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Review

Monitoring ecological change during rapid socio-economic and political transitions: Colombian ecosystems in the post-conflict era

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ABSTRACT

After more than 50-years of armed conflict, Colombia is now transitioning to a more stable social and political climate due to a series of peace agreements between the government and different armed groups. Consequences of these socio-economic and political changes on ecosystems are largely uncertain, but there is growing concern about derived increases in environmental degradation. Here, we review the capacity of Colombia to monitor the state of its ecosystems and their rate of change over time. We found several important programs currently set in place by different institutions as well as by independent groups of scientists that address different aspects of environmental monitoring. However, most of the current initiatives could be improved in terms of data coverage, quality and access, and could be better articulated among each other. We propose a set of activities that would increase the capacity of Colombia to monitor its ecosystems, provide useful information to policy makers, and facilitate scientific research. These include: 1) the establishment of a national center for ecological synthesis that focuses on analyzing existing information; 2) the establishment of an ecological observatory system that collects new information, integrates remote sensing products, and produces near real-time products on key ecological variables; and 3) the creation of new platforms for dialog and action within existing scientific and policy groups.

1. Introduction

Monitoring ecosystem functions and services is a challenging task that only a few countries and regions with strong economies are starting to tackle through large scientific infrastructure programs. Some of those include NEON (National Ecological Observatory Network) in the USA,

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Table 1
Classification of main monitoring categories and examples of variables with existing monitoring/measuring programs.

Category	Variables	Existing programs
Climate and biogeochemistry	Meteorological variables: air temperature, precipitation, solar radiation, wind speed and direction, etc.	IDEAM station network
	Hydrology: stream and river stage, flow, and discharge	IDEAM network, Hydro-SIG software
	Land-atmosphere interactions: Ozone, UV radiation, aerosols, trace gases, particulate matter, greenhouse gas concentrations.	IDEAM, single investigators
	Carbon cycle: biomass and C stocks, primary production	National Forest Inventory, IGAC soil surveys, Rainfor and CTFS-ForestGEO plots, single-investigator projects
Biodiversity	Species inventories: specimen collections, species catalogs	Herbariums, Universities, SiB Colombia (IAvH)
	Biodiversity assessment: species distributions, diversity indexes	Biomodelos platform (IAvH), single-investigator projects
	Ecosystem assessment: vegetation distribution maps, land use, land-use-change maps	IDEAM, IAvH
Socio-economic variables	Demography: birth and mortality rates, life expectancy, migration	DANE
	National agricultural and livestock census	DANE
	Economy: gross domestic product, inflation, basic living costs, interest rates	DANE, Central Bank
	Social conflict: internal migration, violent deaths, human-right violations, peace processes	DANE, Planeación Nacional, Observatory of Peace and Conflict (Unal)

or ICOS (Integrated Carbon Observatory System) in Europe, among others. Monitoring ecosystems in countries experiencing fast socio-economic and environmental transitions and with much lower investments in science and education is a more challenging endeavor. This is the case of Colombia, which covers only 0.7% of the global land area, but hosts approximately 10% of all known species on Earth (up to date 56,343 species of animals, plants, fungi, algae, and lichens are registered for Colombia; (SiB-Colombia, 2017)). Despite its relatively small size compared to countries such as Brazil or China, Colombia is ranked first in terms of species richness of birds and orchids, second for plants, amphibians, freshwater fishes, and butterflies, third for reptiles and palms, and fourth for mammals (GBIF, 2017; SiB-Colombia, 2017). Colombia is thus one of the so-called megadiverse countries.

Colombia has also suffered one of the longest armed conflicts in the world, lasting for over 50 years. With more than 8 million victims (RUV, 2017) and nearly 6 million refugees, Colombia is currently the country with the second largest internally displaced population in the world after Syria (CODHES, 2014). This long-lasting internal conflict has significantly shaped rural landscapes and ecosystems through changes in livelihoods, modes of economic production, and land cover (Arias et al., 2014; Pinilla, 2013). Armed conflict and civil unrest have resulted in contrasting consequences for ecosystems and natural resources. In some cases, military hideout zones and buffers among territories in conflict regions have promoted the conservation of natural areas. In other contexts, war has increased pressure on natural resources leading to environmental deterioration (Álvarez, 2001; Dávalos, 2001; Etter et al., 2006a,b; Gaynor et al., 2016; Sánchez-Cuervo et al., 2012). Conflict is also associated with poor governance in many regions, which results in lack of commitment on long-term government-sponsored development programs, and subsequent increases in deforestation rates (Dávalos et al., 2016).

During the last decade, Colombia has experienced dramatic changes in the internal conflict as a consequence of both intense negotiations with armed actors and the increased military control of vast areas of the territory. Today, Colombia has been closer than ever to achieve peace. Unprecedented agreements have been reached with paramilitary groups and the FARC (Fuerzas Armadas Revolucionarias de Colombia), the largest guerrilla group, that are leading the country to transition toward the so-called "post-conflict" era. Central to this process is the implementation of a series of incentives to promote rural small-land-owner development, land restitution, consolidation of ongoing and projected large investments on road development, large-scale energy projects (particularly dam construction), commodity agriculture, and mining (Clerici et al., 2016; Negret et al., 2017). The consequences of these rapid socio-economic and political changes on the state of natural ecosystems, their biodiversity, and services are not clearly known, but may include negative effects such as increased deforestation and degradation due to timber extraction, agricultural and industrial expansion, or positive effects such as better environmental governance. Our ability to assess these changes and facilitate environmental stewardship depends largely on the capacity of the country to monitor relevant ecosystem variables and their rate of change in near-real time, so actors can respond quickly (Baptiste et al., 2017).

In this manuscript, we assess the capacity and needs of Colombia to monitor ecosystem change during the rapid social, political, economic, and environmental changes that the country is currently facing. Therefore, we address the following two questions: *what is the current capacity of Colombia to monitor relevant ecosystem variables and their rate of change? What are cost-effective initiatives that can be implemented to improve this capacity?* To address these questions, we present an inventory of major initiatives for ecosystem monitoring in Colombia. We identify major gaps and issues with current programs, and recommend a set of actions that can serve as guidance for other countries under similar circumstances.

2. Assessment of ecosystem monitoring capacity

We consider of fundamental importance to monitor the state of Colombian ecosystems in three broad categories: 1) climate and biogeochemistry, 2) biodiversity, and 3) socio-economic variables (Table 1). Climate and biogeochemistry variables include: energy, water, carbon, and nutrient budgets and fluxes. Biodiversity variables include: composition, structure and functioning of plant, animal, fungi, and lichens, as well as information on diversity of genes and ecosystems from a multi-scale perspective (Noss, 1990; Pereira et al., 2013). Socio-economic variables include those related to the demand for ecosystem services, the governance mechanisms that modulate that demand, the effect of those demands and governance mechanisms on ecosystem biogeochemistry and biodiversity, and the relationship between ecosystem services and human well-being. In the following, we outline Colombia's capacity to measure and monitor some of these variables.

2.1. Climate and biogeochemistry variables

2.1.1. Hydro-meteorological network

Colombia has a well-established network of hydro-meteorological stations distributed across different bioclimatic zones. This network is managed by the "Instituto de Hidrología, Meteorología y Estudios Ambientales" (IDEAM, see Box 1 for other acronyms), which is the governmental institution in charge to produce hydrological, meteorological, and environmental information.

Although the network has a reasonable spatial and temporal

Box 1
The National Environmental System of Colombia (SINA)

In 1993, the Colombian senate created the Ministry of Environment and the National Environmental System (SINA) under the so-called Law 99-1993. The SINA was conceived as a comprehensive set of regulations, activities, resources, programs and institutions in charge of Colombia's environmental policy and management. The system is coordinated by the Ministry of Environment, who is also the main institution in charge of developing environmental law. SIAC is the System of Environmental information of Colombia were SINA makes its information available (SIAC, Table 2).

The main institutions that are part of the SINA are: the Ministry of Environment, 5 governmental Research Institutions, 4 Urban Environmental Units, 34 Regional Environmental Authorities (locally known as Corporaciones Autónomas Regionales), the National Natural Park System, community and non-for-profit organizations with an environmental focus, public and private research organizations. Some of the main actors of the system that actively produce and manage ecological information are described in the table below.

Institution	Acronym	Mission
Ministry of Environment and Sustainable Development	MADS	Define the national environmental policy. Promote the recovery, conservation, planning, management, use, and extraction of renewable natural resources. Guarantee sustainable development and the civil right to a healthy environment
Institute of Hydrology Meteorology and Environmental Studies	IDEAM	Provide technical and scientific support to the SINA through knowledge creation and production of reliable information that is consistent and timely. This knowledge should facilitate the definition or modification of environmental policies and decision making
Research Institute on Biological Resources Alexander von Humboldt	IAvH	Promote, coordinate, and develop research that contributes to conservation and sustainable use of biodiversity for the well-being of the Colombian population
Environmental Research Institute of the Pacific	IIAP	Develop research in the Chocó biogeographic region to support decision making and public policies on the environment that promotes sustainable development of the inhabitants of this region
National Natural Parks	PNN	Administer the National Natural Park system and coordinate the National System of Protected Areas with the aim to preserve biological diversity and ecosystem representativeness. Provide and maintain ecosystem services, protect cultural heritage and the natural environment where traditional cultures developed
Institute of Marine and Coastal Research	INVEMAR	Develop basic and applied research on marine and coastal resources with the aim of developing policies and supporting policy making. Research is directed toward sustainable management of resources, restoration of marine and coastal environments, and improvement of life quality of citizens
Amazon Institute of Scientific Research	SINCHI	Generation of knowledge, innovation, and technology transfer on biological, ecological and social aspects of the Amazon region
National Authority on Environmental Licenses	ANLA	Guarantee the transparent evaluation and control of projects and activities subject to environmental licensing or permitting. Contribute to an equilibrium between environmental protection and societal development

coverage over the Andean and Caribbean regions, where most of the population lives, it still needs to improve coverage in zones with complex topography in the Andes, high-altitude regions (> 3500 m asl), over less populated areas in the Pacific (Chocó) region, and the Amazon and Orinoco river basins (see Fig. 1). Despite the relative large number of stations, only about 300 stations provide continuous historical records for trend detection in temperature, and around 1000 stations provide continuous records for precipitation (IDEAM et al., 2015).

In recent years, IDEAM has made its information freely available to the public, and although station-level information is slowly making its way to publicly available repositories, a wealth of aggregated information is already available in web portals (Table 2).

Another important initiative related to hydro-meteorology is the Hydro-SIG software, a geographic information system of Colombia's hydro-climatology developed by a university research group (Poveda et al., 2007a,b). This system provides data-products resulting from the integration of information from multiple stations.

2.1.2. Land-atmosphere interactions

Monitoring of land-atmosphere interactions focuses on five main categories: 1) ozone vertical distribution and total column, 2) ultraviolet (UV) radiation, 3) precipitation chemistry, 4) pollutants, trace gases and aerosols, and 5) greenhouse gas (GHG) fluxes. IDEAM monitors UV radiation at 2 urban and 3 remote sites since 1998 (Benavides, 2010a), conducted about bimonthly ozone soundings between 1998 and 2008 (Benavides, 2010b), and forecasts nationwide O_3 total column, and from this, UV radiation using a radiative transfer model. Satellite O_3 total columns have been validated with the O_3 sounding data and are also consistent with measured UV radiation. IDEAM also monitors rainwater chemistry (pH, conductivity, nitrates and sulfates) since 1999, mostly at airport weather stations.

There are currently 163 air quality surveillance stations in Colombia, run by 21 regional environmental authorities (IDEAM, 2016). Most of these sites are urban, some are industrial or aimed at large-scale mining or agriculture. The few suburban and rural sites are perimeter-intended and cannot be considered representative of background unpolluted conditions. Particulate matter (PM) is the most concerning air quality problem in Colombia. PM10 (PM size ≤ 10 μm) concentration is monitored at 80% of the sites. Recent investigations show that aerosols and other emissions of pollutants from biomass burning (Merino-de-Miguel et al., 2011), particularly in the Orinoco

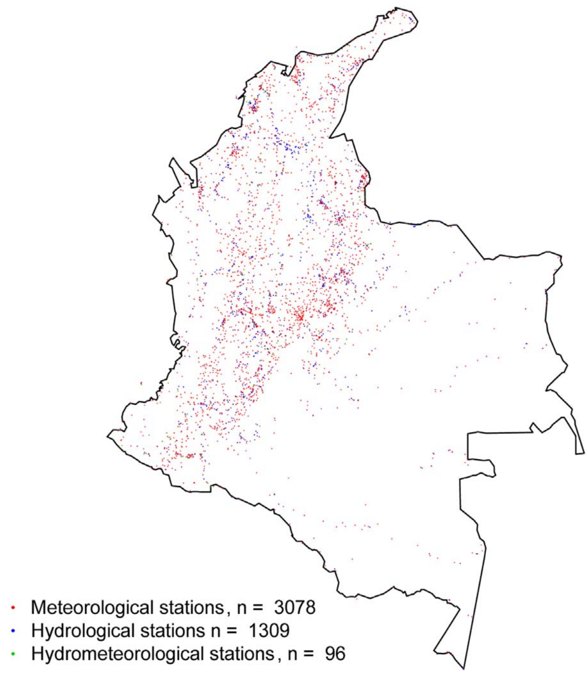

Fig. 1. Network of meteorological and hydrological stations managed by IDEAM.

river basin (Anaya and Chuvieco, 2012), significantly affect air quality at local to synoptic scales in Colombia (Chacón, 2015).

A detailed estimation of Colombia's anthropogenic GHG emissions, including time series since 1990 and regional disaggregation, has been recently released in the country's third communication to the United Nations Framework Convention on Climate Change (Pulido et al., 2016). Other results show that methane emissions from Colombia's natural wetlands (seasonal and permanent) are high enough to be globally significant (Guerrero et al., 2011).

There are currently 5 eddy covariance (EC) systems in operation in Colombia, of which 4 measure crop CO_2 fluxes (coffee, oil palm, sugarcane, corn-soybean). Only 1 EC system measures CO_2 fluxes in a natural ecosystem (native savanna in the Orinoco river basin), and there are plans to install one in the Colombian Amazon.

2.1.3. Soils and ecosystem distribution

Maps on soil and ecosystem classifications have been produced by major governmental institutions such as IDEAM and the National Geographic Institute IGAC. Soil classification maps have been motivated mostly by determining best land-use practices and the agronomic potential of Colombian soils. Ecosystem classification maps have mainly focused on the spatial demarcation of main categories such as biomes, life-zones, land use, etc. In most cases however, maps are not validated against independent observations (Armenteras et al., 2016) and care must be taken for their use in research.

2.2. Biodiversity

2.2.1. Vegetation monitoring plots

Forest monitoring plots have been central to the study of Colombian forests in terms of structure, composition, and function. With some exceptions, most plots have been established by independent researchers, and only in 2015 a National Forest Inventory (NFI) was started. Most of the existing plots contain basic information such as tree abundance, diameter at breast height, species identities, and tree height. Plot size is variable, from 0.02 to 25 ha, and their location respond to specific research questions for individual projects and not necessarily to a comprehensive plan of forest monitoring (Phillips et al., 2016). Many of these plots have been revisited at least twice (Fig. 2; Álvarez-Dávila et al., 2017; González-Caro et al., 2014; Phillips et al., 2016), but their continuous monitoring is contingent to the efforts of individual researchers to guarantee funding.

Colombian investigators have also actively participated in global forest monitoring initiatives including the Center for Tropical Forest Science – Forest Global Earth Observatory CTFS-ForestGEO (Anderson-Teixeira et al., 2015), and the Amazon Forest Inventory Network RAINFOR (Malhi et al., 2002). Monitoring efforts have also expanded from the Amazon to other regions such as the Andes, the Caribbean and the Chocó region, and have contributed to pantropical analyses of forest structure and function (e.g. Álvarez-Dávila et al., 2017; Báez et al., 2015; Feldpausch et al., 2016; Sullivan et al., 2017). Independent studies using permanent plots have also made important contributions to the understanding of patterns of biodiversity and primary production in the tropics (Duque et al., 2015; Quinto-Mosquera and Moreno, 2017; Sierra et al., 2007). Other initiatives not mentioned above, may also possess a large number of plots not depicted in Fig. 2.

With the new NFI coordinated by IDEAM, there is now a standardized effort to establish and monitor a large network of plots using rigorous sampling and monitoring standards. A total of 1924 sampling locations will be inventoried (190 sites already monitored up to May 2017) using circular plots of different radius according to vegetation size. Plot data will be collected every 5 years and it includes multiple ecosystem compartments such as soils and litter. It is expected that this information will be available in an open-access server.

In addition to forest plots, there are other research sites and networks for the collection of important ecosystem variables. For instance, the Poleka Kasue Mountain Observatory, which is part of the Global Network of Mountain Observatories, collects information on biodiversity, climate, hydrology, carbon stocks, and socio-economic variables in the Central Andes (Ruiz-Carrascal, 2016). Other relevant regional efforts are for example the network of dry forest ecosystems coordinated by the Instituto de Investigación de Recursos Biológicos, Alexander von Humboldt (IAvH) (Pizano and Garcia, 2014), and a synthesis network on Andean forests (Condesan, 2017). These programs have established and synthesized a reasonably large number of monitoring plots, and have collected information on genetic and functional diversity and ecosystem processes in these highly threatened ecosystems. All of the above-mentioned monitoring plots are located in forests, but other ecosystems such as savannas, wetlands, and mangroves, are poorly represented in these initiatives.

2.2.2. Biodiversity information systems

Universities, herbariums, botanical gardens, scientific societies, and governmental institutions have collected and organized a substantial amount of information on the biodiversity of Colombian ecosystems (Table 2). Some of this information is well organized in a central information system on biodiversity (Sistema de Información en Biodiversidad SiB), a node of the Global Biodiversity Information Facility (GBIF), which is coordinated by the IAvH with the participation of the major governmental research institutes and the National University of Colombia. This system contains information on species occurrences at different taxonomic levels. The platform allows the user to obtain spatial information on where and when particular specimens have been collected and described. In addition, the platform allows users to contribute new records following rigorous protocols and standards.

Additionally, there are other systems that store and distribute information on biodiversity (Table 2). For example, Biomodelos is a repository of species distribution models that integrates expert knowledge for their calibration and validation, but also facilitates dialog among

Table 2
Examples of information systems and webportals that manage and distribute information on relevant ecological variables for Colombia.

System	Leading institutions	Description	Data format	Spatial coverage	Url
Systems reporting environmental variables including climate and biogeochemistry					
Sistema de Información Ambiental de Colombia (SIAC)	MADS, IDEAM, IAvH, INVEMAR, SINCHI, IIAP, ANLA	Repository of information on water, air, soils, biodiversity, climate, and waste	html, pdf, shp	National	http://www.ideam.gov.co/web/siac/index
Geoportal IDEAM	IDEAM	Spatial information on climate and environmental variables	html, pdf, geoviewer	National	http://www.ideam.gov.co/geoportal
Portal Geográfico Nacional (PGN)	IGAC	Repository with official geographic information of Colombia	pdf	National	http://data.pgn-icde.opendata.arcgis.com/
Geoportal IGAC	IGAC	Maps and aerial photographs, Continuously operating reference station (CORS)	html, pdf, RINEX	National and sub-national	http://www.igac.gov.co/geoportal
Geoportal Servicio Geológico Colombiano	SGC	Geological maps	html, pdf, ArcGIS viewer	National	http://geoportal.sgc.gov.co/geoportalsgc/catalog/main/home.page
Hydras	IDEAM	Field station data is transmitted using satellites to the internet	TXT	National and sub-national	http://hydras3.ideam.gov.co/
Sistema de información de alertas tempranas	TREMARCTOS	Environmental impact assessment portal	html	National	http://www.tremarctoscolombia.org/
Sistema de Alerta Temprana de Medellín y el Valle de Aburrá (SIATA)	AMM, AM	Rapid alert system on air quality and weather.	html	Regional	https://www.siata.gov.co/siata_nuevo/index.php/mapa/
Observatorio Ambiental de Bogotá	–	Rapid alert system on air quality	html	Sub-national	http://oab.ambientebogota.gov.co/
Systems reporting environmental variables including biodiversity					
Sistema de Información sobre Biodiversidad de Colombia (SiB)	MADS, IDEAM, IAvH, INVEMAR, SINCHI, IIAP, Unal	Catalog of species occurrences	html	National	http://www.sibcolombia.net/
BioModelos	IAvH	Repository of species distribution models	html	National	http://biomodelos.humboldt.org.co/
Catalogo Virtual de la flora de Alta Montaña	EIA	Catalog of species occurrence at Los Nevados National Park	html	Sub-national	http://catalogofloraaltamontana.eia.edu.co/
Red de Monitoreo del bosque en Colombia – ColTree	UNAD, JBMED, UT, UL, Fundación ConVida	Repository of information on permanent and temporary plots of the ColTree network.	xls, txt	National	http://www.forestplots.net/
Sistema de información ambiental de Medellín	SIAMED	Biodiversity database of Flora and Fauna	html	Sub-national	https://www.medellin.gov.co/servicios/siamed_portal/
Red global de observaciones de aves	eBird	Occurrence database of bird inventories	html, txt	Global	http://ebird.org/content/ebird/
Systems reporting environmental and socio-economic variables					
Terra-i	CIAT	Datasets on land-cover changes resulting from human activities in near real-time, producing updates every 16 days	html, shp	Pantropical	http://www.terra-i.org/terra-i.html
Sistema de Información Geográfica para la Planeación y el Ordenamiento Territorial (SIG-OT)	IGAC	Spatial information on environmental and socio-economic variables	pdf, shp, others	National	http://sigotn.igac.gov.co/sigotn/
Sistema de Información Ambiental Territorial de la Amazonia Colombiana (SIAT-AC)	SINCHI	Repository of spatial and census information on environmental and social variables	html, shp	Sub-national	http://siatac.co/web/guest
Sistema Nacional de Información Forestal (SNIF)	IDEAM	Information system on forest monitoring. Includes information on forest management and harvest permits	html, shp	National and sub-national	http://snif.ideam.gov.co:8380/ideam-snif-web/
Monitor	OCHA, PNUD	Map of violent events with population affected by the social conflict	html	National	http://monitor.umaic.org/

scientist from several taxonomic groups. The models can be used to predict species-range shifts due to land-use pressure. Moreover, Colombia is also an active node of the International Bar Code of Life, with important contributions on the DNA barcoding of threatened species (Contreras et al., 2014; Mendoza et al., 2016).

As part of GEOBON, the IAvH leads the Bon in a Box project, a toolkit that allows users to share and discover state-of-the-art tools for data collection, management, analysis, and reporting of biodiversity observations. As part of this work, an assessment of existing tools for biodiversity observation showed that more than 100 different information tools are used to manage biodiversity data. Results of this assessment also showed that governmental institutions have strengths for monitoring ecosystem structure, but are limited in their capacity to implement observation systems related to community composition, functional traits, ecosystem function or genetic composition.

The amount of available information for biodiversity research is large, and the country has recently made good progress in organizing it in open-access repositories with international standards for data management.

2.2.3. Land cover change and carbon monitoring systems

In recent years, Colombia has made important efforts to monitor changes in forest cover and forest carbon stocks. The carbon and forest monitoring system of Colombia led by IDEAM has used Landsat satellite images to produce forest cover and forest cover change maps for the years 1990, 2000, 2005, 2010, 2012, 2013 and 2014 at a 30 m spatial resolution. Another important step for forest monitoring is the recent implementation of a Deforestation Early Warning System by IDEAM that uses data from the satellite MODIS to produce reports every three months, identifying active deforestation hotspots. A similar system has also been implemented by the Colombian-based International Center for Tropical Agriculture, but with a pantropical scope (Terra-i, 2017).

The SINCHI institute has also generated sequential land-cover maps for the Amazon region (2002, 2007, 2010, 2012, 2014) following standard protocols and quality assessment (Murcia García et al., 2016). Their periodicity has increased recently, and they have been used to detect forest change and increases in grassland area. These maps, available at 1:100.000 scale, cover more than one third of Colombia's continental land. For the entire country, there are also three land cover maps available (2001–2005, 2010, 2016) that provide a general assessment of Colombian natural and agricultural lands. Nevertheless, their application for comparative analyses is limited due to important differences in the base satellite images, and protocols for their interpretation. There are also concerns that these maps do not perform well in detecting wetlands, which may cover around 27% of the continental territory (Flórez et al., 2016). Source satellite images are mostly available for the dry season due to cloudiness in other parts of the year, and for this reason wetlands, paramos, and other ecosystems may not be well represented in these national ecosystem maps (Etter and van Wyngaarden, 2000; Etter et al., 2010; Andrade-C., 2011; Romero-Ruiz et al., 2012; Baptiste and Ruggiero, 2012; Patiño and Estupiñan-Suarez, 2016).

2.3. Socio-economic variables

Collection, organization, and distribution of most socio-economic information in Colombia is coordinated by the National Statistical System (SEN). This system is led by the National Department of Statistics (DANE), with participation from the ministry of finance, the Colombian central bank, and the department for national planning, among others. The SEN organizes and distributes information on national censuses; produces relevant demographic information such as birth and mortality rates; economic indicators such as inflation, public and private debt, market indicators, interest and exchange rates, gross domestic product (GDP), among others.

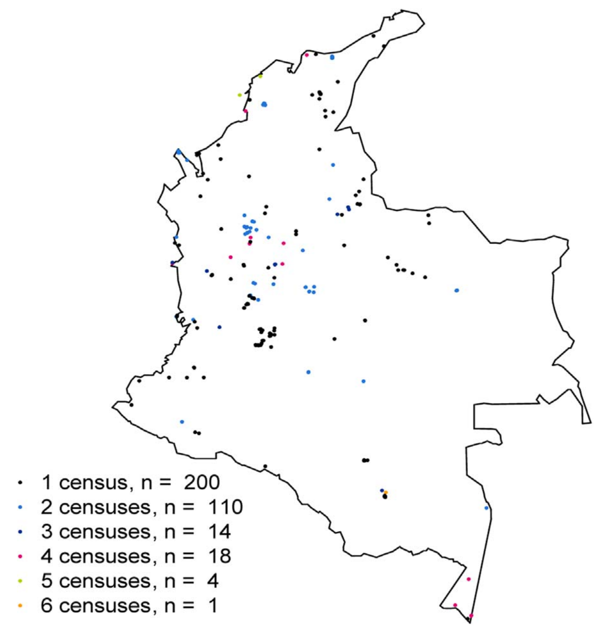

Fig. 2. Location of some vegetation plots established in forest ecosystems by multiple investigators and research teams. This sample is not representative of all plots in the country, but it gives an overview of the amount of information already available.

DANE distributes most of its information through reports, and also through a web-platform that allows users to make queries on a geographic information system.

One major accomplishment for monitoring socio-economic variables relevant to national ecosystems was the third National Agricultural and Livestock census finished in 2014. This census was produced after 45 years from its previous one. With a coverage of 99%, it provides important information on demography, total area of land holdings and per land use, access to basic services and technology, poverty and environmental sustainability. Statistics can be downloaded in tabular format, aggregated at the Departmental level (DANE, 2016).

It is also relevant to mention the work of other institutions on monitoring social aspects of the Colombian conflict. For example, the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) has established a geographical system (webportal) for monitoring and reporting violent events with statistics on the population affected (Table 2). Other groups such as the Observatory of Peace and Conflict of the National University, and CERAC (Centro de Recursos para el Analysis de Conflictos), produce reports and analyses on the internal armed conflict, dynamics of the actors in the conflict, processes of conflict resolution, etc. These are only examples of institutions that collect and report information about social aspects of the internal conflict, but other governmental and non-governmental institutions also collect this important type of data.

2.4. Other webportals and repositories

A relatively large number of webportals with environmental information have emerged in Colombia during the past 3–5 years (Franco, 2016). These webportals usually contain spatial information on relevant environmental variables, and others compile different sources of information into a searchable site (Table 2). The Environmental Information System for Colombia (SIAC) for example, compiles datasets, maps, and links to other sites with relevant environmental variables.

All major research institutions in Colombia have also a web application that displays information relevant for ecosystem monitoring (Table 2). In particular, the institutions that comprise the National Environmental System (SINA, see Box 1) centralize their information in the SIAC, although many individual institutions also have their own web portal (Table 2). For many variables, the information is available in geospatial format (e.g. .shp), and in other cases, the information is available in tabular form (e.g. .txt, .xls), or as documents (e.g. .pdf). In not all cases, it is possible to directly download the data (Franco, 2016); and in some cases, it is necessary to fill-in data request forms that need to go through an approval process before information can be released.

In addition to these institutional initiatives, individual researchers are also starting to deposit their data into open-access repositories. A few examples of the wealth of data on the state of ecosystems in Colombia that are already collected, processed, and distributed include ForestPlots.net, a repository of data from permanent tropical forest plots (Álvarez-Dávila et al., 2017; Lopez-Gonzalez et al., 2011). Similarly, data on the long-term dynamics of Colombian ecosystems is also archived in the Latin American Pollen Database (LAPD, Flantua et al., 2015). Data on composition of plant and animal communities have been also included in the Predicts-project database (Hudson et al., 2017).

3. Major gaps and proposed initiatives

With the exception of some hydro-climatological variables, air-pollution in major cities, and forest cover change, Colombia lacks an integrated system for near real-time monitoring of the state of its ecosystems. Such a system is of fundamental importance to detect and respond to major ecosystem perturbations including fires, deforestation or extreme climatic events. Long-term monitoring is also essential for detecting responses to long-term processes such as those induced by global climate change.

Although Colombia has recently made exceptional progress in developing information systems on biodiversity and ecosystem variables, this information needs better curation and articulation among the different available systems. Datasets are frequently available without estimates of accuracy or uncertainty. Furthermore, there is a major need for synthesis activities and readily accessible tools that translate large amounts of data from institutional repositories into scientific knowledge and information relevant for policy making. There is a lack of platforms for scientific discussion on transdisciplinary topics, and current discussion or activities at the level of scientific societies or governmental groups need to include a larger group of stakeholders.

Based on this analysis, we propose three specific sets of actions that can largely improve the capacity of Colombia to quantify the state of its ecosystems and how they change over time. These proposed actions are considered the most essential priorities given the limited economic resources available in Colombia, as in many other developing countries, for investment in science and technology.

3.1. National center for ecological synthesis (CES)

Given the large amount of information already available in institutional repositories, investigators' databases, and free remote sensing products, it is essential to develop synthesis activities around specific research questions or policy/management problems, particularly for regions experiencing accelerated changes. Centers for Ecological Synthesis (CES) have been a very successful model in other countries for this purpose (Hampton and Parker, 2011; Rodrigo et al., 2013).

We propose the creation of a national center for ecological synthesis in Colombia. An organization with multiple sources of funding that provides grants to scientists and policy makers to organize workshops and synthesis groups around specific topics. Such a CES does not necessarily require new physical infrastructure since meeting space and computational resources can be provided by different participating institutions. Funding would only be necessary for organizing meetings, and support staff for database management and administration.

This approach can yield unprecedented and high-impact results, without investing in the collection of new data or the establishment of new experiments. Such a system would be the first in South America (see ISC, 2017), it would empower local scientists, and create a larger culture of transdisciplinary and multi-institutional research.

3.2. Ecological observatory system (EOS)

Despite all efforts to implement information systems and deploy them in webportals, Colombia still lacks a unified program to constantly and consistently collect information on ecosystem variables and make this information available in near-real time to the public. Such a system is fundamental to detect ecosystem change and provide information to decision-makers and on-the-ground professionals to enable prompt action.

We envision an ecological observatory system (EOS) for Colombia that integrates publicly available information from both remote sensing, and in situ observations on relevant ecosystem variables. The relevant variables would have to be selected based on their ability to inform about ecosystem state, trends, functions and process from open data sources. They must not be redundant, consistent through time and in some cases, those derived from satellites, are capable to offer a baseline.

This EOS can build upon existing monitoring sites and permanent plots, but would require standard protocols for data collection, storage, and distribution. Priorities for field data collection should be on the three major themes described above: climate and biogeochemistry, biodiversity and socio-economic variables. Regarding the remote sensing data, we can take advantage of freely available satellite data-products with global coverage as well as locally collected by airborne or unmanned aerial vehicles.

This effort would require the creation and establishment of new infrastructure such as instrumented and well-staffed research stations as well as a data management center for processing and publishing data in near real-time. We propose here a multi-stage implementation, starting with a) synthesis of readily available global data products and national information to develop static products at national scale, and b) the development of a platform that facilitates accessing to different repositories, data storage, and data processing. The system must simultaneously c) develop protocols for in-situ data collection, and d) proceed to the establishment of a set of field stations located in strategic locations across the country for continuous data acquisition. At a later stage, the system must e) integrate both remote-sensing based products with in-situ information, and deploy this information in near real-time to the public.

3.3. Platforms for interdisciplinary dialog and action (PIDA)

Spaces for scientific dialog on transdisciplinary environmental topics are limited in Colombia, despite all efforts from individual researchers and governmental institutions. Most current scientific dialog occurs within topical scientific societies, or working groups within the SINA. Also, most discussion and activities are centralized in the capital cities with poor involvement of stakeholders from other regions. A culture of transdisciplinary and multi-institutional collaboration needs to be promoted in order to create new knowledge, test previous ideas or misconceptions, and produce and share relevant information for policy making that cannot be provided by a single discipline alone.

We propose the development of new platforms for dialog and action, including: 1) special sections or symposiums on transdisciplinary topics at annual meetings of local scientific societies, 2) an annual conference on the state of Colombian ecosystems and their change over time, 3) broader participation of other communities in meetings of the members of SINA. These are low-cost but high-benefit actions that would help scientists and policy makers get a broader view of the complexities of the current transitions of Colombian ecosystems.

4. How much would it cost?

Improving the ability of Colombia to monitor the state of its ecosystems and their rate of change over time requires major national efforts to increase the national investment in science and technology, and particularly to increase investments in ecological research. Current private and public investment in research and technology in the country corresponds to 0.38% of the national GDP, or approximately 60 million dollars annually. We argue that the national government should make important efforts to increase investments in science and technology to levels comparable to the global average of 2.1% of GDP. Given the ongoing sensitive threats to the stability of ecosystem derived from deforestation and mining activities, among others, and the implications for environmental quality and social wellbeing, a healthy annual investment on environmental research should be no less than 0.5% of the GDP, or 80 million dollars annually. This would require important efforts by the scientific community and the public in general to raise political awareness about the importance of funding ecological research as a social investment that can derive into better environmental quality and societal wellbeing.

CES: We anticipate that an annual budget to operate a CES for the first five years would be between US$ 150,000 to 200,000 per year. This funding would cover 2 to 3 working groups annually, and the salary of an IT specialist that would serve as liaison between the working group and different organizations that archive and distribute data. Compared to the annual cost of running a CES in other parts of the developed world (e.g. $ 400,000 per year for NCEAS in California), we expect much lower costs for running a CES in Colombia given differences in currencies, salaries, and administration costs.

EOS: We are aware that such an EOS is expensive, requires careful planning, and coordination among many different Colombian institutions, researchers, and funding agencies. Any estimate of the potential cost of such a system should be the result of a careful planning process that identifies the scope of data collection, archiving and distribution as well as the interest and contribution of different researchers and institutions to collaborate in the system. However we believe that such a system could be made possible with a total investment of around 40 million dollars in total over the next decade. The annual investment (4 million dollars) would correspond to 0.1% of the total royalties received by the country from mining and oil production in 2012. This amount would be less than 10% the cost of NEON in the United States (Tollefson, 2011)

PIDA: Most activities for dialog and action can benefit from existing platforms such as annual meetings of scientific societies at no, or very little, additional cost. An annual conference on the state of Colombian ecosystems would require an additional financial effort, but we believe that such a conference may have a modest cost, between $30,000 to $50,000, depending on number of participants.

5. Summary and conclusions

The unprecedented achievements in Colombia to end the more than 50 years of internal war entail rapid socio-economic and political transitions with largely uncertain consequences for ecosystems and the benefits derived from them. Much progress has been made in recent years to improve the capacity of the country for data collection on relevant ecosystem variables and making it publicly available in institutional repositories. The national environmental system SINA and the national statistics system SEN are major existing programs that already have a mission for collecting and distributing environmental and social information. We argue that it is the right moment to build on these important efforts in order to improve the capacity of Colombia to monitor the state and changes in ecosystems. For this purpose we consider essential to build capacity on synthesis of available information for an improved understanding about drivers of ecosystem change; and to implement a network of research sites where data is collected periodically using standard protocols. It is also very important to facilitate scenarios for multidisciplinary discussion and action between relevant academics and policy makers, making use of the current infrastructure of existing institutions. We specifically propose the creation of two major programs: 1) a national center for ecological synthesis similar to those already established in other countries, and 2) an ecological observatory system for the collection of new information integrating field and remote observations. We consider that such programs are fundamental to address essential questions regarding the state of Colombian ecosystems, their changes, the main drivers of change, how likely will ecosystems change in the future, and what are the consequences of those changes for society.

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