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Mapping ecosystem services in Colombia: Analysis of synergies, trade-offs and bundles in environmental management

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ABSTRACT

Ecosystem services (ES) have gained significant attention in recent years from the global environmental initiatives that involve science and policy. Multiple scholars have analyzed how ES are integrated with environmental policies, plans, and strategic assessments. However, there is a lack of information on how countries translate these policies, plans and assessments into concrete environmental management actions that integrate an explicit ES approach. To help fill this gap, we analyze how the Colombian Regional Autonomous Corporations (CARs) have used the ES approach in their environmental management projects implemented between 2004 and 2015. This study aims to analyze the type and diversity of ES managed by the CARs, as well as the synergies, trade-offs, and bundles of ES prioritized by them. We used content analysis of the CARs reports and statistical analysis to explore whether CARs explicitly use the ES concept. Our results showed that provisioning, regulating, and cultural ES were similarly prioritized by the CARs, however, explicit mention of ES was limited. Regulating services showed remarkable potential for synergies, and there was a pattern of trade-offs between cultural and some regulating and provisioning services. We found three bundles of ES: "Restoration and conservation of agrosystems", "Mosaic of services" and "Farming and fibers" occupying, respectively, 9, 36 and 55% of the total area of Colombia. Our findings show that multiple ES are targeted and affected by environmental management actions.

The contribution of this study has the potential to inform adequately policy decisions to be used in environmental management and planning practices to prioritize areas for maximizing ES provision.

1. Introduction

Ecosystem services (ES) are promoted as an approach that recognizes and values the range of goods and services provided by nature to human well-being, facilitating the management of social-ecological systems (Bennett, 2017; Carpenter et al., 2009; Kareiva et al., 2011). The supply of these ES has been assessed in different ways over the last two decades, including participatory mapping and biophysical assessment, and also in different environments such as terrestrial and freshwater ecosystems (Dittrich et al., 2019; IAvH et al., 2021; UK NEA, 2014). The ES have

garnered attention in science and policy, being central to several international agreements at global scales (e.g. CBD/DEC/14/1, 2018; UNEP/CBD/COP/DEC/X/2, 2010; UNEP/IPBES.MI/2/9, 2012), as well as regional scales such as the European Union (e.g. EU, 2011). However, there is still a need for operationalizing the ES approach into practical and concrete applications such as in land-use planning and environmental management (Beery et al., 2016; Daily et al., 2009; Dick et al., 2018; Schubert et al., 2017).

The provision and flow of ES is strongly affected by policies, planning, and management practices (de Groot et al., 2002; Arkema et al.,

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2015; Mandle et al., 2021; Mitchell et al., 2021). This provision can be neutral, namely, the increase of one ES does not affect other ES either positively or negatively (Jopke et al., 2015). However, some relationships between ES can be identified and classified as trade-offs, synergies or bundles, which are critical to identify to adequately inform policy decisions and management (Cord et al., 2017; Förster et al., 2015). Trade-offs occur when the increase of one ES leads to a decrease of another ES (Bennett et al., 2009; Raudsepp-Hearne et al., 2010). Synergies occur when increases in one ES increases another, or conversely when the decrease of one reduces another (Felipe-Lucia et al., 2014). Synergies and trade-offs can be the result of a relationship between two or more ES or a relationship to a shared driver (Bennett et al., 2009). For example, there is a common synergy between soil conservation and carbon sequestration, where the better the conservation status of the soil, the higher the potential for carbon sequestration (Rodríguez et al., 2015; Shen et al., 2020). On the contrary, an example of a common trade-off is the case of agricultural production and water quality, which is driven by those ES's relationship to fertilizer, a shared driver (Qiu et al., 2021). Both trade-offs and synergies can be managed to either reduce their associated costs to society or enhance landscape multifunctionality and human well-being (Rodríguez et al., 2005). ES bundles are defined as a set of ES that repeatedly appear together across space or time (Raudsepp-Hearne et al., 2010), emerging as another way to understand the relationships between multiple ES.

Considering ES bundles have several benefits for enhancing the planning and management of ES as a way to connect the often-compartmentalized decision-making process (Saidi and Spray, 2018; Meacham et al., 2022). This might facilitate to take advantage of potential synergies, and to avoid unintended consequences (Meacham et al., 2022). Assessments of ES bundles have been used to help managers to prioritize conditions and contexts conducive to the provision of multiple ES (e.g. Crouzat et al., 2015; Queiroz et al., 2015; Rocha et al., 2020; Mitchell et al., 2021). The increasing number of ES assessments has made ES and ES bundles information more understandable and accessible for decision makers. However, there is limited understanding of which ES and ES bundles are targeted by management actions.

In Colombia, there is a complex system of environmental governance, which is coordinated by the National Environmental System (SINA in Spanish) (Law 99, 1993). It involves multiple dimensions (social, territorial, institutional and *trans*-sectoral), and multiple organizations, such as the Indigenous territorial entities (known in Colombia as “Resguardos”), the National Planning Department, national research institutes, and the 33 environmental regional authorities, named Regional Autonomous Corporations (Corporaciones Autónomas Regionales, CARs) (MADS, 2012). SINA is in charge of setting guidelines and standards, promoting activities, and allocating resources for biodiversity conservation and management. CARs have the main responsibility of implementing all SINA policies, many of them focused on ES, such as the National Policy for the Integral Management of Biodiversity and its Ecosystem Services (PNGIBSE in Spanish; MADS, 2012) where the goal is the promotion and management of ES.

The ES approach has been integrated broadly into different policies and guidelines to support decisions in many places over time and around the world (Costanza et al., 2017; Mandle et al. 2019). Echeverri et al., (2023) showed this ES integration by analyzing the Colombian biodiversity conservation policies between 1959 and 2020. This integration can be articulated to the Mace's conservation paradigm framework (Mace, 2014), which explains conservation evolution based on four stages of relationships between people and nature. Thus, the national policies have evolved to three stages of the paradigm framework: 1) intrinsic view “nature for itself”, e.g. protected areas, 2) instrumental view “nature for people”, e.g. payment for environmental services and, 3) relational view “people and nature”, e.g. policies on poverty which are necessarily linked to biodiversity policies (Mace, 2014; Rodríguez-Castro et al., 2015; Furumo and Lambin, 2020; Echeverri et al., 2023). As a highlight, the integration of ES in Colombia is presented in a variety

of national policies and tools focused on ES implemented by CARs, in order to guide environmental management, e.g. water (MAVDT, 2010) or wood (MMA et al., 2000).

Many studies integrating ES have addressed ES in Colombia (see Appendix 1). They have focused on social or ecological measures of the social-ecological system (e.g. Escobedo et al., 2015), assessing individual ES (e.g. Armenteras et al., 2015), or on a limited number of ES (e.g. Angarita-Baéz et al., 2017); most of the studies targeted specific natural regions (e.g. Aldana-Domínguez et al., 2017) rather than the national scale (e.g. Ricaurte et al., 2017) (Appendix 1).

The aim of this paper is to analyze how the CARs are integrating individual and bundles of ES into their environmental management projects, and how (if so) this approach has evolved between 2004 and 2015. Specifically, we addressed the following research questions: (1) How has the explicit use of the concept of ES changed over time in the implementation of the CARs' projects? (2) How diverse is the range of ES managed by the CARs, and which ones became prioritized? (3) What trade-offs and synergies are found between the ES managed by the CARs?, and (4) What ES bundles are managed by the CARs? This work will contribute to the understanding of how national environmental policies are translated into specific management actions using a novel approach of ES assessment that can be easily replicated and compared between countries.

2. Materials and methods

2.1. Study area

Colombia is the fourth largest country of South America and is divided into five natural regions: Caribbean, Pacific, Andean, Amazon, and Orinoquia (IDEAM et al., 2017; Rodríguez et al., 2015) (Fig. 1). Colombia covers 0.7 % of the global land area and is one of the countries with the highest biodiversity (Andrade-C, 2011; Rangel-Ch., 2015). It ranks as the most species rich country for birds and orchids, second in the number of amphibians and freshwater fishes, and hosts ~ 10 % of known plant species (Clerici et al., 2019).

Colombia has more than 70 natural and transformed types of ecosystems (IDEAM et al., 2017). Those ecosystems supply many ES for human well-being. For example, the Páramos (an ecosystem consisting of mountain grasslands above 3400 m and mainly located in the Andean region) covers 2.216.000 ha and provides water for 70 % of the Colombian population (IDEAM et al., 2017; Morales et al., 2007). Forests, the largest terrestrial ecosystem (more than 45 million hectares, 52 % of its territory; IDEAM et al., 2017; Furumo and Lambin, 2020) are mainly located in the Amazon and Pacific regions, which provide the highest levels of carbon storage and water regulation and provision in the country (Armenteras et al., 2015; IAvH et al., 2021; Rodríguez et al., 2015). Agricultural lands occupy 5.3 million hectares, and they are mainly located in the Andean region (MinAgricultura, 2014).

Furthermore, Colombia presents a rich cultural diversity. Out of its 48 million people, 30.8 % identify themselves as Afro-Colombian, Raizals, and Palenqueros, while 31.8 % are peasants, and 4.4 % belong to Indigenous Peoples (DANE 2019a, b, 2020). These groups are considered in Colombia as “Indigenous Peoples and Local Communities (IPLC)”. IPLC encompass individuals and groups who self-identify as Indigenous or as members of distinct local communities, playing a crucial role in the conservation and sustainable utilization of biodiversity through their knowledge, practices, institutions, and values (Bron-dizio et al., 2019; IPBES, 2019).

In Colombia, over the last 27 years, the SINA (Law 99, 1993), and in particular the 33 CARs (Fig. 1) have managed the ecosystems and their ES. We used the CARs as our units of analysis because they cover the entire country and have defined boundaries, besides, each CAR implements all environmental guidelines, and is charged with ensuring defined standards. It counts with a significant environmental budget (75 %) of the SINA (Blackman et al., 2005; Sánchez-Triana et al., 2007;

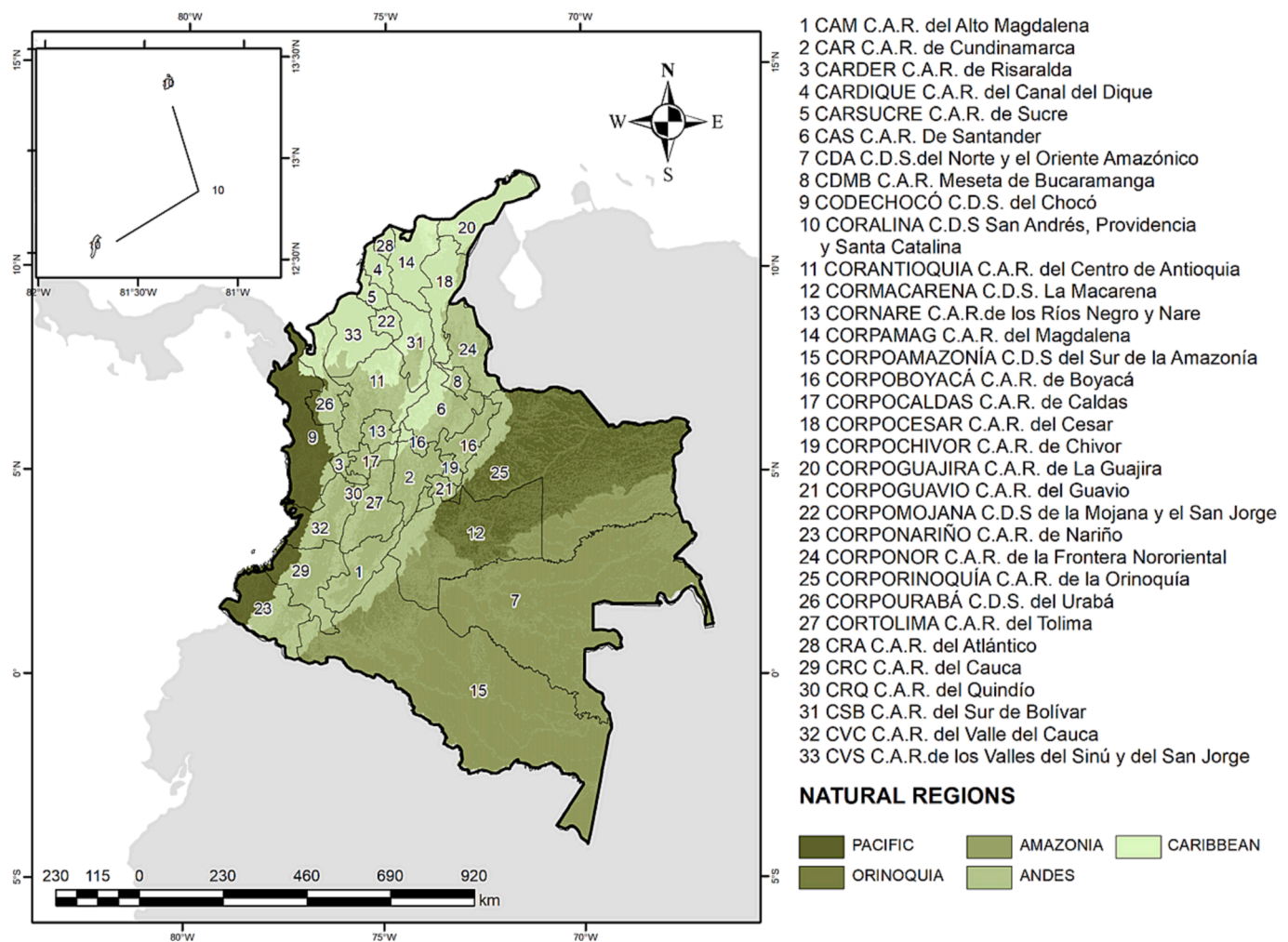


Fig. 1. Study area. Location of the natural regions (Caribbean, Pacific, Andes, Amazonia, Orinoquia) and the 33 Regional Autonomous Corporations (CARs) in Colombia. Acronyms in Spanish are: C.A.R. Corporación Autónoma Regional and C.D.S. Corporación Autónoma Regional de Desarrollo Sostenible.

Rodríguez-Castro et al., 2015). This budget is used to implement the Triennial Action Plans (TAP) of the CARs, which are operationalized by environmental management projects (MAVD, 2004). The CARs annually report all projects executed to the Ministerio de Ambiente y Desarrollo Sostenible (Ministry of Environment and Sustainable Development; MADS in Spanish). From 2004 to 2015, the CARs executed three TAPs, which cover the periods: 2004–2006, 2007–2012 and 2013–2015.

2.2. Data collection

We used CARs annual reports to analyze the environmental management projects implemented between 2004 and 2015 in Colombia. From a total number of 396 expected reports, we identified 322, since some CARs did not complete all of them during the first TAP. Those reports were collected between January and June 2017 from the CARs' official websites. Local planning officers and officers at the National Environmental System in the MADS were also contacted (personal communication, August 2017) to obtain those reports unavailable on the websites. The 322 reports were in Word, PDF and Excel format. However, those reports in Excel format (27) were excluded, because they contained no codable information. Information was presented as short sentences or single words which did not correspond to any of our key words on ES or referred to ES at all. Amongst the reports in Excel format, eight were from the CAR Corporinoquia, which did not make available any other type of report, resulting in the exclusion of this CAR from the analysis. Thus, our final sample were 294 of reports. On average, 9

reports were analyzed per CAR (Appendix 2).

For the analysis of the 294 reports, we did not include the introduction, the presentation, and other sections of the document that did not provide specific information about ES projects. The total number of pages analyzed was 31,123 and the average per CAR was 927 (sd +/- 536,3) (Appendix 2).

2.3. Data analysis

2.3.1. Coding scheme: Characterizing ES

To analyze how the CARs are integrating the individual and bundles of ES, we used a qualitative coding scheme. This coding was based on the Common Classification of Ecosystem Services, known as CICES (Haines-Young et al., 2018; <https://cices.eu/>, 2018), a hierarchical classification of ES typically used to identify ES bundles (e.g. Ditttrich et al., 2017; Zoderer et al., 2019). CICES identifies 29 ES (group level) clustered in 3 main types of ES (section level): provisioning, regulation & maintenance, and cultural. This classification is slightly different from the one proposed in the Millennium Ecosystem Assessment (MA, 2005), and better aligned with the revisions introduced by the Economics of Ecosystems and Biodiversity and The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services classifications. CICES' classification provided us with umbrella terms that allowed us to account for the diversity of language used in the CARs reports. Indeed, the language used from one CAR to the other differs and it was helpful for us to relate it to broader categories so that comparisons could be

established.

In order to link CICES classification with the current usage of ES in Colombia, the following steps were performed. First, we identified diverse terms or names of the distinct types of ES from scientific publications developed in Colombia and in Colombian’s official documents that consider this concept. We used Web of Science to find the scientific publications on ES that included Colombia as a case study between 2005 and 2019 (keyword search: “ecosystem services” OR “environmental services” & “Colombia” in Topic). We found 141 papers, where references to different ES were searched in the abstract, method and results sections. We did not perform a systematic literature review because the aim was only to identify references to ES used by previous studies in the country. We searched scientific publications to ensure that usual academic terms related to ES were also included in our non-academic language revision.

For Colombia’s official documents, we identified relevant policy and environmental management documents from the MADS (e.g., the PNGIBSE MADS, 2012), the National Biodiversity Reports (Moreno and Andrade, 2019, 2018) and the National Assessment of Biodiversity and Ecosystem Services (IAvH et al., 2021). Then, to find terms used by the environmental managers on the projects related to ES, we reviewed a random sample of 10 annual reports by TAP (N = 30 reports reviewed). In these reports, we searched for the mention of ES either explicit or implicitly as a support for the achievement of the objectives of the project. In all the cases we connected mentions of ES in the reports with CICES classification. For instance, for the cultivated terrestrial plants ES, we search within the document’s key terms as “agricultural”, “farming”, or “agroecology” (the search was performed in Spanish; Appendix 3). We also identified new terms used by the reports referring to ES. We identify 123 key terms from the scientific literature, official documents and the annual reports.

Finally, the coding scheme was based on associating each key term (1 23) to one ES under the CICES classification (Appendix 3). Sixteen ES

were listed in the coding scheme, where 5 are related to provisioning, 6 to regulation and maintenance, and 5 to cultural ES (Table 1). To guide the coding of the ES, we designed 16 analytical questions, one per ES, where each term was associated with specific activities of the project that depend on fostering the provision of one or more ES (Appendix 3). To increase its reliability, the scheme was reviewed by three ES experts, all native Spanish speakers and two of them from Colombia (all co-authors in this paper).

2.3.2. Content analysis

We used the 123 key terms as a proxy to search within the 294 annual reports for the presence of the 16 ES defined in the coding scheme. The unit of analysis was at paragraph level. Each key term that appeared within a paragraph led to coding that paragraph under the corresponding code to determine whether one or more ES were addressed by the project (or none of them). For this task we used the 16 analytical questions (Appendix 3). For instance, for “cultivated terrestrial plants” (a provisioning ES), a key term of search was “crop”, and one of the associated activities (actions) identified in a paragraph was “promotion of sustainable management of sugarcane crops”. This way, we determined the frequency of activities fostering the provision of ES in each CAR. This coding delivered a matrix of 16 ES x 32 CARs, that we also divided into the 3 TAPs. We coded and analyzed all the explicit mentions to ES and EnS identified in the reports, to capture which is the term most commonly used by the environmental managers (Balvanera and Cotler, 2007). Although “ecosystem services” (ES: *servicios ecosistémicos in Spanish*) is a widely used concept in academic contexts, it is convenient to clarify that in Colombia, like in other Latin American countries, ES may be interchangeably with “environmental services” (EnS; *servicios ambientales in Spanish*). We used the software NVivo11 to implement the coding process (www.qsrinternational.com).

2.3.3. Statistical analysis

We quantified the frequency of the terms related to ES and EnS identified in the environmental management projects and, in the reports that consider provisioning, regulating and cultural ES (RQ1). We quantified and mapped the 16 ES addressed by the projects in each CAR.

To estimate the diversity of ES within a CAR in each TAP (RQ2), we used Simpson’s index (Library vegan, R software). Simpson’s index is a measure of evenness, and it allowed us to calculate whether there is an even presence of all types of ES in a CAR, versus CARs focusing on one or a few ES. This index, originally used to estimate biodiversity, has been used in previous studies of ES (e.g. Queiroz et al., 2015; Quintas-Soriano et al., 2019; Raudsepp-Hearne et al., 2010). The value of this index ranges between 0 and 1, where 1 represents a more diverse set of ES addressed by the CARs. Kruskal-Wallis *H* test was used for measuring differences in the diversity of ES in the CARs and between TAPs. Subsequently, in order to understand the associations among pairs of ES (RQ3), the Pearson’s correlation coefficient was calculated with values ranging between −1 to 1, where −1 is a strong negative correlation and 1 is a positive one. We sought to identify both weak and strong relationships between multiple ES, as a proxy for synergies and trade-offs between the ES addressed by the CARs (Queiroz et al., 2015).

We used Principal Component Analysis (PCA) and hierarchical clustering (HCA) to map ES bundles (RQ4). These methods allow us to explore the distribution of ES across the CARs and similarities between CARs based on their ecosystem service profiles. The PCA reveals the main factors explaining the variability of ES addressed by the CARs. We used Ward’s method to minimize variability within groups, and conducted the HCA to identify groups of CARs with similar ES. We used NbClust function to show the optimum number of clusters following by a sensitivity analysis outlined in Charrad et al. (2014). We used as variables for the PCA and HCA the frequency of ES mentioned in the CARs annual reports. To normalize these variables, we divided the total number of paragraphs coded as a specific ES by the total number of paragraphs coded in the annual reports of each CAR. The 32 CARs were

Table 1
ES-List based on the CICES classification.

ES Category	ES-List	ES-Code (short name)
Provisioning	Cultivated terrestrial plants	Cultivated plants
	Fibers and other materials from cultivated plant	Fibers
	Reared and wild animals	Reared animals
	Genetic material	Genetic material
	Surface and groundwater	Water
Regulation & Maintenance	Control of erosion rates and buffering and attenuation mass movement	Control of erosion
	Hydrological cycle and water flow regulation	Water regulation
	Lifecycle maintenance, habitat and gene pool protection	Lifecycle maintenance
	Pest and disease control	Pest and disease control
	Regulation of soil quality	Regulation of soil
	Atmospheric composition and conditions	Atmospheric composition
	Physical and experiential interactions with natural environment	Experiential interactions
Cultural	Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge	Scientific & traditional ecological knowledge (TEK)
	Characteristics of living systems that enable education and training	Education & training
	Characteristics of living systems that are resonant in terms of culture or heritage	Culture & heritage
	Spiritual, symbolic and other interactions with natural environment	Spiritual & symbolic

included in the PCA as supplementary variables and in the HCA as grouping objects. All Statistical analyses were conducted in R stats 3.4.0 package (R Core Team 2020) (see in Appendix 4 the summary of the statistical analyses performed and their purpose).

3. Results

3.1. Changes in the adoption of the ES concept

Between 2004 and 2015 the explicit mention of the term “Environmental services” (EnS) increased over time in the annual reports (Fig. 2). The use of the term “Ecosystem services” (ES) appeared later, mainly after 2012, when the PNGIBSE was launched, and it increased over time. Out of 294 reports, 74 % (n = 218) mentioned EnS and 27 % (n = 78) ES.

The CARs that more frequently used the term EnS in their reports were CRC, CRA, Corponor, Corpoboyacá, Coralina, Corpochivor, Corpoamazonia and CDMB (more than 90 % of the total number of mentions), while ES was most frequently used by Cormacarena (72 %), CRQ (57 %) and Cader (50 %) (Appendix 5).

The explicit mention of the terms ecosystem services (ES) and environmental services (EnS) by the CAR's, and its presence (%) related with the total specific activities implemented within the projects to foster the provision of ES is shown in Table 2. The explicit mention of the terms ES and EnS is not directly related with the broader ES framework (Table 2). This is shown by the few overlaps between the explicit mentions of ES and EnS terms and the implicit use of the ES concept by the total activities implemented within the projects to foster provision, regulating, and cultural ES.

3.2. Spatial distribution and diversity of ES

Out of the 9,370 activities implemented in total by the CARs to foster or improve the provision of ES, 39 % were focused on provisioning, 33 % on cultural and 28 % on regulating ES. For the 16 ES analyzed, the distribution varied across the CARs (Fig. 3). Provisioning ES were mainly prioritized by CARs located in the Andean (e.g., Corpoboyacá or Corponor) and the Amazon (e.g., Corpoamazonia, and CDA) regions. Within this type of ES, cultivating plants was the most highly and uniformly distributed service, while water provisioning was seldom addressed. Activities related to regulating services, such as control of erosion, water regulation, lifecycle maintenance or atmospheric

Table 2

Explicit mention of the terms ecosystem services (ES) and environmental services (EnS) by the Regional Autonomous Corporations, and its presence related with activities implemented.

ES Category	Explicit mention of the terms (%)		Specific activities implemented within the projects to foster the ES provision
	ES	EnS	
Provisioning	11 (0,30)	60 (1,63)	3,678
Regulating	17 (0,65)	32 (1,22)	2,617
Cultural	15 (0,49)	60 (1,63)	3,075
Total	43 (1,44)	133 (4,48)	9,370

composition, were concentrated in CARs located in the Andean (e.g., Corantioquia, or CAR), Caribbean (e.g., CSB or Corpocesar) and Pacific (e.g., CVC, Corponariño) regions. Cultural ES were broadly addressed by all regions, and education & training was the most frequent and uniformly distributed ES.

Broadly, the diversity of ES identified by each RA did not vary over time (Kruskal-Wallis $X^2 = 3.05$; $p = 0.21$; for the three TAPs), and most CARs developed activities addressing a diverse set of ES (Fig. 4). CARs showing the highest diversity of ES were located in the Pacific (i.e., CRC) and in the Andes (i.e., CDMB and CRQ) regions. But CAS, also in the Andes region, was the CAR with the lowest diversity of ES.

3.3. Interactions among ecosystem services

From 120 pairs of possible interactions among ES, 15 pairs were positively correlated (synergies) and 14 pairs were negatively correlated (trade-offs) (see p-values in Fig. 5). The highest number of significant positive interactions were found for control erosion, water regulation, regulation of soil, atmospheric composition and cultivated plants (mainly regulating services interacting with other regulating services). Experiential interactions and education & training were significantly negatively correlated with a high number of ES (Fig. 5), most regulating services and some provisioning services. It implies that while cultural ES increase, provisioning and regulating ES decrease. For example, environmental education programs, workshops, or training were abundant

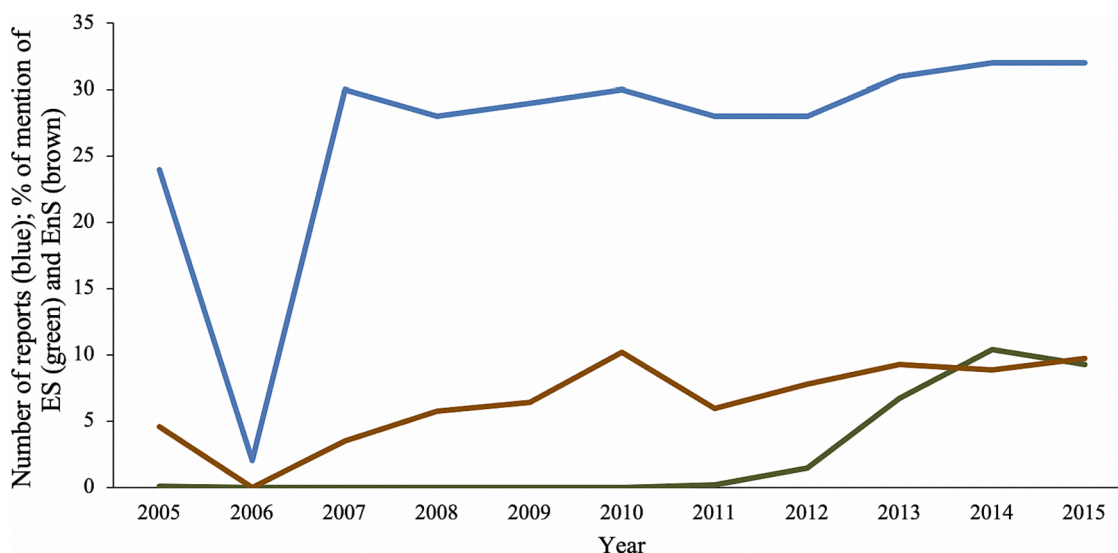


Fig. 2. Number of reports yearly (blue) and the percentage of explicit mentions of the terms ecosystem services (ES, green) and environmental services (EnS, brown); 100% represents the total of mention of ES plus EnS between 2004 and 2015. EnS and ES were mentioned explicitly a total of 1089 and 425 times, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

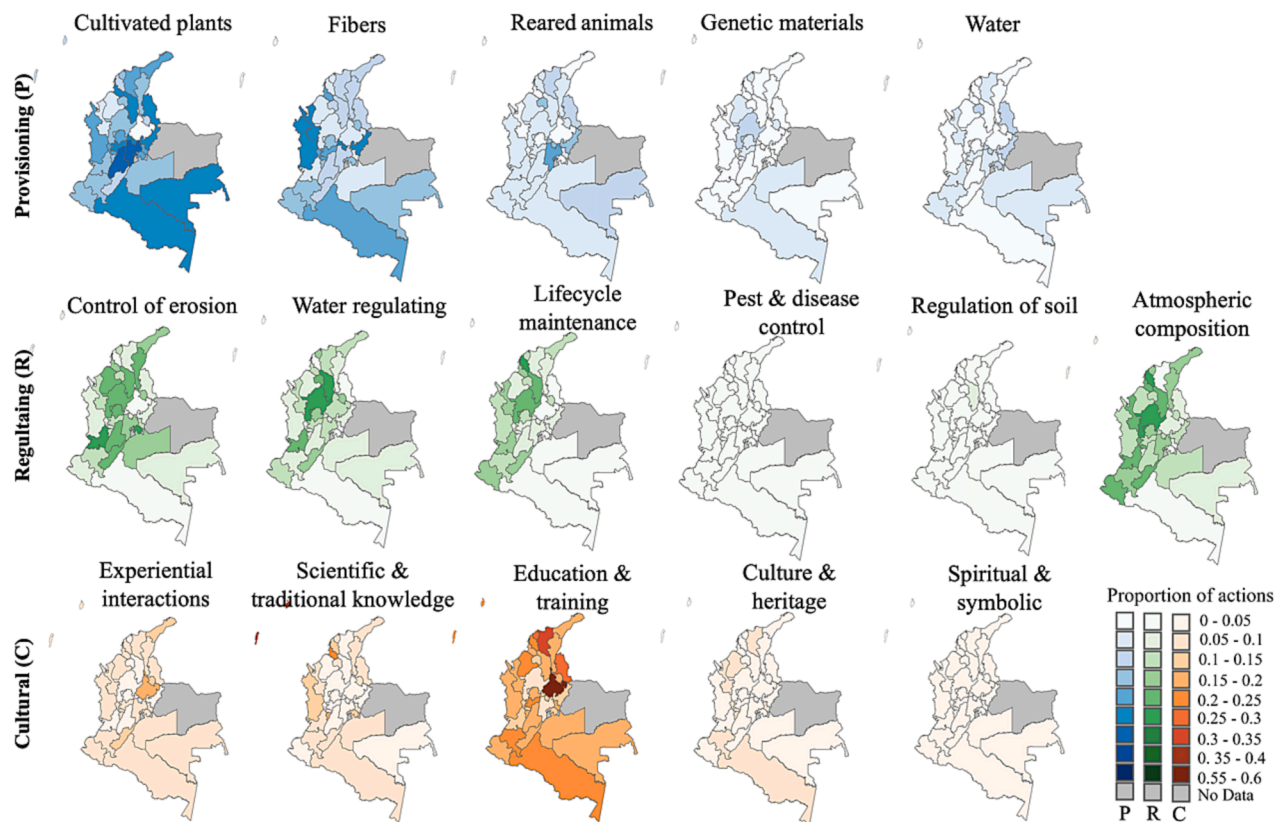


Fig. 3. Distribution patterns of ES addressed by the environmental management projects across the 33 Regional Autonomous Corporations. In the maps, the blue, green and orange gradients represent increasing the proportion of actions to produce provisioning (P), regulating (R) and cultural (C) ES respectively. Gray: No data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

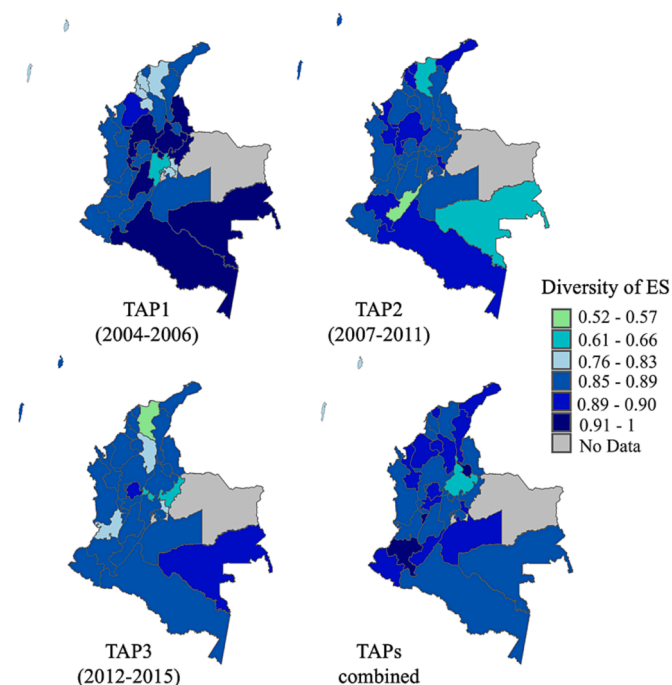


Fig. 4. Diversity of ES across the Regional Autonomous Corporations by Triennial Action Plans (TAP) and for the three TAPs combined. Higher values represent CARs with an even distribution of services. Gray: No data.

activities, but soil conditions or reforestation did not benefit from these numerous activities.

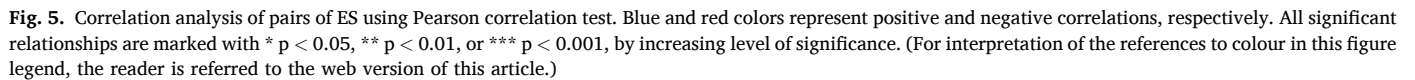
3.4. Bundles of ES in the implementation of environmental management projects

We used a PCA to study the bundles of ES addressed by the CARs. The first four components of the PCA (F1-F4) accounted for 60.5% of the total variance (Fig. 6; Appendix 5). PCA1 explained 23.9% of the variance and showed a gradient from regulation activities (e.g. forest reforestation that increase carbon storage, or activities on soil retention) (negative axis) to social-driven activities ES (e.g. sustainable agriculture training) (positive axis), reflecting the trade-offs between regulating and cultural ES. PCA2 accounted for an additional 16.2 % of the variance, describing a gradient from social-based activities (e.g. environmental education programs) (positive axis) to land-based activities (regulating and provisioning ES such as soil recovery) (negative axis).

The 32 CARs clustered into 3 bundles with coherent sets of ES (Fig. 7). *Restoration and conservation of agrosystems* (N = 4 CARs) was the smallest bundle (9 % of the total of Colombia's area). CARs within this bundle focused on implementing activities that fostered the provision of regulating ES (mainly through restoration or conservation activities) while enhancing plant cultivation. For example:

“...production and distribution of fruit plants, timber and ornamental plants to be planted by rural communities located around the river basins with clear deforestation signals” (CAR Corpomojana, 2009; translated from Spanish).

or “...implementation of rural environmental schools of sustainable livestock and organic agriculture for maintaining soil conservation systems” (CAR Corpoboyacá, 2013, translated from Spanish).



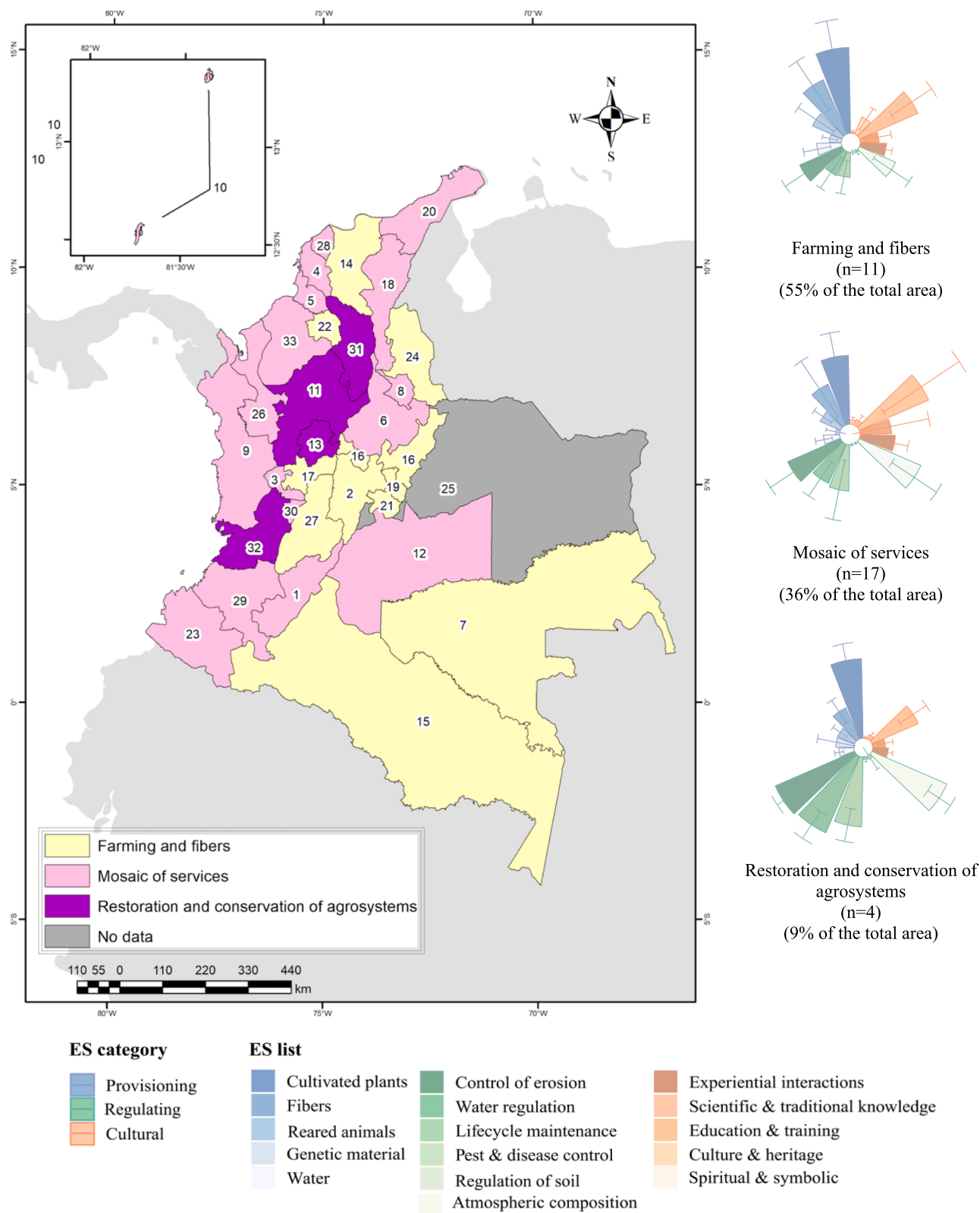


Fig. 7. ES bundles identified by Hierarchical Clustering on Principle Components for the study area. The three CAR groups are represented by flower diagrams and named according to the bundles of ES targeted by their actions. Gray: No data available.

In this bundle, the implementation of activities linked to cultural ES is very limited. This bundle of ES is addressed by CARs in the Caribbean, Pacific and Andean region.

Farming and fibers (n = 11 CARs) clusters CARs that prioritize provisioning ES, specially cultivated plants, reared animals and fibers.

There was a limited emphasis on regulating and cultural ES, although education & training activities were widely implemented. Examples included planting and monitoring fruit and timber plantations in agroforestry systems (CAR, 2009; Corpomoazonía, 2007), training farmers in agricultural and livestock conservation techniques (CAR, 2007), or

training on organic farming, home gardens, organic fertilizers and agroforestry (Cormacarena, 2007). This bundle of ES is addressed by many CARs located in the Andean region, and some of them from the Amazon and Caribbean region, occupying 55 % of the total of Colombia's area.

Mosaic of services ($n = 17$ CARs) was the most common bundle, in 36 % of the Colombians' territory. It was characterized by CARs implementing activities fostering the provision of the full set of ES analyzed. Cultural ES, such as education & training, experiential interactions, and scientific & traditional ecological knowledge (TEK), had a high expression in this bundle. Examples included activities that contribute to establishing the Botanical Garden "Eloy Valenzuela" as a place to do research, planting species to recover Páramos ecosystems, environmental education, and ecotourism (CDMB, 2008) or, working on forest, ecotourism an agro-tourism planning (CRQ, 2011), CARs within this bundle were concentrated in the Pacific and Caribbean region.

4. Discussion

4.1. Operationalizing the ES approach in environmental management

Scientists have consistently argued over time that the ES approach has the potential to reconnect people and nature (MA, 2005; Carmen et al., 2018; Dick et al., 2018). For this reason, it has been adopted in many environmental policies, plans and guidelines worldwide (Maczka et al., 2016; Schubert et al., 2017). Environmental institutions and managers, for their part, have used EnS more frequently, especially in Latin America, referring to payments for environmental services or environmental legislation (Balvanera and Cotler, 2007; Bonin and Antona, 2012).

We found that managers use more the term EnS than ES in management practices. This may be a consequence of the existence of environmental regulations that mention EnS, e.g. on EnS payments (e.g. MADS, 2017). However, we found an increase in the explicit mention of the term ES in environmental management projects (Fig. 2) after the declaration of the latest biodiversity policy in 2012 (MADS, 2012), which explicitly contemplated ES as a central axis. We argue that although the use of the ES concept has received critiques and embodies uncertainties for policies and management (Barnaud and Antona, 2014; Schröter et al., 2014), an increasing number of studies have suggested that the operationalization of the ES concept in grounded environmental practices helps to raise environmental awareness and serves as a common language. Then, it facilitates communication strategies, participation, collaboration and science-based knowledge to support planning, management and decision-making (Beery et al., 2016; Carmen et al., 2018; Dick et al., 2018).

4.2. Diversity and interactions among ES in environmental management

Fostering the provision of a diversified set of ES is desirable, as it often means broadening the group of beneficiaries (Fischer et al., 2017). For example, maintaining ES, as ornamental, medicines, food, fodder, or handicraft, in the Colombian Amazon helps to meet the needs of IPLC (Ricaurte et al., 2014).

Our results show a high spatial diversity of ES managerial actions throughout Colombia. This is because of the existing range of national policies and regional plans fostering the consideration of ES in decision-making along the country. Some examples are Ecotourism policies (MCIT and MAVDT, 2003), the National policy of integral management of water resources (MAVDT, 2010), or the National policy of environmental education (MMA and MEN, 2002). These policies are based on social-ecological singularities of the different regions, which might promote a diversity of ES, suggesting that a territorial understanding of ES supply and their benefits exists at the national and regional levels.

However, our results also show a high focus on provisioning services across all regions. On the one hand, focusing on provisioning services

happens at the detriment of other fundamental ES, for example, prioritizing agriculture-related ES could negatively affect water quality (MA, 2005; Raudsepp-Hearne et al., 2010; Rodríguez et al., 2006). On the other hand, the literature also argues that management actions focused on promoting provisioning ES might support conservation (Margules and Pressey, 2000). In this research, we found both cases, suggesting that there is not a single rule on the effects that policies focusing on provisioning services have on other services or policies supporting them. Besides, ES such as water provision are key to support other ES, and yet those were rarely explicitly included in our data, which is a common problem pointed out in the literature (Naidoo et al., 2008).

Regulating ES were the least addressed by the CARs, although this type of ES shows the highest number of synergies in our results. For example, actions to increase reforestation or repair wetlands help to control erosion, which in turn, increases lifecycle maintenance. Scholars have found similar results for regulating services in Colombia (Rodríguez et al., 2015), and other places (Ma et al., 2020; Raudsepp-Hearne et al., 2010). More efforts are needed to avoid underestimating regulating ES and make them explicit in policy documents and research so that they can be better preserved (Bennett et al., 2009). They could for example be included in national policies such as the National policy of integral management of water resources (MAVDT, 2010), or the National policy of integral management soil environment (MADS and IDEAM, 2013). We speculate that investment on regulating services requires long term intervention plans. Thus far the policy documents analyzed focused on short term gains (three year cycles) which might be insufficient to target regulating or supporting services, or bias managers to focus on provisioning services that lend themselves to quantification on the national accounts.

Cultural services were frequently targeted by the CARs, but mainly focused on education & training activities. The implementation of these activities was promoted by a combination of environmental and educational policies in the last decades. Burgos-Ayala et al., (2020a) showed that it is necessary to analyze the nuances of different activities (e.g. goals, scale, budget, stakeholders targeted) to understand the intent and expected outcomes they promoted. For example, education, as an ES, might have a dual effect in IPLC. On the one hand, IPLC hold TEK of rituals, farming, hunting, or fishing techniques, where education has an essential role in passing their traditions to younger generations (Angarita-Baéz et al., 2017; Berkes, 2009). On the other hand, there is a lack of knowledge on how environmental managers design and implement educational processes (e.g. ethnic education) involving (or targeting) IPLC (Burgos-Ayala et al., 2020a). IPLC are poorly involved in environmental management plans or projects, and education is frequently addressed as a top-down process (e.g., talks, or training on specific skills), where TEK is barely integrated into the management strategies (Angarita-Baéz et al., 2017; Burgos-Ayala et al., 2020a, Burgos-Ayala et al., 2020b).

4.3. ES bundles prioritized in environmental management

We identified three bundles of ES management actions in Colombia, which do not necessarily reflect the biophysical provision of ES on the ground. Instead, they are planned actions that CARs take through projects to manage sets of ES. In other words, they are intentions, at best actions, but they are not necessarily translated into the delivery of one or more ES on the ground. Four CARs focused on regulating and agricultural services (*Restoration and conservation of agrosystems*). 11 CARs focused on provisioning services (*Farming and fibers*), covering the largest geographic area, followed by a group of 17 CARs combining all types of ES (*Mosaic of services*).

The *Restoration and conservation of agrosystems* bundle exemplifies management efforts to maintain regulating services supply and their synergies. Near 33 % of the Colombian territory is inhabited by people living in collective territories in forest areas supplying many regulating services (Mosquera et al., 2016; Rodríguez et al., 2015). However,

deforestation levels in the country keep growing (e.g. 5.116.071 ha between 1990 and 2005 and 1.409.868 ha between 2005 and 2010; between 2001 and 2021, Colombia lost 4.93 million ha of forest cover-corresponding 6.0 % of the total la forest cover) (Armenteras et al., 2013; Global Forest Watch, 2022; IDEAM, 2018a). This approach to ES management may result from the National Forest Development Plan, which seeks to foster reforestation.

This bundle highlights the success of combining regulating and agricultural services, the first being fundamental to produce the latter. For example, actions that increase soil regulation are beneficial to agriculture, contributing to reduce the overruns and maintaining the topsoil. Nevertheless, the geographical location of the four CARs of focus for this bundle does not correspond with the CARs with the highest deforestation (IDEAM, 2018a), or with key supply regions for regulating services identified in previous studies. These studies demonstrated that water regulation and carbon storage in biomass have high values of supply in the Pacific and Amazon regions, while control erosion and carbon storage in soil have high values of supply in the Andean regions (Armenteras et al., 2015; Rodríguez et al., 2015). According to our results, this bundle of ES was prioritized in one CAR in the Pacific, two in the Andean region, and none in the Amazon region. To sum up, there is a mismatch between the authorities who prioritize certain ES, and the places within the country where they are actually co-produced.

The bundle *Farming and Fibers* concentrated actions on provisioning services in 55 % of the Colombian territory. Agriculture (cultivated plants), livestock (reared animals) and timber production (fibers) are the main social-ecological drivers of landscape transformation in Andean and Amazon regions (Armenteras et al., 2011; Etter et al., 2006; Etter and Van Wyngaarden, 2000). Specifically, the need to manage the provision of fibers is consistent with the high market demand for wood, the use of firewood for local consumption, and the intense level of illegal timber exploitation of many wood species, particularly in the Amazon (MMA & Asocars 2002 in Olaya-Álvarez, 2006). In 2018, illegal timber exploitation represented 71 % of total Colombian deforestation (IDEAM, 2018b). We found consistency between the location of areas supplying some specific services and the ES prioritized by the CARs, e.g., cultivated plants in the Andean region. However, services like water provision, abundantly provided by the Amazon region (Spracklen et al., 2012), were not prioritized by any of the 3 bundles identified in this study.

In the CARs prioritizing the *Mosaic services* bundle, managers targeted the provision of a broad range of ES for a variety of beneficiaries (Fischer et al., 2017). This type of multifunctional bundles is usually linked to the prevalence of regulating ES (Raudsepp-Hearne et al., 2010). Yet, our results show that, in addition to the regulating ES, the cultural ES are also characteristic of this bundle, while limited in the other two bundles. The Pacific and Caribbean regions (where CARs focusing on the *Mosaic services* bundles are mainly located) have a high frequency of experiential interactions ES, which might be due to the high number of ecotourism projects in the area and its relatively easy access. Additionally, scientific & TEK ES relate to the biological and cultural richness of the area, with a high number of IPLC, as Afro Communities, living in the Pacific and Caribbean regions. Multifunctional bundles are commonly related to long-term sustainability (Mas-kell et al., 2013), which in our study could potentially lead to successful environmental management of 36 % of the Colombian territory. Despite this, the *Mosaic services* bundle identified also showed an imbalance in the type of cultural services with an emphasis on education & training services.

4.4. New approaches to understand ES bundles: contributions and limitations

Our study contributes with an innovative methodology to understand ES distribution from the perspective of the environmental management activities implemented in the territory. These activities, described in the annual reports of the CARs, serve as a proxy to

understand the prioritization made by the environmental managers of these entities concerning to the provision of particular ES over others. It enables the exploration of how management efforts are located in the regions where the supply of these ES is more likely to happen.

This qualitative approach contrasts with the biophysical measures frequently used to map ES (e.g., hectares of land under certain use) (Dittrich et al., 2019; Malinga et al., 2015; Queiroz et al., 2015), as well as with the work developed on social perceptions or participatory mapping of ES (Jericó-Daminello et al., 2021; Martín-López et al., 2012; Plieninger et al., 2019). While the previous approaches focus on land uses and users, respectively, we emphasize the environmental management activities that connect ES policies and practice. Our approach is replicable and comparable at different spatial and temporal scales and especially useful when there is a limited capacity for analyzing management practices more exhaustively (Queiroz et al., 2015). However, using CARs reports as our source of data also entails some limitations. While they are an official document delivered periodically to the MADS and (supposedly) publicly available, it remains a challenge for both the CARs and the MADS to make them more accessible (especially the first TAP reports) and to improve their uniformity and comparability (e.g., only excel tables vs full documents), as well as their quality (e.g., length of the projects description). Nevertheless, our data was reliable enough to perform the analysis presented here, and we could successfully identify the activities implemented and how they related to different ES.

We report ES prioritization by environmental managers at the regional scale (CAR's) in Colombia. Future efforts could focus on the local scale (i.e. municipalities). Although environmental policies to foster coordinated ES planning and management at the regional scale (e.g. maintaining water production and regulating water processes is fostered by the Planning of River Basin management structures -POMCA in Spanish- or by regional forest or páramos ecosystems planning and management), many authors suggest studying ES should be done at the local scale. For example, 1) it is at that scale that many decisions regarding planning and landscape management, 2) this scale is the expression of trade-offs among services that might happen at other spatial scales (e.g. variation of services with a regional -or global- expressions, such as carbon sequestration or water quality regulation), and 3) stakeholder groups at this scale use and manage directly the ecosystems and their ES (Queiroz et al., 2015; Zoderer et al., 2019; Mancilla et al., 2019). The municipal scale should indeed receive further attention since it is the smallest administrative unit where decision-making and planning impacts supply, demand, and management of ES more directly (Arnaiz-Schmitz et al., 2018; Queiroz et al., 2015; Raudsepp-Hearne et al., 2010). In addition, environmental planning and programs at the local scale have frequently integrated an ES approach (Nordin et al., 2017; Schubert et al., 2017). In our particular case, it is worth noting that most projects in the CARs studied were done at a local scale (Burgos-Ayala et al., 2020a).

5. Conclusions

We proposed an innovative approach to assess how bundles of ES are prioritized by environmental managers, focusing in Colombia as case study. Our approach facilitates identifying the types of ES targeted by specific projects, the presence of bundles under a spatial approach, and what blind spots emerge when actions over emphasize some ES over others. The proposed approach can be replicated, and it has the potential to support the identification and understanding of the ES targeted by environmental management in other regions or countries.

Based on our research questions, we can conclude that after 15 years of introduction of the ES concept in environmental policies, its explicit consideration by the different actors involved in the context of environmental management is still in an early stage. This might mean a risk in the environmental policies implementation, giving a lack of a common language and understanding between managers and other stakeholders usually related with management actions. Secondly, the

identification of synergies and trade-offs is a critical aspect to be considered at the moment to develop new environmental management plans, because they are critical to identify to inform adequately policy decisions and management. This because they can connect the decision-making process, to take advantage of potential synergies, and to avoid unintended consequences. Thirdly, the identification of bundles provides important information to support decisions for present and future environmental management when the multifunctionality of landscapes and the supply of a range of benefits for human well-being is an important planning and development objective. Despite the early adoption of ES concepts in environmental management programs, we identify two big challenges for Colombia: 1) to increase actions on regulating and supporting ES that are crucial to produce other ES, and 2) to diversify the mosaic of ES which are needed for a variety of beneficiaries. These challenges could be mainstreamed through education & training, actions that have the potential to reconnect people to nature. Thus, education can be used as conservation leverage in management actions; nevertheless, it needs a careful and a context-based approach, for example, by respecting ethnic TEK and cosmologies. More research is needed in integrating detailed ecological indicators with implemented environmental management activities to better understand linkages between ES supplied by the ecosystems and environmental management activities.

CRedit authorship contribution statement

Aracely Burgos-Ayala: Writing - original draft, Writing - review & editing, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Amanda Jiménez-Aceituno:** Writing - review & editing, Resources, Conceptualization. **Megan Meacham:** Writing - review & editing, Methodology, Conceptualization. **Daniel Rozas-Vásquez:** Writing - review & editing, Supervision, Conceptualization. **María Mancilla García:** Writing - review & editing, Methodology. **Juan Rocha:** Writing - review & editing. **Alexander Rincón-Ruiz:** Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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