (Gibbs & Salmon, 2015). To support restoration planning, we developed a novel methodological framework that focuses on soil indicators and land suitability for rapidly identifying, mapping and quantifying degrading lands with potential for cost-efficient ecological recovery based on remote sensing data available at the national level. We note that in the Colombian context, the ecological recovery concept is typically applied to lands that are actively managed for forestry, agriculture and agroforestry. As nations proceed with turning international restoration commitments into action, an integral piece of the puzzle will be recovering productive capacity of agricultural and forestry lands in order to reduce deforestation pressures and achieve multiple environmental and socioeconomic objectives.

While ecological restoration to pre-disturbed conditions can be accomplished by taking land out of agricultural production, this is potentially in conflict with meeting food security goals and can increase deforestation pressures by displacing pre-existing land uses (Latawiec, Strassburg, Brancalion, Rodrigues, & Gardner, 2015; Melo et al., 2013; Meyfroidt & Lambin 2009). Conversely, ecological recovery can be achieved while simultaneously sustaining and improving agricultural production through the establishment of SLUS that restore and safeguard soil health by using ecologically-based agricultural practices that align with sustainable livelihoods and conservation of ecosystem services (Van Dexter & Visseren-Hamakers, 2018). Moreover, recovering productivity of degraded lands can reduce the sensitivity of agroecological systems to climate change impacts (Webb et al., 2017). By mapping and evaluating soil degradation variables, conflicts in land use, and land suitability, the present study was able to identify over 10.3 million ha of productive land in Colombia that, from a biophysical perspective, has potential for low-cost ecological recovery. Further investigation in these areas will present opportunities for sustainable agricultural intensification, soil degradation mitigation and biodiversity and forest cover recovery.

We found that moderate and light erosion is widespread in our targeted areas, and it is coupled with prevalent overutilization, indicating that degradation is likely worsening in these areas. Through the NRP framework, Colombia aims to address the nation's land degradation and achieve its international and national restoration commitments. Concurrently, the government is developing and implementing policies and initiatives to address peacebuilding and sustainable rural development as the country emerges from a period of armed conflict (Morales, 2017). Initiatives such as the Cocoa, Forests and Peace Initiative (Cocoa & Forests Initiative, 2018) aim to simultaneously restore forest biodiversity and ecosystem functions, promote the sustainable intensification of cacao production and provide sustainable livelihoods while combating deforestation. As public and private sector resources are finite, and Colombia strives to tackle many complex issues, the efficiency of use of available resources will be a top priority. Therefore, the proposed planning tool can be used to assess a combination of national-level, geospatial datasets to determine and prioritize regions where resources can be used to efficiently achieve particular restoration objectives.

Our results, as well as Colombia's NRP, emphasize targeting the Andean region for ecological recovery, which is home to approximately 70% of Colombia's population (MADS, 2019). Many past ecological restoration projects in Colombia have targeted the Andean region – most of which were small scale and focused on recovering watershed services (Murcia et al., 2016). Nevertheless, the Andean region continues to boast large areas of degraded land suitable for productive uses, which present opportunities for investments in ecological recovery initiatives and SLUS. For example, among the biogeographic regions, the highest proportion of overutilized lands identified by our methodology was in the Andean region on lands suitable for production forestry. Targeting these lands for ecological recovery presents an opportunity to establish sustainably productive forestry systems that restore forest functionality, improve habitat connectivity and recover ecosystem services all while providing economic benefits (Maginnis & Jackson, 2003). Priority should also be given to the Caribbean region, where large, clustered areas of moderate degradation are found – most of which are on under- or overutilized land suitable for agriculture.

In the Andean, Caribbean and Orinoquia regions alone, we identified over 1.2 million ha of suitable agricultural land that is being underutilized. According to the National Planning Department, a key strategy for agricultural and rural development in Colombia is to promote the efficient use of land and natural resources (DNP, 2019). Recovering land through SLUS can increase productivity by replenishing soil fertility and improving efficiency in water use (Metternicht & von Maltitz, 2019). For instance, agroforestry systems where trees are established and managed on active agricultural land can be used to improve or maintain crop productivity, increase soil fertility and enhance water retention, all while providing alternative, sustainable livelihoods for farmers (Reed et al., 2016; Sabogal et al., 2015; Van Dexter & Visseren-Hamakers, 2018). In developing countries, sustainable land-use practices have increased average crop yields by 79 percent on 3 percent of agricultural lands (IPBES, 2018). Therefore, agroecological restoration techniques that restore soil quality and stabilize erosion can be implemented to "produce more from less" and mitigate future land degradation (Lal, 2015). On the other hand, we identified over 8.7 million ha of land that is overutilized, which if left unabated will likely progress to more severe levels of degradation that would require more intensive and costly restoration interventions.

Land degradation is a multi-dimensional phenomenon; and while this study focused on soil indicators for salinization and erosion to identify land degradation, we expect that the open access principles for public data that was recently adopted by the Government of Colombia (MinTIC, 2019) will increase access to data on other indicators of natural and anthropogenic land degradation and thus make it possible to include other geospatial layers in this rapid approach. For instance, previous studies have proposed the use of several indicators of land degradation that are directly affected by land management including land productivity, land cover, normalized difference vegetation index and above- and below-ground carbon stocks (Nkonya et al., 2016; Yengohet al., 2015). Yet, the challenge is accessing data on key degradation indicators at the appropriate resolution and of satisfactory quality. The results of the present study will require field validation, which is becoming feasible as the country emerges from conflict and as rural areas become more accessible. It may also be useful to expand the definition of soil degradation to include nutrient depletion, but national datasets were not currently available for this. Furthermore, due to the nature of the dataset on conflicts in land use, we could not determine whether the occurrence of under- or overutilization was due to the type of land use currently being employed (e.g. presence of agriculture in an area suitable for agroforestry) or to the management of the current land use (e.g. subpar agricultural production in an area appropriate for agriculture). Future applications of the proposed methodology must carefully consider what datasets are available and what limitations they might present and move forward with planning accordingly.

Conclusions

Restoration of degraded lands is essential for meeting national development objectives and for meeting several SDGs. Because financial resources for restoration are limited, careful planning and prioritization of lands for restoration is required, so that these are spent wisely. Our study presents a simple approach for prioritizing interventions. We targeted agricultural lands and used easily available national datasets for this assessment. Because this rapid approach was able to capture the spatial heterogeneity of different land degradation attributes, it will facilitate more cost-effective restoration actions. The approach focused on soil indicators, in contrast to many land degradation assessment approaches that focus on vegetation. For planning ecological recovery in agricultural landscapes, focusing on soil degradation makes sense; the approach could be adapted easily using other indicators for other types or dimensions of land degradation. This approach could be replicated at department levels using higher resolution data for sub-national prioritization to provide even greater specificity. The GIS analysis should be used in conjunction with socioeconomic factors, as restoration planning must consider a combination of social, economic and environmental factors and the interests of local, regional and national stakeholders to ensure interventions are designed to meet local needs.

For our case study in Colombia, we showed that large areas of agricultural lands are slightly degraded and a much smaller area is moderately degraded. This suggests that prophylactic measures on slightly degraded lands in the near term will avoid high restoration costs in the future. We also show that the Caribbean proportionally has a much higher prevalence of moderately degraded agricultural and agroforestry soils, and addressing these requires remedial measures. A large percentage of production forestry soils in the Andes region are also degraded to varying degrees. Our results aid in the identification and prioritization of areas where multifunctional SLUS can be developed, such as agroforestry, agroecology or climate-smart agriculture. These systems can aid in restoring biodiversity and habitat connectivity, while safeguarding soils and avoiding further degradation that is often brought about by overuse and unsustainable land practices.

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Table 1. Map layers and attribute classes selected for soil degradation, land suitability and conflicts in land use variables in Colombia. Map layer selections were limited to publicly available, national level (1:100,000) datasets from government sources. Agroforestry and agrosilvopastoral classes include permanent and temporary crops, agriculture classes include permanent and temporary crops under all climatic conditions, and production forestry includes tree production under all climatic conditions.

Variable	Category	Attribute	Description	Source
Soil degradation	Soil erosion	No evidence of erosion	Physical-mechanical loss of the soil. Selected classes correspond to a 25% or 50% loss of soil from horizon A.	IDEAM, 2012[1]
		Light erosion		
		Moderate erosion		
	Soil salinization	Very light	Increase, gain, or accumulation of salts in the soil. Selected classes correspond to soils with electrical conductivity of < 2 dS/m; ≥ 2 and < 4 dS/m; ≥ 4 and < 8 dS/m, respectively.	IDEAM, 2017[2]
		Light		
		Moderate		
Land suitability	Agriculture	Intensive cropping	Most appropriate land use for each soil type that results in sustainable production without the deterioration of natural resources based on biophysical characteristics.	IGAC, 2012[3]
		Semi-intensive cropping		
	Agroforestry	Agroforestry		
		Agrosilvopastoral		
		Silvopastoral		
	Forestry	Production forestry		
		Protection-production		
Conflicts in land use	Overutilization	Light, moderate and severe	Corresponds to discrepancies between current land use and the most suitable land use that is in accordance with environmental, ecological, cultural, social and economic factors of the land.	IGAC, 2012[4]
		Improper use in burned areas		
	Underutilization	Light, moderate and severe		

[1] Zonificación de la degradación de suelos por erosión. Línea base 2010 - 2011; Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) (https://bit.ly/31xopkt)

[2] Zonificación de la degradación de suelos por salinización para el área continental e insular de Colombia a escala 1:100.000 y 1:10.000 respectivamente. Año 2016 - 2017; IDEAM (https://bit.ly/31tSQYG)

[3] Mapas de Clasificación de las Tierras por su Vocación de Uso a escala 1:100.000; Geographic Institute Agustín Codazzi (IGAC) (https://bit.ly/32wnbHa)

[4] Mapa de Conflictos de Uso del Territorio Colombiano a escala 1:100.000; IGAC (https://bit.ly/2Pafcfp)

Table 2. Percentage of potential ecological recovery areas with moderate (M), light (L) and no evidence (NE) of soil erosion in the different biogeographic regions of Colombia. Values are given as percentages of the respective biogeographic region.

Land Suitability	Amazon (%)			Andean (%)			Caribbean (%)			Orinoquia (%)			Pacific (%)		
	NE	L	M	NE	L	M	NE	L	M	NE	L	M	NE	L	M
Agriculture (2,612,113 ha)	0.04	0.12	0.14	0.28	1.46	2.20	0.38	3.20	3.40	0.26	0.64	1.12	0.09	0.20	0.36
Agroforestry (1,283,651 ha)	0.05	0.24	0.42	0.09	0.60	0.93	0.05	1.20	1.60	0.02	0.17	0.29	0.06	0.17	0.07
Production forestry (6,363,259 ha)	0.13	0.37	1.12	1.22	6.80	7.03	0.40	1.91	1.55	0.07	0.24	0.38	0.89	1.41	0.71

Table 3. Percentage of identified areas with moderate (M), light (L) and very light (VL) soil salinization in the different biogeographic regions of Colombia. Values are given as proportions of the respective biogeographic region.

Land Suitability	**Amazon (%)**			**Andean (%)**			**Caribbean (%)**			**Orinoquia (%)**			**Pacific (%)**		
	VL	**L**	**M**	**VL**	**L**	**M**	**VL**	**L**	**M**	**VL**	**L**	**M**	**VL**	**L**	**M**
Agriculture (2,612,113 ha)	0.30	0	0	3.35	0.14	0.46	2.76	0.74	3.48	2.01	0	0.01	0.35	0	0.31
Agroforestry (1,283,651 ha)	0.71	0	0	1.40	0.04	0.18	0.85	0.79	1.22	0.47	0.01	0	0.17	0	0.13
Production forestry (6,363,259 ha)	1.62	0	0	12.50	0.28	2.26	1.17	0.41	2.28	0.69	0	0	2.54	0	0.46

Table 4. Area of land in hectares with a combination of no to moderate erosion and very light to moderate salinity in Colombia. Colors correspond to the degradation levels presented in Figure 2, which are as follows: very light (orange), light (yellow) and moderate (purple) degradation. In addition to these levels of degradation, these soils also experience some degree of either overutilization or underutilization.

	Very light salinity (VLS)	Light salinity (LS)	Moderate salinity (MS)
No erosion (NE)	724,634	28,059	90,455
Light erosion (LE)	3,201,927	166,508	863,967
Moderate erosion (ME)	4,150,036	181,026	852,411

Table 5: Proportion of land under agriculture, agroforestry and production forestry in each biogeographic region that is overutilized or underutilized.

Land Suitability	Amazon (%)		Andean (%)		Caribbean (%)		Orinoquia (%)		Pacific (%)	
	Under-utilized	Over-utilized	Under-utilized	Over-utilized	Under-utilized	Over-utilized	Under-utilized	Over-utilized	Under-utilized	Over-utilized
Agriculture (2,612,113 ha)	0.17	0.13	1.62	2.32	3.17	3.82	1.92	0.10	0.32	0.33
Agroforestry (1,283,651 ha)	0.02	0.69	0.13	1.49	0.22	2.64	0.16	0.32	0.09	0.21
Production forestry (6,363,259 ha)	0.04	1.58	0.08	14.96	0.04	3.82	0.34	0.36	0.00	3.01

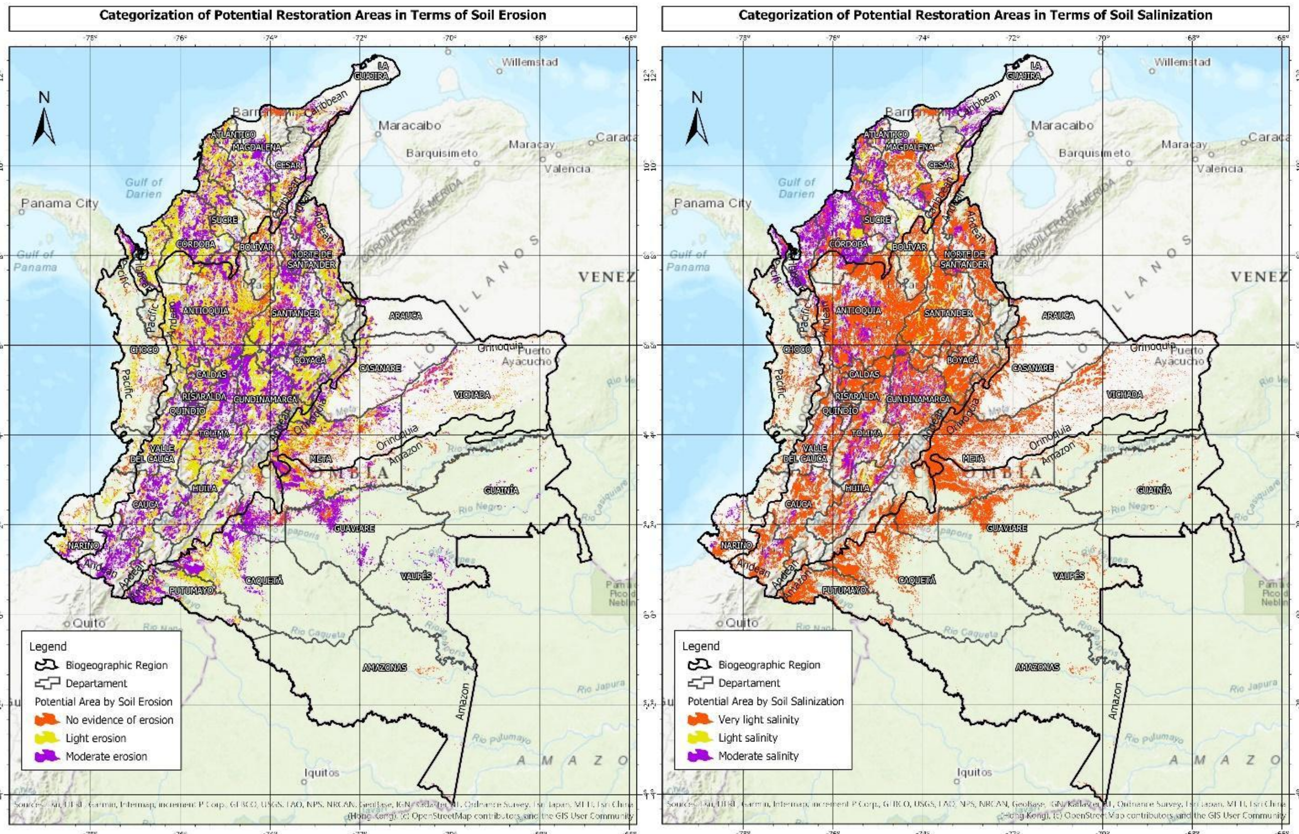

Figure 1. Spatial distribution of soil erosion (left) and soil salinization (right) in areas identified for potential low-cost ecological recovery in Colombia using the methodology proposed in the current study.

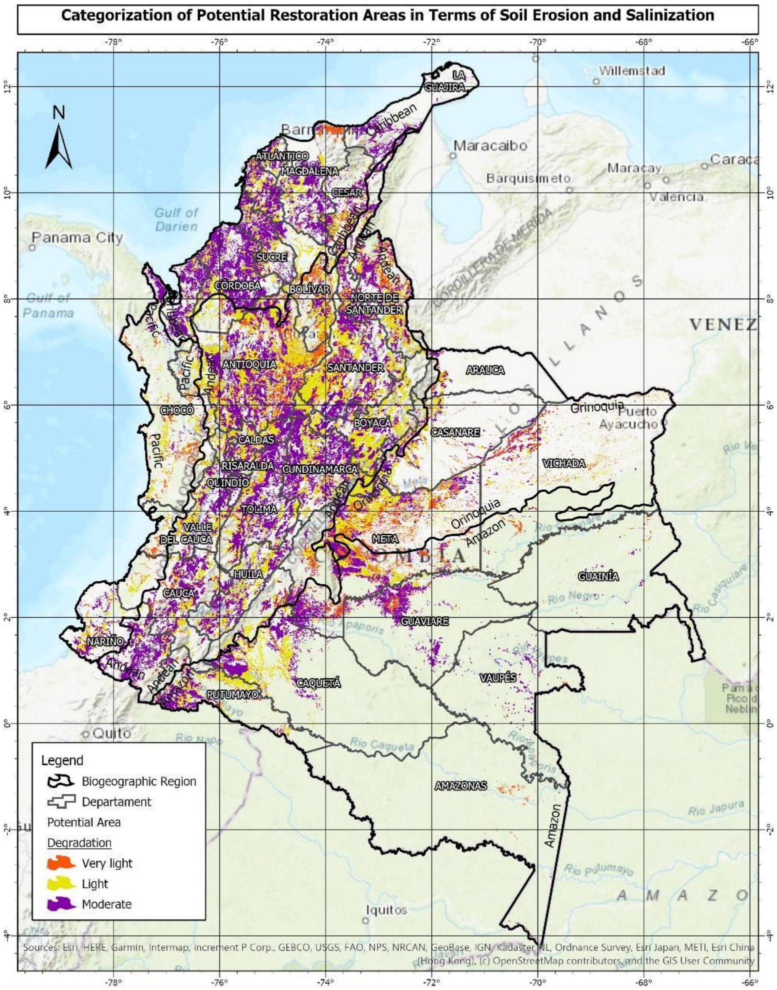

Figure 2. Spatial distribution of moderate to very light soil degradation based on soil erosion and soil salinization variables in areas identified for potential ecological recovery in Colombia. Degradation levels correspond to the following combinations of soil erosion and salinization levels displayed in Table 4: Very light (NE-VLS); Light (NE-LS, LE-LS and LE-VLS); and Moderate (NE-MS, LE-MS, ME-MS, ME-LS and ME-VLS).

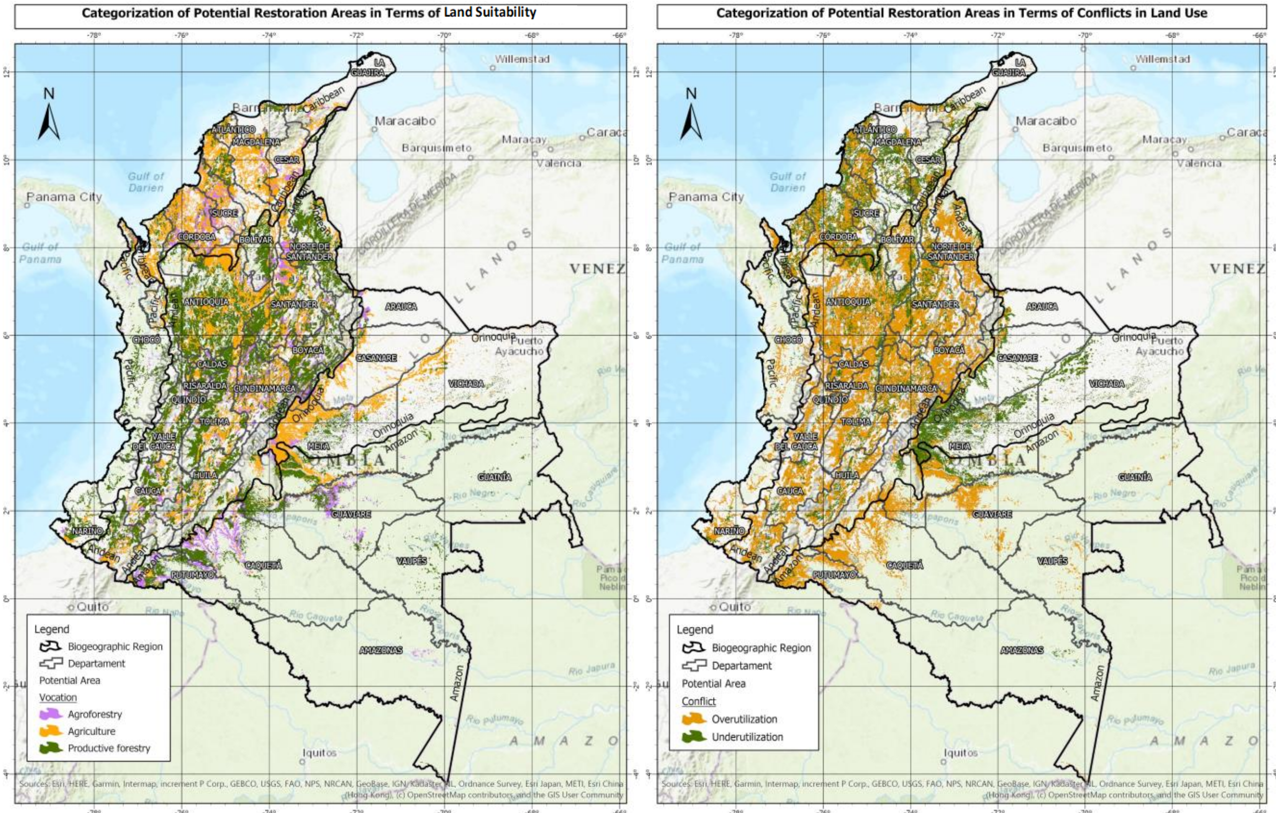

Figure 3. Spatial distribution of land that is suitable for agriculture and forestry production (left) and conflicts in land usage due to overutilization and underutilization (right) in areas identified for potential low-cost ecological recovery in Colombia.

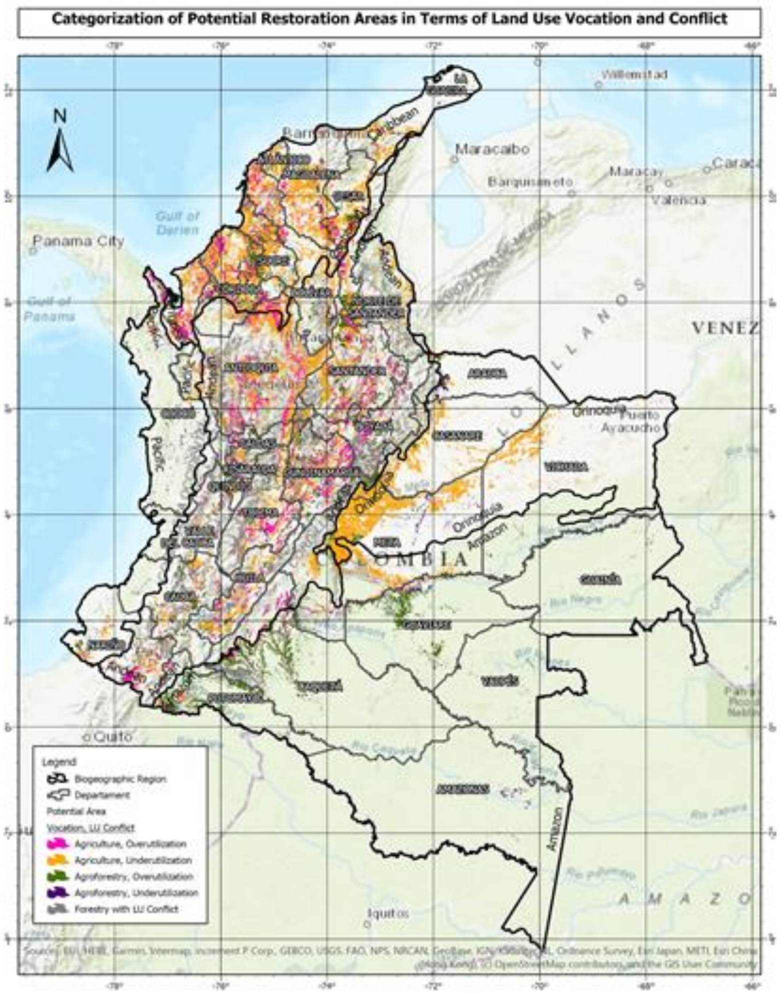

Figure 4. Areas with potential for ecological recovery in Colombia with issues related to land suitability and conflicts in land use (LU Conflict) due to either overutilization or underutilization.