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Monitoring Biodiversity and Ecosystem Services in Colombia's High Andean Ecosystems: Toward an Integrated Strategy

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There is growing consensus that biodiversity losses resulting from global change profoundly affects ecosystem services and human welfare. However, biodiversity and ecosystem processes are commonly monitored independently and on spatiotemporal scales inadequate to inform decision-making. The high Andean ecosystems of Colombia, extending from high Andean forests and páramos to glacier ice caps, form dynamic landscapes because of the interaction of climate and land use change in a complex socioeconomic and political context, including new demographic dynamics and policies associated with the peace process and strict regulations for economic activities in the páramos. Moreover, they are part of a global biodiversity hotspot and provide key ecosystem services, including substantial carbon accumulation and water regulation and provision for large rural and urban populations. There is substantial experience in environmental monitoring of Colombia's high mountain ecosystems, including programs addressing biodiversity, carbon stocks, hydrology, glaciers, and land use dynamics. However, a conceptual and institutional framework for integrating these diverse initiatives is required. Here, we present a proposal to promote integrated monitoring of biodiversity and ecosystem services in high mountain ecosystems in Colombia as a contribution to consolidating a national ecosystem monitoring program. We describe the methodology used to design this integrated strategy based on an extensive process of consultation with monitoring experts in the region. Then, we review the state of the art of environmental monitoring in the Colombian High Andes. Based on the experience accumulated, we propose a multiscale conceptual framework for analyzing drivers of change and response variables from the local to the national scale, emphasizing the importance of monitoring along altitudinal, land use, and ecosystem restoration gradients. Finally, we describe the expected outcomes and possible institutional arrangements for the strategy, as well as some key next steps for promoting its implementation.

Keywords: *Adaptive management; Andean forests; carbon; climate change; environmental policy; land use change; páramo; water.*

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Introduction: integrated monitoring of biodiversity and ecosystem services

There is growing consensus that the loss of biodiversity resulting from global change profoundly affects ecosystem services and human welfare (Isbell et al 2017). This results from the tight relationship between biodiversity and ecosystem productivity, resource use efficiency, and resilience to human transformations (Tilman et al 2014). Multilateral agencies, such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), have emphasized the need for long-term data on biodiversity and ecosystem services in natural and transformed ecosystems and their contribution to human welfare on regional to global scales (Díaz et al 2015). However, ecosystem processes (eg regulation of water provision or carbon storage) are commonly monitored independently of biodiversity and, in many cases, on spatiotemporal scales that are not large enough to capture the complex spatial dependencies and temporal lags linking human-induced transformations with their socioecological impacts (Isbell et al 2017). Consequently, the development of long-term monitoring systems combining multiple spatial scales constitutes a key step in consolidating effective systems of adaptive ecosystem management (Nichols and Williams 2006; Lindenmayer et al 2013).

There are 2 main types of environmental monitoring systems, called mandated monitoring and question-driven monitoring (Vos et al 2000; Lindenmayer and Likens 2010). The first are generally national programs that respond to the requirement to generate reports on the state of natural resources. The second type refers to more focused systems on a regional scale, which typically evaluate explicitly formulated questions on aspects such as the relationship between changes in land use and their environmental consequences. A major challenge in designing monitoring systems relevant for decision-making is to combine both types of strategies. This would allow monitoring to be guided by questions formulated on both regional and national scales, explicitly considering key bidirectional links between these scales (eg how national policies affect regional land use or how regional differences in socioecological dynamics scale up to determine national trends).

From this perspective, some key components should be included in a fully structured monitoring strategy that can inform decision-making: (1) explicit objectives, questions, and conceptual models linking drivers of change and their effects on response variables; (2) a detailed cost-effective design, including replicable protocols, which explicitly considers uncertainties and the power to detect changes given these uncertainties; (3) schemes for data management and analysis, system maintenance, and quality control; (4) flexible institutional arrangements, including mechanisms for stakeholder participation; and (5) a knowledge-sharing strategy, including adaptive feedback loops, explicitly linking monitoring with policy formulation (Legg and Nagy 2006; Lindenmayer and Likens 2010; Díaz et al 2015).

In Colombia, the Ministry of the Environment and other agencies of the National Environmental System (SINA in Spanish) have been working on the design of a national ecosystem monitoring program to guide decision-making. In this context, two key SINA agencies, the Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM) and the Institute of Biological Resources Alexander von Humboldt (IAvH), with the support of the Consortium for Sustainable Development of the Andean Ecoregion (CONDESAN), set out to formulate a joint proposal for an Integrated Strategy for Monitoring High Andean Ecosystems of Colombia (called EMA, its Spanish acronym, hereafter).

There is substantial experience in Colombia in environmental monitoring both on a national scale and in high mountain ecosystems (Table 1; Sierra et al 2017; Vallejo and Gómez 2017). An integrated conceptual and institutional framework would allow articulation of these diverse initiatives. Hence, the design of the EMA can be understood both as a contribution to consolidate the national monitoring program and as a conceptual exercise that could be replicated in other ecosystems in Colombia and other countries in which an integrative, ecosystem-oriented framework is lacking or is being developed.

Our objective in this paper is to present the key elements of a strategy for integrated monitoring of biodiversity and ecosystem services in high Andean ecosystems in Colombia (see the full proposal in IDEAM et al 2018 and a policy-brief publication in Spanish in Llambí et al 2019). First, we discuss the significance of high mountain ecosystems in Colombia. Then, we describe the methodology used to design the proposal and review the state of the art of environmental monitoring in the Colombian High Andes. Finally, we describe the conceptual framework, expected outcomes, and proposed institutional arrangement for the strategy, as well as some key next steps to promote its implementation.

Why focus on high mountain ecosystems in Colombia?

Because of their outstanding biodiversity and the provision of essential ecosystem services, mountain ecosystems are recognized as global priorities for conservation and sustainable management in the United Nations 2030 sustainable development goals (target 15.4, UN General Assembly 2015). To design the proposal, we defined as target ecosystems those located in the high mountain belt, above 2800 m in elevation, according to the ecosystem map of Colombia (IDEAM et al 2017a). This belt includes a complex mosaic of high Andean forests, *páramos,* wetlands, periglacial snowfields, and glacier ice caps, as well as secondary vegetation units and a diverse array of agroecosystems, including pastures and annual crops. The high mountain belt is characterized by a marked heterogeneity of environmental conditions because of steep elevation gradients and the presence of complex mountain landscapes with contrasting climates, geology, human occupation, and land use histories (Sarmiento and Leon 2015). The main mountain systems are the Perija; the Eastern, Central, and Western Cordilleras; the Sierra Nevada de Santa Marta massif in the north; and the Colombian massif in the south (Figure 1). This belt covers a total surface area of 4,125,500 ha (3.6% of the continental area of Colombia), of which 2,906,137 ha (70.4%) correspond to *páramos* (Sarmiento et al 2017).

The Colombian High Andes are part of an important biodiversity hotspot and part of the largest tropical mountain region on Earth, the tropical Andes; they also comprise a large proportion of the *páramo* biome in South America (Myers et al 2000; Llambí and Cuesta 2014). Moreover, they provide key ecosystem services, including a high capacity for carbon accumulation in soils and biomass, and regulation of the provision of high-quality water resources for a growing urban and rural population, including the inhabitants of Bogotá and numerous intermediate cities (Castaño-Uribe 2002; Sarmiento et al 2017).

Andean forests in Colombia have been exposed to important historic processes of transformation and are estimated to occupy today less than 50% of their potential surface. The main drivers of change include cattle grazing, agriculture (including illicit crops), hydropower and transport infrastructure, hunting, wood extraction, and climate change in a general context of rapid population growth and urbanization (Etter and Wyngaarden 2000; Armenteras and Gast 2002; Etter et al 2006; Armenteras et al 2011; Morales and Armenteras 2013).

In the case of the *páramos,* it is estimated that 15% (449,500 ha) has been replaced by pastures, crops, and exotic plantations (pines and eucalyptus), while 45% of their surface area is included in the National System of Protected Areas. Other models of environmental governance in the region include legal indigenous lands (*resguardos*) of more than 16 ethnic groups and multiple initiatives for participatory land planning and sustainable agriculture implemented by community-based organizations. However, there are also numerous carbon and gold mining concessions and intense social conflicts associated with them. This lead to a complex legal process, starting with the reform

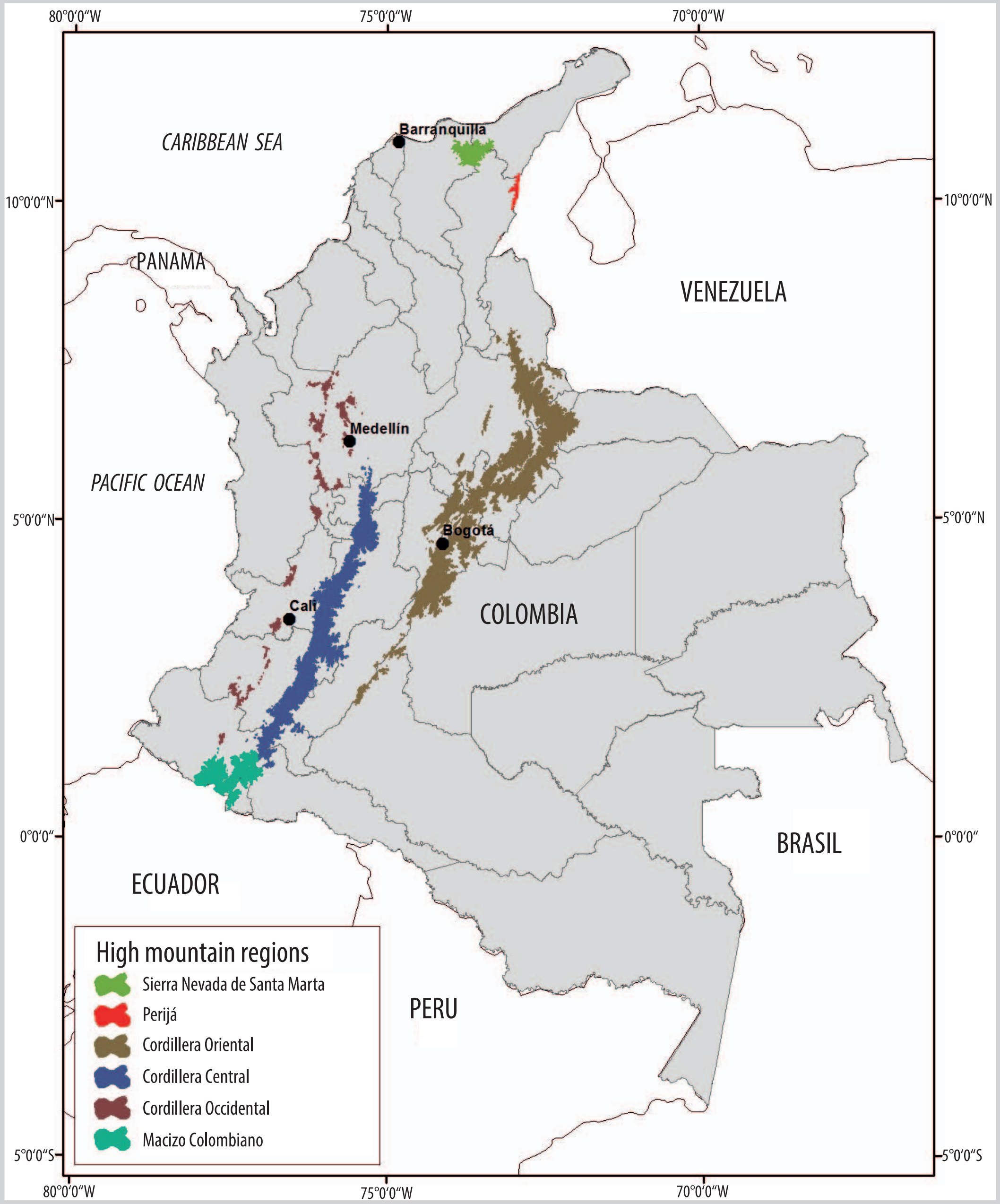
TABLE 1 Long-term monitoring initiatives identified in high Andean ecosystems of Colombia, indicating the name of the program, coordinating institutions, key variables monitored, spatial extent and sites included, monitoring interval, and available protocols or key publications. (Table extended on next page.)

Topic	Program	Institutions	Main variables
Biodiversity and keystone species	Periglacial colonization plots	IDEAM	Composition and cover of lichens, mosses, and vascular plants
	GLORIA-Andes network in Colombia	Javeriana University, CONDESAN	Plant species abundance and composition, soil temperature
	Warming experiment in the *páramo*	Los Andes University	Plant species abundance and composition, microclimate, photosynthesis and net primary production, decomposition, soil respiration
	Oak forests monitoring along an elevation gradient	Natura Foundation, Distrital University	Vascular plant abundance and diversity, dendrometric data, biomass carbon (C), wood density, functional diversity
	Permanent plots along an elevation gradient in the Quindío River watershed	Tolima and Quindío Universities, Quindío Regional Corporation, ColTree Fundacíon, Amazon Forest Inventory Network (RAINFOR)	Vascular plant abundance and diversity, dendrometric data, root and litter production, microclimate, soil humidity, other edaphic variables
	National program of stem rosette infection by pathogens and herbivores	Javeriana University, Bogota Botanical Garden, Jorge Tadeo Lozano University, others	Demographic variables (*Espeletia* spp.), damage distribution and intensity, organisms involved (fungi, insects)
	Management and conservation of Andean Bear populations	Wildlife Conservation Society, Andean Bear Conservation Alliance, National Parks of Colombia, others	Threats and land use strategies, stakeholders and conflicts, occupancy patterns, effectiveness of management strategies
Biomass and C	C and biomass monitoring in high mountain ecosystems (forests and *páramos*)	IDEAM, Javeriana University, National University of Colombia–Medellín	C in biomass and soils, decomposition, soil respiration, litter production
	C monitoring in wetlands and *páramos*	Instituto Geográfico Agustin Codazzi, Instituto Humboldt	Soil C, other edaphic variables (pH, soil bulk density, texture, cation exchange capacity, etc)
	National Forestry Inventory	IDEAM, others	Dendrometric data, tree species composition, C in soils, biomass and necromass, soil properties
	Dynamics of Andean forests	National University of Colombia–Medellín, others	Dendrometric data, tree species composition, C in biomass and soils, soils properties
	Permanent plots along the forest–*páramo* transition belt	IAvH, others	Vascular plant species composition and abundance, functional and phylogenetic diversity, soil genetic diversity, primary productivity, decomposition, sonic landscape
Hydrology and glacier dynamics	Hydrological monitoring in the Colombian *páramos*	IDEAM, IAvH	Climate, water discharge (runoff), water quality indicators (biological and physicochemical), isotopic and hydrochemical studies
	Glacier dynamics	IDEAM	Glacial area and perimeter, ice thickness, glacial mass balance and equilibrium line, fusion runoff
	Poleka Kasue Mountain Observatory	Escuela de Ingenieros de Antioquia University, International Research Institute for Climate and Society–Columbia University	Climate, ecohydrology, land use change, C in soils and biomass, vegetation dynamics, socioeconomic aspects
Land use change	Land use change in Andean forests	Javeriana University, National University of Colombia, others	Land use strategies, land cover change, landscape structure, socioeconomic drivers
	Land use change in *páramos* of Colombia	IAvH-Adaptation Fund, others	Land use strategies, land cover change, landscape structure, socioeconomic drivers, social actors and conflicts

TABLE 1 Extended. (First part of Table 1 on previous page.)

Topic	Spatial extent and sites	Monitoring interval	Protocols or publications available
Biodiversity and keystone species	Santa Isabel Nevado (2 transects, 6 plots in each, elevations between 4651 and 4725 masl)	Baseline available (2017)	Cuellar 2017
	Cocuy National Park (4 summits between 4056 and 4411 masl)	Baseline available (2012)	Pauli et al 2015; Cuesta et al 2017
	Sumapaz-Cruz Verde (2 sites, 10 experimental and 10 control plots per site)	Baseline (2016) and repeated measurements with different frequencies for each variable	International Tundra Experiment Methodology; Molau and Moolgard 1996
	Eastern Cordillera, Guacha River watershed (38 plots of 0.1 ha between 1940 and 3270 masl)	Baseline (2007) and repeated measurements every 3 years	Avella et al 2017
	Quindío River watershed (21 permanent plots of 0.25 ha between 1800 and 3800 masl)	Baseline (2014), with resampling of woody plants in 2019 (diameters $\geq$ 5 cm)	Restrepo-Correa et al 2014
	Cordillera Oriental: Chingaza (Los Calostros watershed); Boyaca region; proposed replication on a national scale and in the tropical Andes	Program started in 2011; repeated measurements were variable in each region	Medina et al 2009; Salinas et al 2013
	In Colombia: Las Orquídeas-Paramillo, Tama-Cocuy-Pisba, Tatama-Farallones-Munchique, Nevados-Hermosa-Doña Juana, Chingaza-Sumapaz-Picachos; other sites in Ecuador	Long-term studies	Márquez et al 2017
Biomass and C	Los Nevados and Chingaza National Parks (elevation transects in each site, going from 3152 to 4382 masl)	Baseline (2013), yearly monitoring	Rueda et al 2015
	National, pilot region in Boyacá	Proposal	IAvH and IGAC 2018
	National, 97 sites in the Andean region	Baseline (2015), ongoing	IDEAM 2017b
	National, with many sites located in Antioquia and Cordillera Oriental	Baseline and repeated measurements (different dates in each region)	Duque et al 2015
	Iguaque Flora and Fauna Sanctuary, Cordillera Oriental (6 transects between 3200 and 3700 masl)	Baseline (2014), repeated measurements up to 2017	Several, IAvH
Hydrology and glacier dynamics	National, 36 *páramo* complexes in Colombia	Proposal	García-Herrán 2018
	National in the 6 remaining glaciated regions; detailed analysis in the Santa Isabel and Ritacuba Blanco Nevados	Baseline (2009), national monitoring every 2 years; detailed monitoring in Santa Isabel and Cocuy every 3 months	Key publications: Ceballos et al 2012; Rabatel et al 2017
	Los Nevados National Park, Rio Claro River watershed (high Andean forests and *páramos*)	Baseline (2008), monitoring every 3 months	GNOMO protocols; Ruiz-Carrascal 2016
Land use change	National	Long-term studies	Integrated protocol: Sierra et al 2017 Key publications: Etter and Wyngaarden 2000; Armenteras et al 2011
	National, 21 *páramo* complexes	Long-term studies	Ungar and Osejo 2015; Sarmiento et al 2017

FIGURE 1 Distribution in Colombia of the different regions located in the high mountain belt (above 2800 m), based on the ecosystem map of Colombia at a 1:100,000 scale. In the map, different colors indicate the regions corresponding to the main mountain ranges (Perija and Eastern, Central, and Western Cordilleras) and massifs (Sierra Nevada de Santa Marta and Colombian). (Source: adapted by Avella and Córdoba; IAvH 2018)



of the Mining Code in 2010, which has established the delimitation of the *páramo* regions in the country, the exclusion of mining operations, a mandate to convert intensive cattle ranching and agriculture toward more sustainable alternatives, and the design of monitoring or management programs for each *páramo* region (Law 1930 promulgated in 2018). This sociopolitical scenario overlaps with the new demographic dynamics and policies associated with the peace process and postconflict interventions, including policies for land restitution, agrarian development, and illicit crop management (Sarmiento et al 2017; Sierra et al 2017).

The ecosystems of the high tropical Andes are also considered to be among the most exposed and vulnerable to climate change (Castaño-Uribe 2002; Tovar et al 2013). Although average warming rates in Colombia during the second half of the 20th century reached 0.1–0.2°C per decade (IDEAM et al 2017b), faster increases in mean temperature of up to 0.5°C per decade have been recorded above 3000 m in the tropical Andes (Vuille and Bradley 2000; Vuille et al 2018) and up to 0.7°C per decade in Colombian *páramos* where records are available (Ruiz-Carrascal et al 2008). Changes in precipitation are spatially more heterogeneous (Buytaert et al 2011), with a general trend for an increase but localized regions in which reductions of 5% or more are projected (IDEAM et al 2017b; IDEAM and UNAL 2018). These changes could induce an altitudinal displacement of species, ecosystems, and agroecosystems, resulting in alterations in community composition and diversity in high Andean forests (eg Duque et al 2015) and a significant reduction of *páramo* area of up to 75% during the present century in the more pessimistic scenarios (van der Hammen et al 2002). One of the most marked indicators of climate change in the Colombian Andes is the accelerated retreat of glaciers, with a current estimated cover of 42 km^2, corresponding to 62% of their documented area in the mid-20th century (Ceballos et al 2012; Rabatel et al 2017).

Methodology

Formulating the integrated strategy involved the following activities, based on the contributions of multiple actors with experience in monitoring high Andean ecosystems in Colombia and across the tropical Andes (see IDEAM et al 2018 for details):

1. Compilation, analysis, and synthesis of technical documents, scientific literature, maps and existing reviews, protocols, and monitoring proposals.
2. Electronic questionnaires directed to experts in environmental monitoring programs in Colombia, with emphasis on high Andean ecosystems. Twelve experts completed these questionnaires, which served as the basis for a catalog of monitoring initiatives, documenting their objectives and questions addressed, driving factors and response variables monitored, spatiotemporal design, data management, maintenance, and institutional arrangements.
3. Face-to-face semistructured interviews with 24 experts, in which a more in-depth analysis of the existing monitoring programs was carried out, including the aspects mentioned earlier and topics related to information demands from decision makers, lessons learned, spatial and thematic gaps, and opportunities for integration.
4. Organization of the workshop Diversity and Functioning of Colombian Andean Ecosystems in Environmental Change Scenarios. More than 60 participants attended the workshop, including representatives from the SINA, decision makers, universities, and environmental organizations (see IDEAM 2018 for details). First, discussion focused on the proposal and lessons learned from international networks active in the tropical Andes. Then, work was structured around thematic panels on biodiversity, biomass or carbon, climate or hydrology, and land use. Finally, working groups addressed key cross-cutting topics, including thematic gaps, scale integration, and models for institutional organization and information synthesis.

Results of the process

State of the art of monitoring in Colombian high mountain ecosystems

On an international scale, several monitoring networks have active sites in the Colombian Andes. These include (1) the Global Network of Mountain Observatories (GNOMO), based on an socioecological approach and active in Los Nevados National Park (Poleka Kasue Mountain Observatory; Ruiz-Carrascal 2016); (2) the World Glacier Monitoring Service (WGMS), which incorporates data collected by IDEAM on glacier dynamics in Colombia; (3) the Global Observation Research Initiative in Alpine Environments (GLORIA)-Andes network, monitoring vegetation dynamics and temperature at 17 sites along the tropical Andes of South America, including 1 active Colombian site (Cuesta et al 2017); (4) the Andean Forest Network, monitoring forest diversity and biomass dynamics in 343 plots in South America, including several active sites in Colombia (Osinaga et al 2014; Baez et al 2015); and (5) the Regional Initiative for the Hydrological Monitoring of Andean Ecosystems, integrating 12 *páramo* watersheds in the tropical Andes (Celleri et al 2011). The experience accumulated in these networks has been important for demonstrating strategies for south–south cooperation and the development of standardized protocols for data collection and integration.

On a national scale, the Environmental Information System of Colombia (SIAC), includes the Biodiversity Information System, the National System of Hydrological Monitoring, the System for Monitoring Forests and Carbon, and the Research and Monitoring Plans of the National Parks. In particular, IDEAM reports national environmental variables or indicators on climate change, water quality or quantity, air quality, soil degradation, and forest cover. This information feeds national periodic reports (eg the Status of Natural Resources Report and the National Water Report). In high mountain ecosystems, there is a long-standing tradition of ecological research (Rangel-Churio 2000; van der Hammen et al 2002). This research has been accompanied by the development of several monitoring initiatives and protocols studying four aspects (Table 1; see details in IDEAM et al 2018).

Species and functional diversity: This aspect involves the establishment of permanent plots of variable size (1 m^2 to $\geq$1 ha) for monitoring plant species and functional and phylogenetic diversity. Examples include monitoring of plant colonization in glacial retreat areas of the Santa Isabel Nevado (Cuellar 2017) and on *páramo* summits of the GLORIA-Andes network in Cocuy National Park (Cuesta et al 2017), as well as permanent plots in Andean forest in several regions of the country (eg Duque et al 2015; Quintero et al 2017; Avella et al 2017). Some of these programs (eg in the Iguaque Sanctuary) also monitor critical components of biodiversity, such as soil microbial diversity and vertebrates, but more systematic efforts are urgently needed (Ichii et al 2019). In addition, two emblematic initiatives to monitor keystone species are the Andean Bear Program (in which monitoring is an integral part of an adaptive management strategy; Márquez et al 2017) and the program monitoring population dynamics and phytosanitary problems in stem rosettes of *Espeletia* spp. (Medina et al 2009; Salinas et al 2013).

Biomass and carbon: Many plots monitoring forest diversity are used for analysis of biomass and carbon stocks in vegetation and soils. A key initiative is the establishment of permanent plots within the National Forest Inventory, which already includes 17 sites above 2800 m (IDEAM 2017b). There has been significant recent progress in monitoring biomass or carbon dynamics in high Andean forests and *páramos* in permanent plots along elevation gradients in two mountain ranges using a standardized protocol (Rueda et al 2015; IAvH and IGAC 2018).

Climate, hydrology, and glaciers: The national hydrometeorological network managed by IDEAM includes 613 stations between 2000 and 3000 m and 169 stations above 3000 m. New monitoring technologies are being integrated into the system, including remote sensing and isotopic and hydrochemical techniques. Moreover, IDEAM and IAvH have developed a detailed multiscale protocol for *páramo* hydrological monitoring (García-Herrán 2018). IDEAM also leads a program monitoring the 6 glaciated areas in the country, which includes detailed glacier mass balance and hydrological analyses in 2 of the areas (Ceballos et al 2012; Rabatel et al 2017; Morán-Tejeda et al 2018).

Land use dynamics: In the case of Andean forests, several authors have carried out multitemporal analyses of changes in ecosystem cover and land use on a national scale (eg Etter et al 2008; Morales and Armenteras 2013). The Observatory of Andean Forests of Antioquia is a multidisciplinary initiative that aims to characterize ecosystem health and transformation trends in the region (Quintero et al 2017). For *páramo* ecosystems, the national project for official delimitation included a detailed analysis at a 1:25,000 scale of ecosystem cover, land use change, and socioecological dynamics in 21 of the 36 *páramo* complexes in the country (IAvH 2016; Sarmiento et al 2017).

Thematic gaps and challenges for integrated monitoring

Based on the available literature and the expert consultation process, the following key thematic gaps and challenges were identified:

1. The ecohydrological component is seldom integrated in biodiversity or carbon dynamics studies using permanent plots, and ecosystem processes (eg productivity, decomposition, evapotranspiration, and nutrient leaching) and species interactions (eg facilitation and pollination) are rarely monitored, limiting comparative studies across regions.
2. Monitoring systems are generally not designed to capture gradients of land use transformation and natural regeneration (both inside and outside protected areas). Hence, important questions about the sustainability of alternative productive systems and the effectiveness of land planning strategies and restoration programs remain difficult to address, particularly on a national scale.
3. Environmental monitoring schemes rarely integrate socioeconomic drivers of change, the welfare impacts of these changes, and the governance responses of different types of actors. More emphasis is also needed on participatory monitoring, in which these diverse actors can be involved in all stages of the monitoring cycle.

Proposed objectives

The proposed objectives for the strategy are as follows:

1. Evaluate the dynamics of variables and indicators linked with the ecological integrity, biodiversity, ecosystem functioning, and services of high Andean ecosystems in Colombia.
2. Relate these dynamics with the main drivers of change operating at different spatiotemporal scales, including climate change and demographic, socioeconomic, and land use change processes.
3. Evaluate the effectiveness of the main biodiversity conservation, ecosystem management and restoration strategies, and territorial governance schemes in the country to guide the decision-making process on local, regional, and national scales.

Conceptual framework

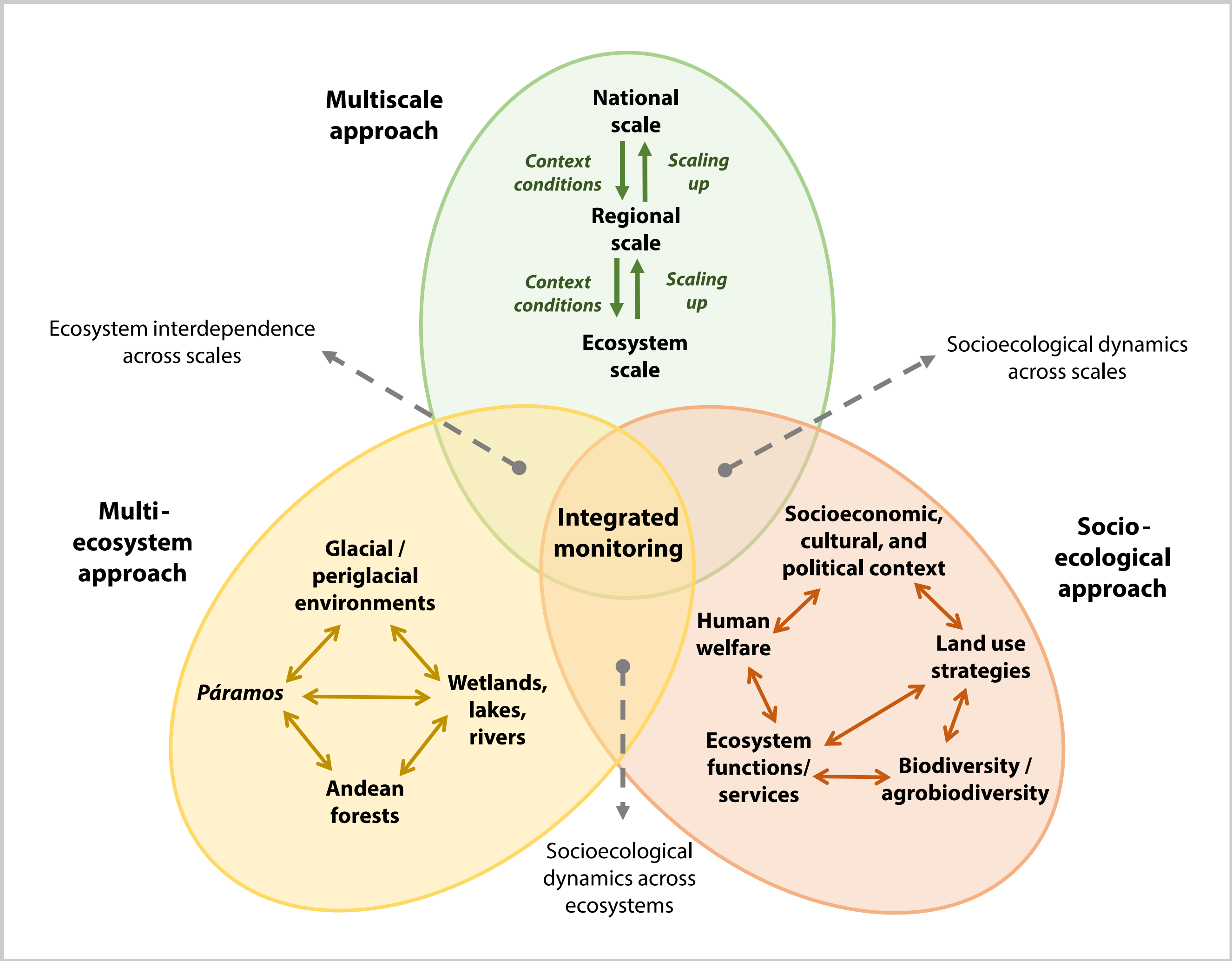
The conceptual model was developed to provide a general framework for integrated monitoring, building upon the existing programs, protocols, and information available (Table 1). In this context, integrated monitoring is understood as combining (1) a multiscale approach, linking drivers of change and response variables from ecosystem and plot scales to regional and national scales; (2) a multiecosystem approach, analyzing the interdependences among the ecosystems that make up the high Andean belt (at different stages of ecosystem transformation or regeneration); and (3) a socioecological approach, analyzing the links between changes in the socioeconomic, cultural, and political context and changes in the dynamics of land use systems, as well as how they interact with biodiversity, ecosystem services, and human welfare (Figure 2; Table 2).

Given the need for a multiscale approach, an important and difficult challenge is to explicitly consider the dynamic relationships that link the scales of analysis, from the top down and from the bottom up (Turner et al 2001). On the one hand, the drivers of change that operate on larger spatial scales, such as climate change or national demographic dynamics, can function as determinants or context conditions that modify socioecosystem responses on more local scales (van Riper et al 2018). On the other hand, spatiotemporal heterogeneity needs to be explicitly considered for scaling up driver and response variables from plots to landscapes and from landscapes to the national scale (eg for estimating national carbon stocks in high mountains based on measurements on plot and landscape scales; Figure 2). Consequently, scale integration requires explicit consideration of the nested environmental and human transformation gradients and processes that shape socioecosystem dynamics on both national and regional or landscape scales (eg among cordilleras and across regional topographic gradients). Moreover, it requires devising explicit institutional arrangements for sharing information and protocols, as well as analytic and management tools, among a network of regional nodes and between these nodes and the national level.

On the national scale, priority is given to analyzing the interactions between climate and land use change and how they affect biotic and social indicators (Figure 2; Table 2; Llambí and Llambí 2000; Isbell et al 2017; Mathez-Stiefel et al 2017). SIAC documents changes on the national scale in multiple indicators linked with biodiversity and ecosystem services (described earlier). The key is to re-evaluate these indicators specifically for the high Andean belt and generate integrated analysis and reports, in which the relationships among changes in land cover, biodiversity, hydrology, carbon stocks, and socioeconomic performance, among others, can be explored.

On the regional or landscape scale, several land use and production systems coexist, and their dynamics are driven by

FIGURE 2 Conceptual diagram in which integrated monitoring is understood as monitoring that explicitly combines analyses on multiple spatial scales, across the ecosystems that make up the high Andean belt, and that applies a socioecological, transdisciplinary approach.



changes in the political and socioeconomic context at both national and regional levels (eg land use regulations, governance strategies, and environmental conflicts). We emphasize the need to analyze changes in biodiversity and ecosystem services along gradients of anthropogenic transformation and elevation both inside and outside protected areas (Figure 3). This is important, because land use and climate change can interact along these gradients in complex ways, with largely unknown consequences. For example, although the intensity and spatial extent of land use can decline with increasing elevation, the rate of warming has been shown to increase at higher elevations (MRI 2015). Special attention should be given to processes that occur at ecotones, which can serve as sensitive indicators of global change effects, such as the dynamics of the mountain tree line or the glacier line. In addition, it is critical to document the trajectories of biodiversity and ecosystem processes or services comparing scenarios, such as intensive production systems, alternative or diversified management, and secondary ecosystems, as well as the impact of restoration strategies (Figure 3). This framework should provide critical information on the impacts of ecosystem management alternatives, which in many cases are assumed to promote sustainability or the recovery of ecosystem services without solid evidence to back up these claims.

This approach requires combining information on landscape dynamics from remote sensors with ground data derived from hydrometeorological stations and permanent plots distributed along elevation gradients in different landscape or ecosystem units (Figure 3). Mathematical modeling and simulation strategies may become important tools for integrating information across scales. Given the difficulties of establishing long-term permanent plots in all situations (including different levels of restoration or along glacier retreat zones), the strategy should also incorporate a chronosequence approach, in which replicate plots with different previous histories are studied simultaneously (eg Abreu et al 2009; Zimmer et al 2018).

On the ecosystem or plot scale, emphasis is given to integrating biodiversity monitoring (ie changes in species composition and abundance) with indicators of the carbon and hydrological balance in permanent plots (Figure 4). Here, it is important to define a minimum monitoring package for all sites, and complementary variables that can be measured in selected sites. The minimum package should

TABLE 2 Proposed processes that can act as drivers of change and some key response variables or indicators that can be monitored on national, regional or landscape, and plot or ecosystem spatial scales within the integrated monitoring program.

Spatial scale	Drivers of change	Response variables or indicators
National	• Political context: eg postconflict policies, national *páramo* delimitation process • Socioeconomic dynamics: eg mining concessions, agrobusiness • Land use history, demographic processes: eg urbanization, expansion of the agricultural frontier • Climate change: temperature warming, changes in precipitation	• Ecosystem cover change • Gamma diversity • Threatened species and ecosystems (indicators) • Soil degradation indicators • High mountain carbon stocks, biomass and soils • Water provision from high Andean ecosystems • National human welfare indicators
Region or landscape	• Regional land use or production systems • Models of territorial governance: eg protected areas, native reservations • Stakeholder networks or land use conflicts • Regional climatic variability • Topographic or geological gradients	• Ecosystem cover change • Landscape diversity, fragmentation, or connectivity • Beta diversity • Water quality and quantity: watershed scale (physical, chemical, and biological indicators) • Regional carbon stocks: biomass, soils • Regional human welfare indicators
Plot or ecosystem	• Land use practices, history, successional stage: eg intensive agriculture, agroforestry, active restoration • Local climate: temperature, precipitation, incident radiation • Slope, elevation, aspect	• Species, functional and phylogenetic diversity • Aboveground and belowground biomass or productivity • Soil organic matter, carbon and nutrients, physical and chemical properties (soil density, pH, etc) • Decomposition rates, litter production, soil respiration • Soil water, evapotranspiration, infiltration, runoff

consider the main ecosystem compartments, including aboveground plant diversity or biomass, necromass, and soil organic matter (Chapin et al 2002; Osinaga et al 2014; IDEAM 2017b; Cabrera et al 2018). Measurements of soil water content could be combined with more detailed studies in some sites of water interception, infiltration, runoff, and evapotranspiration (eg Ataroff and Rada 2000). For the carbon cycle, complementary studies in selected sites could estimate fluxes such as litter production, soil respiration, or decomposition (Rueda et al 2015). A link between biodiversity and ecosystem functioning could be provided by the study of plant functional traits (eg height, specific leaf area, and wood density; Pérez-Harguindeguy et al 2013; Salgado-Negret 2015). Finally, complementary modules should include the study of keystone indicator species, such as soil fauna, birds, or amphibians (eg using bioacoustic methods or camera traps) and ecological interactions (eg pollination and seed dispersal). It is important to strengthen monitoring of threatened or critical fractions of biodiversity for which large-scale, long-term data are insufficient or lacking (eg insects, microorganisms, and parasites), promoting a better understanding of their role in regulating ecosystem services (Ichii et al 2019).

Expected outcomes and institutional framework

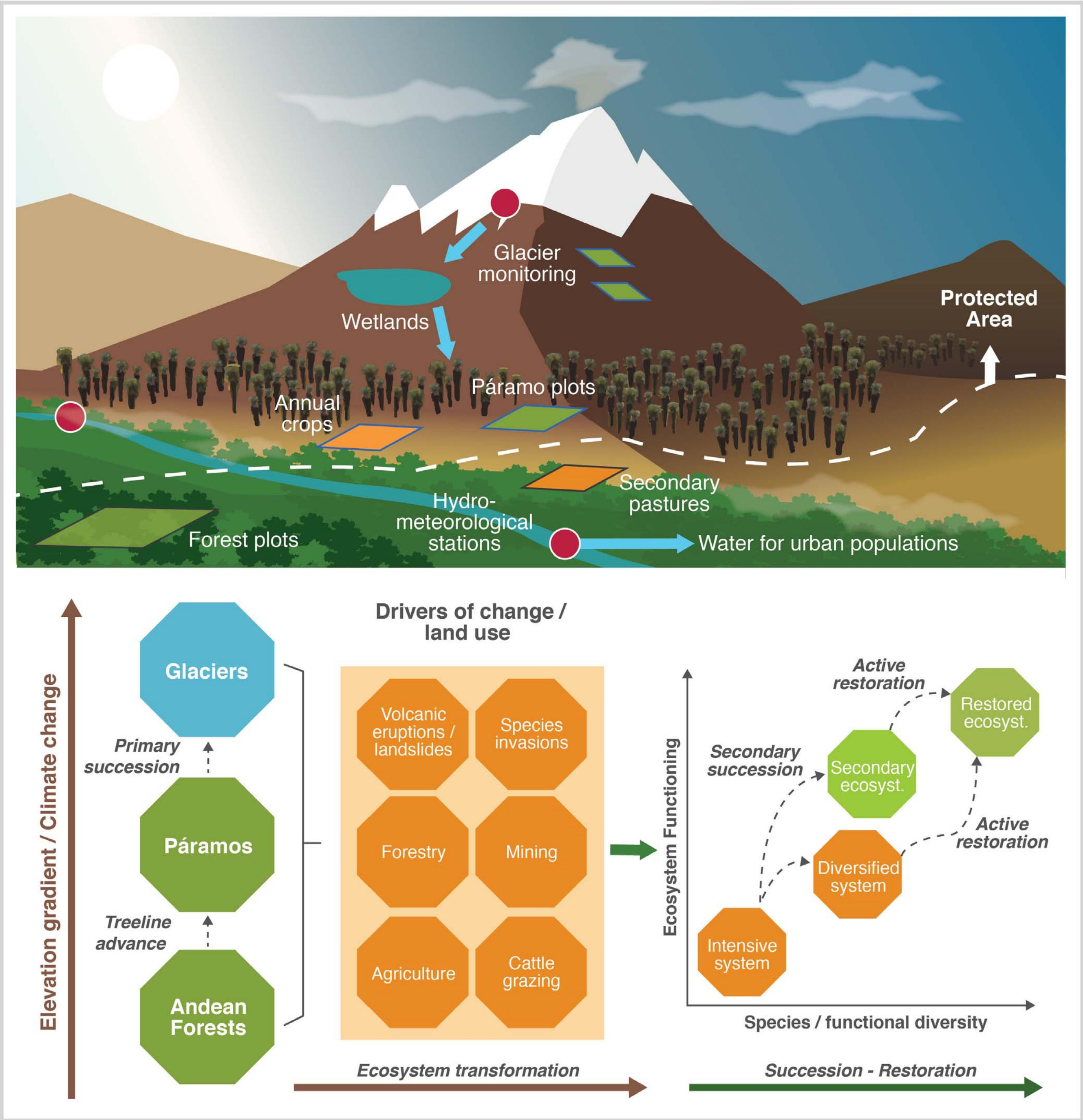
The expected outcomes of the EMA are oriented to support environmental decision-making on the local, regional, and national levels. The main outcome would be the generation of periodic reports on the status, integrity, and trends of high Andean ecosystems. Other associated products would include (1) periodic symposia on the dynamics of high Andean ecosystems; (2) an online platform, including databases and modules for information analysis, visualization, and reporting; (3) a catalog of management and conservation policies, as well as existing monitoring programs and protocols; and (4) outreach products for a broader audience, which could include short social-media updates, touring exhibitions for museums, and an attractive synthesis publication on the impacts of climate and land use change in the high mountains of Colombia (see eg IAvH 2018; IDEAM 2014; IDEAM 2017a; Ceballos et al 2012).

The institutional arrangements could include a directive and technical committee on the national scale, with participation of institutions from the SINA, universities, and nongovernmental organizations. It should also include a dialog platform, with participation of social organizations and decision makers from different sectors (Sierra et al 2017). The system should consider mechanisms for integration with SIAC and monitoring networks in the region (eg GNOMO and GLORIA-Andes). Finally, the integration of working nodes in the different regions in the country should be promoted, as well as the active involvement of local stakeholders and community organizations using participatory approaches.

Where do we go from here?

After formulating the EMA, the interinstitutional team leading the process (at IDEAM, IAvH, and CONDESAN) identified some key steps that could guide its progressive implementation: (1) promote a wide consultation process to define essential variables to monitor biodiversity and ecosystem services on national and regional scales and consolidate an online information system (linked with SIAC), including a catalog of monitoring initiatives, synthetic maps, and an integrated analysis of the variables and indicators available, and (2) promote information synthesis in pilot sites, both in areas with active long-term monitoring programs (eg Los Nevados and Chingaza) and in high-priority areas, given the existence of environmental conflicts (eg Santurban, Tota-Bijagual, and Pisba). This would provide

FIGURE 3 Conceptual diagram illustrating the monitoring strategy of high Andean ecosystems (glaciers, *páramos,* and Andean forests) along elevation and human transformation gradients on regional landscape scales. We indicate some main drivers of change and possible or hypothetical trajectories of biodiversity and ecosystem processes from intensive land use systems to restored ecosystems. Dotted arrows indicate ecosystem dynamics resulting from climate and land use change (eg tree line dynamics and primary or secondary succession) or from active management decisions (eg implementation of sustainable management alternatives or active ecosystem restoration strategies).



a dynamic and holistic view of these territories, identify thematic gaps, and generate integrated protocols on landscape and ecosystem scales. The idea is to strengthen active monitoring sites, promote networking around regional observatories, and use these sites as pilots for replication.

Finally, it is essential to promote new forums for discussing the strategy with decision makers, international cooperation agencies, the private sector, academics, and social organizations on different scales so that monitoring can more explicitly respond to the needs of the large diversity of stakeholders involved in the management and conservation of high mountain ecosystems in Colombia.

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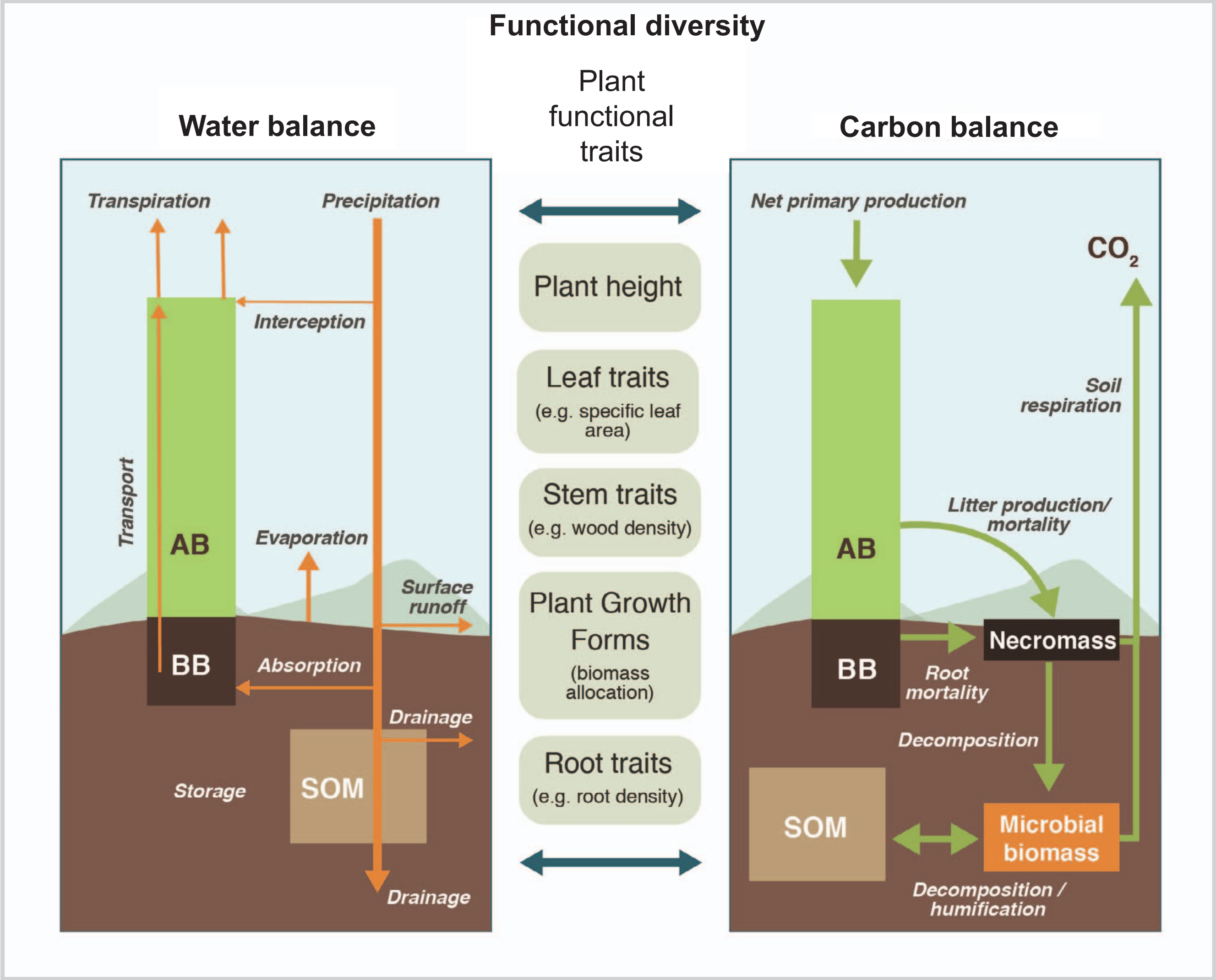
FIGURE 4 Main ecosystem compartments (AB, plant aboveground biomass; BB, plant belowground biomass; SOM, soil organic matter; necromass; and microbial biomass) and processes linked with carbon balance and water balance on the ecosystem scale (indicated in bold and italics). We also indicate plant functional traits that can help to link functional diversity with ecosystem functioning.



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