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Published in:
Global Ecology and Biogeography

DOI:
10.1111/geb.13804

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2024

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Garzon-Lopez, C. X., Miranda, A., Moya, D., & Andreo, V. (2024). Remote sensing biodiversity monitoring in Latin America: Emerging need for sustained local research and regional collaboration to achieve global goals. *Global Ecology and Biogeography*, *33*(4), Article e13804. https://doi.org/10.1111/geb.13804

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Download date: 24-06-2024

Received: 29 April 2023 | Revised: 21 December 2023 | Accepted: 5 January 2024

DOI: 10.1111/geb.13804

REVIEW ARTICLE

Global Ecology and Biogeography A Journal of Macroecology WILEY

Remote sensing biodiversity monitoring in Latin America: Emerging need for sustained local research and regional collaboration to achieve global goals

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Handling Editor: Franziska Schrodt

Abstract

Aim: Biodiversity monitoring at global scales has been identified as one of the priorities to halt biodiversity loss. In this context, Latin America and the Caribbean (LAC), home to 60% of the global biodiversity, play an important role in the development of an integrative biodiversity monitoring platform. In this review, we explore to what extent LAC has advanced in the adoption of remote sensing for biodiversity monitoring and what are the gaps and opportunities to integrate local monitoring into global efforts to halt biodiversity loss.

Location: Latin America and the Caribbean.

Time period: 1995 to 2022.

Taxa studied: Terrestrial organisms.

Methods: We reviewed the application of remote sensing for biodiversity monitoring in LAC aiming to identify gaps and opportunities across countries, ecosystem types and research networks.

Results: Our analysis illustrates how the use of remote sensing in LAC is disproportionately low in relation to the biodiversity it supports.

Main conclusions: Build upon this analysis, we present, discuss and offer perspectives regarding four gaps identified in the application of remote sensing for biodiversity monitoring in Latin America and the Caribbean, namely (1) alignment between remote sensing data resolution and ecosystem structure; (2) investment in research, institutions and capacity building within researchers and stakeholders; (3) decolonized practices that promote access to publishing outlets and pluralistic participation among countries that facilitate exchange of experiences and capacity building; and (4) development of networks within and across regions to advance in ground surveys, ensure access and to foster the use of remote sensing data.

KEYWORDS
biodiversity monitoring, essential biodiversity variables, Latin American and the Caribbean, pluralism, remote sensing, research networks

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1 | INTRODUCTION

Latin America and the Caribbean (LAC) support around 60% of the global biodiversity including biodiversity hotspots of global importance (Myers et al., 2000). At the same time, the region is one of the most threatened areas of the globe in terms of overexploitation, climate change, pollution and land use change, among others (FAO, 2020). LAC biodiversity is distributed across a range of ecosystems—from the high-elevation endemic species in the Andes to the highly diverse areas of tropical forest—and supports the livelihood of millions of people in urban and rural areas (IPBES, 2018). In addition, the region has some of the largest socioeconomic inequities in the world (Laterra et al., 2019). These inequities are derived from (and reinforced by) unsustainable practices in the use of natural resources that have resulted in an alarming rate of biodiversity loss (IPBES, 2019). In this context, protecting LAC ecosystems is a priority and one of the keys to achieve the Sustainable Development Goals (SDG), especially goals on ecosystem protection (13, 14 and 15) and sustainability (6, 11 and 12), and mitigate climate change (Opoku, 2019).

Biodiversity is defined as the variety of life on Earth and the ecological complex which they are a part of, including its genetic variation and functional attributes, and changes in abundance and distribution over space and time from species to the ecosystems they form (IPBES, 2019). Biodiversity monitoring over space and time, critical for the implementation of the Kunming-Montreal Global Biodiversity Framework (CBD Secretariat, 2022), is a challenging endeavour that requires research on a wide range of environmental and social factors, and collaboration in a diverse network of stakeholders with varying degrees of expertise and multiple ways of knowing from all over the world (IPBES, 2022). Consequently, effective biodiversity conservation and management requires monitoring schemes that provide accurate assessments on the current status, trends and interdependencies between biodiversity and society at relevant levels for implementation (Navarro et al., 2017; Pascual et al., 2021).

Biodiversity hotspots worldwide, like the Amazon, Central Chile or the Andes in LAC, are mostly coincident with low-income countries (Barrett et al., 2011), that further drives biodiversity loss while preventing financial resources and technologies needed from being invested in biodiversity monitoring (Carpenter et al., 2006; IPBES, 2019; Mikkelson et al., 2007). Even though biodiversity monitoring schemes are meant to be global, their implementation is local and depends on multiple factors (Proença et al., 2017). In the case of Latin America, the factors vary among and within countries and include government agenda, investments, access to remote locations, environmental and social conflicts and access to technology. Colombia, for example, endured 60 years of armed conflict that limited the access to vast areas of the territory for biodiversity research and data collection until 2016, when the government of Colombia signed a peace agreement with one of the largest rebel groups Fuerzas Armadas Revolucionarias de Colombia (FARC) (Mesa de conversaciones, 2016). The peace agreement allowed access to, on the one hand, researchers that collected biodiversity data at those areas (Wade, 2018) and, on the other, investors that since have intensified land transformation to an alarming increase in deforestation rate of 177% post-conflict (Clerici et al., 2020). Like Colombia, other countries in LAC continuously face complex situations; Venezuela with a lack of government investment in scientific research (Dannemann, 2019); Chiles' political instability and long drought (Bowman et al., 2019), increasing safety concerns for researchers in Mexico (Arellano, 2023), the recent referendum to stop oil drilling in Ecuador (Collyns, 2023), and the list goes on. Such a unique combination of social and ecological factors across countries, with shared ecoregions, determines the characteristics and implementation process of a robust biodiversity monitoring scheme urgently needed, as approved by Kunming-Montreal Global Biodiversity Framework (MK-GBF), and impacts the likelihood of implementing timely measures to sustainable manage and preserve their biodiversity (Gonzalez & Londoño, 2022).

In this context, the availability of free global satellite data has emerged as an opportunity for research and biodiversity monitoring especially in the region where data is scarce and clustered around regions with more investments in data collection and accessible to researchers (Hughes et al., 2021; Ramírez-Barahona et al., 2023). The region has witnessed significant progress in remote sensing development, utilizing globally approved methodologies that can help circumvent scientific data and monitoring challenges amidst internal political conflicts. In 2019, the Instituto Nacional de Pesquisas Espaciais (INPE) published preliminary data showing an alarming 88% increase in forest loss compared to the previous year. Regrettably, political persecution by the Bolsonaro government led to the expulsion of scientific staff from the institution (Deutsch & Fletcher, 2022). A similar controversy arose concerning the discrepancy between official government data reported to the Food and Agriculture Organization (FAO) and scientific evidence. The FAO's official report indicated a national increase in native forests (FAO, 2014), while contrary evidence from Miranda et al. (2017) revealed a declining trend. This divergence was primarily attributed to applying different monitoring methodologies for the Global Forest Resources Assessments (FRA) reported by national agencies to FAO (Miranda et al., 2018). Efforts are being made to standardize methodologies between public agencies and academia; however, having globally validated methodologies to facilitate effective communication among stakeholders at multiple scales could avoid internal conflict and could help the global community to watch the national compliance of international agreements.

Advancements in the use of remote sensing for biodiversity have been instrumental in the growth of research on multiple biodiversity indicators (Petrou et al., 2015; Skidmore et al., 2021). These advancements include cameras and sensors with higher resolution and more portable and autonomous Unoccupied Aerial Vehicles (UAV) as well as the deployment of new satellite missions. In terms of biodiversity monitoring, the Group of Earth Observation Biodiversity Observation Network (GEOBON) has worked on the development of Biodiversity Observation Networks (BON) and the identification of a set of Essential Biodiversity Variables (EBVs) that comprise the multiple dimensions of biodiversity in the context of ecosystem functioning like species traits, abundance and distribution (Navarro et al., 2017; Skidmore et al., 2021). Further research has identified a subset of the EBVs that can readily be measured through remote sensing from local to global levels like ecosystem primary productivity, phenology and disturbances using multispectral, LiDAR and radar data, and spectral and trait diversity including hyperspectral data (Asner & Martin, 2016; Rocchini et al., 2021; Skidmore et al., 2021). However, remote sensing alone is not enough, ground data is required to calibrate and validate the measurements and accurately provide the baseline for a global scale biodiversity monitoring platform (Cavender-Bares et al., 2022). Therefore, researchers have developed methods to assess biodiversity in situ. The in-situ efforts include collated data from multiple sources, e.g. monitoring schemes like the forest dynamics research sites (CTFS Forest-GEO), museums and herbaria like the Mesoamerican Network of Herbaria, and citizen science efforts like iNaturalist, organized and often made available online at the Global Biodiversity Information Facility (GBIF).

Multiple researchers have pointed out that monitoring biodiversity, as well as identifying the drivers of change, is a complex task because its estimates and indicators of change are modulated by the spatio-temporal scales at which they are measured and across regions, and because its dynamics depend on a myriad of environmental, ecological and socioeconomic factors that vary in distribution and magnitude from one ecosystem to another (Cavender-Bares et al., 2022; Chase et al., 2019; Gonzalez et al., 2023; Petrou et al., 2015; Reddy, 2021; Thompson et al., 2021). Therefore, harnessing the expertise of local communities and researchers is crucial to ensure robust biodiversity monitoring and effective implementation of frameworks. Consequently, to involve all parts of society as active participants of a network of biodiversity monitoring platforms, united in a global observing system (GBiOS), as recently proposed by Gonzalez et al. (2023), it is key to understand if and to what extent LAC has advanced in local remote sensing biodiversity monitoring, the needs in terms of cooperation and capacity building, and the opportunities to integrate local monitoring into global efforts to achieve the SDGs, halt biodiversity loss and mitigate climate change (UNEP-WCMC, 2016). If we are to recognize and harness the uniqueness of the region and identify the importance of remote sensing in biodiversity monitoring in LAC, guided by the Kunming-Montreal Global Biodiversity Framework, to mobilize timely and aligned action the question we need to answer is: what needs to be known and how?

To answer this question, we performed a systematic literature review exploring biodiversity indicators, research trends, collaboration among researchers and spatio-temporal coverage of biodiversity monitoring using remote sensing in LAC. In addition, we assessed the gaps, obstacles and opportunities that need to be tackled. With that aim, we applied a formal systematic review approach.

This review aims to lay the groundwork for a novel comprehension of remote sensing advancements on the topic of biodiversity monitoring, with a specific focus on identifying the disparities between global efforts and the current state-of-the-art science and working orientation in LAC. Moreover, we seek to understand these gaps within the context of local realities, considering the regional disparities in economic development. Ultimately, this review endeavours to foster regional collaboration and agreement by emphasizing the significance of local action within global remote sensing endeavours. Through this approach, we hope to promote equity, technological advancements, pluralism and fruitful collaborations that contribute to the progress of remote sensing applications for biodiversity monitoring in the LAC region.

2 | METHODS

The aim of this survey was to assess the state of the art in the use of remote sensing for terrestrial biodiversity monitoring including all taxa and approaches to measure biodiversity (e.g. presence, abundance, taxonomical, functional, etc.). The approach used was a formal systematic review based on the guidelines provided by the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA), to ensure transparency and create standardized procedures that allow robust synthesis reports (PRISMA-EcoEvo) (O'Dea et al., 2021). The data sources used in this review consisted of peer-reviewed articles, on terrestrial biodiversity and all taxa, published over a 27-year period (1995–2022), since the appearance of the first publication on biodiversity using remote sensing in Latin America. We included documents in all languages. A search string that included terms related to biodiversity indicators, remote sensing products and LAC country names was used to identify peer-reviewed articles in Scopus and Scielo databases. To include a wide range of indicators of biodiversity we used the following keywords: *biodiversity*, *richness*, *redundancy*, *evenness*, *diversity*, *similarity*, *divergence* or *abundance*, using the OR connector to include all types of biodiversity namely, taxonomic, functional and ecosystems, and to search for papers using any type of measurements and indicators (e.g. essential biodiversity variables). To capture a wide set of remote sensing products, we included *remote sensing*, *satellite*, *UAV*, *Landsat*, *Sentinel*, *earth observation*, *aerial images*, *LiDAR*, *hyperspectral*, *multispectral*, *MODIS*, *SAR*, *radar* or *drone*. The survey was limited to research performed in the countries part of Latin America and the Caribbean and members of the Economic Commission for Latin America (CEPAL in Spanish), namely *Brazil*, *Chile*, *Mexico*, *Panamá*, *Perú*, *Argentina*, *Bolivia*, *Colombia*, *Ecuador*, *Venezuela*, *Costa Rica*, *Barbados*, *Honduras*, *Puerto Rico*, *Uruguay*, *Paraguay*, *Guatemala*, *Belize*, *Nicaragua*, *Guiana*, *Cuba*, *República Dominicana*, *Haiti*, *Guadalupe*, *Bahamas*, *Curacao*, *El Salvador*, *Aruba*, *Trinidad*, *Martinique*, *Antigua*, *Caicos* and *Cayman* (Appendix S1).

The query resulted in 182 peer-reviewed articles, in three languages (Spanish, English and Portuguese), that were imported into the reference manager program Zotero (https://www.zotero.org/) (Figure 1). Different criteria to include/exclude articles were then applied to evaluate the suitability of the documents according to the scope of this study. To be included, articles should: (1) focus on

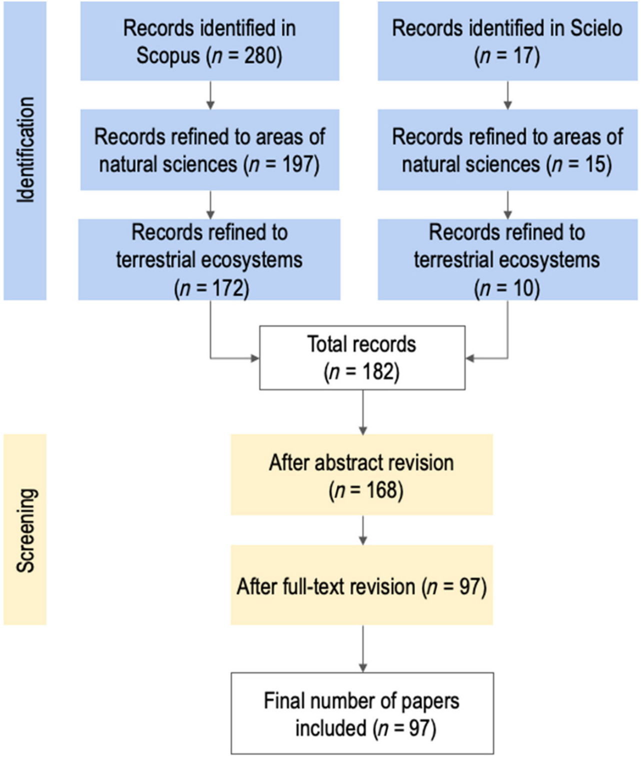


FIGURE 1 Workflow of the criteria for the literature review.

terrestrial systems, (2) have their study sites located in the countries within LAC, (3) focus on estimating biodiversity indicators including, but not limited to, functional, taxonomical and ecosystem, and (4) use remote sensing products at some point in the research. In a first instance, the title and document abstract were reviewed using the inclusion criteria, and in a second instance the full text. The documents that did not meet the criteria were excluded. Documents excluded after examining the title focused on satellite DNA, satellite clusters of species or belonged to astronomy. Other documents excluded were synthesis and commentary papers, research performed at biodiversity hotspots but not estimating biodiversity, and studies performed in aquatic ecosystems. The resulting set of articles were analysed using two approaches: a bibliometric analysis (R package Bibliometrix [Aria & Cuccurullo, 2017]) including a social network analysis to identify scientific collaboration networks and most relevant authors (Isfandyari-Moghaddam et al., 2023), and an in-depth exploration of biodiversity indicators grouped following the EBV framework, ecosystems and taxonomic groups, remote sensing products and research topics covered.

2.1 | Remote sensing for biodiversity in Latin America and the Caribbean: State of the art

The bibliometric analysis allowed us to disentangle the scientific collaboration and publication patterns of studies on the topic of biodiversity monitoring using remote sensing in LAC. The 97 articles matching the selection criteria comprised a total of 490 researchers (a list of data sources is found in Appendix S3). Of the total, 42 articles (43.2% of the total) were authored (first author) by a researcher affiliated to an institution in LAC, while from the remaining 55 articles authored by non-LAC affiliated only 29 articles (52,7%) included a local co-author (Tables S2.1 and S2.2).

According to an assessment on the history and applications of remote sensing for plant biodiversity from Wang and Gamon (Wang & Gamon, 2019), publications applying remote sensing to assess plant biodiversity started appearing in 1990 (Westman et al., 1989). According to our study, in the case of Latin America and the Caribbean and including all organisms, the first publication appeared 5 years later in 1995—one out of five publications in the world that year—, from a research institution based in Europe (Rey-Benayas & Pope, 1995). The studies explored the use of multispectral imagery (Landsat) to estimate plant diversity in Guatemala (Rey-Benayas & Pope, 1995). The first studies from local researchers appeared in 2005. One article from researchers affiliated to a Mexican institution and another from researchers affiliated to a Colombian institution, using Landsat imagery to explore the effect of land cover changes across space (i.e. fragmentation), in the case of Mexico (Hernandez-Stefanoni, 2005); and across time (i.e. 56-year chronosequence), in the case of Colombia (Ruiz et al., 2005), on plant richness, both in tropical dry forests. Since 1995 the number of publications on biodiversity monitoring using remote sensing worldwide has been increasing, but in LAC this increase has been mild and not steady, ranging between 2 (1 article) and 8% (6 articles) of the world publications (Figure 2). Noteworthy, the total share of publications from LAC is expected to be even lower if we compare them to the number of publications including all organisms and not only the subset of plant biodiversity explored in Wang and Gamon (2019).

2.2 | Remote sensing data and biodiversity indicators

Biodiversity patterns occur at genetic, taxonomic, functional and ecosystem levels and across a wide range of spatio-temporal scales. As such, according to the Essential Biodiversity Variables (EBVs), they can be measured by the genetic composition, species' populations, species traits, community composition, ecosystem structure and ecosystem function (Skidmore et al., 2021). At the same time, biodiversity patterns are affected by human activities at multiple scales—from local patterns at the border of a forest fragment to the global context of species range shifts due to climate change (Anderson, 2018; Levin, 1992), making the task of finding drivers of biodiversity change even more challenging (Gonzalez et al., 2023). Such a diverse set of dimensions in which biodiversity patterns can be observed and the dynamics that affect them results in an equally diverse set of tools to measure it. On the one hand, there are ground surveys that collect biodiversity data at high resolution (~1 m plots) and small extents (~50 ha). On the other hand, we have satellite-borne sensors that provide data at lower resolution (>1 km) and

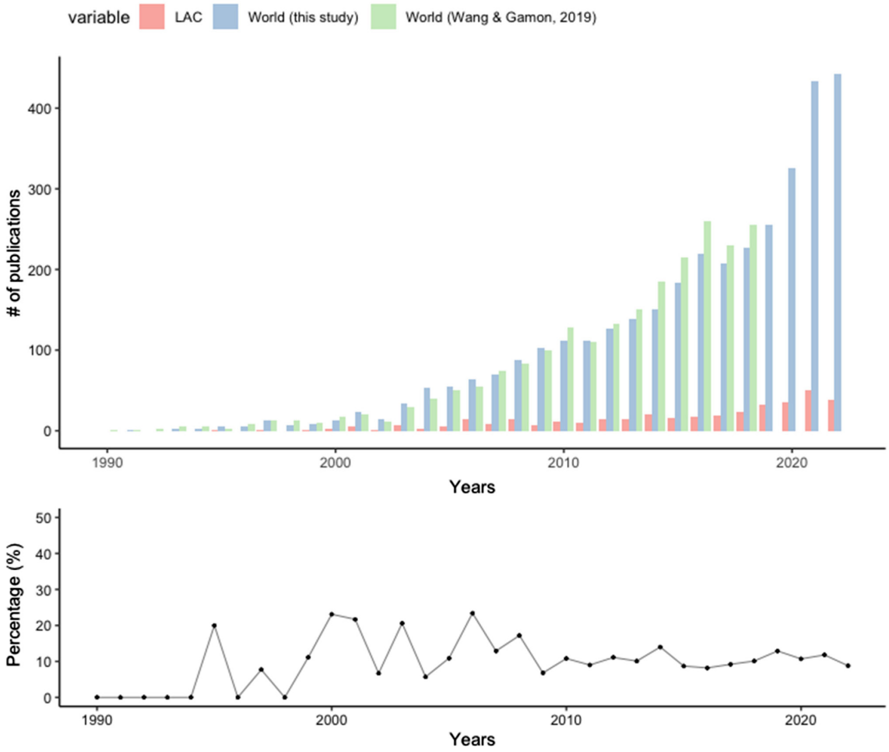


FIGURE 2 (a) Number of publications on remote sensing of plant biodiversity, combining the search terms "biodiversity" and "remote sensing" from Wang and Gamon (2019) for the period of 1990 to 2018, and adding our survey in Scopus and Scielo, of the same terms for all organism's biodiversity, from 1990 to 2022 for the world and for the production in LAC. (b) The percentages of the total number of publications in LAC from the total (figure b) from 1990 to 2021 in the Scopus collection (World—this study) are presented.

over global extents, and airborne and UAV-borne sensors characterized by higher resolution and smaller extents ($<25\,\text{km}^2$) (Figure 3). As a result, biodiversity data are collected at multiple spatial domains covering a wide range of dynamics and responses to change (Anderson, 2018). The challenge is to coordinate efforts, identify drivers of change and make all sources relevant for their context.

RGB imagery consists of three bands (red, green and blue) and is often used for manual identification of features like land cover, organisms' presence and abundance, among others; it is a low-cost method commonly used mounted in UAV and has gained some track for its potential applications for citizen science and conservation (Ierodiaconou et al., 2022; Sauls et al., 2023). Multispectral and thermal imagery, spaceborne imagery like MODIS, Landsat, ASTER or Sentinel, among others; or at higher resolution from WorldView, Quickbird or SPOT (Anderson, 2018); collects data of between three and eleven spectral bands, allowing to capture more information on the spectral properties of the sensed landscape/objects. It has been classically used for land cover classification, and for biomass, moisture and temperature estimations at landscape level (from satellite) and in precision farming (from UAV). Because some of the multispectral sensors, like Landsat (started in 1972), have been collecting data since more than 30 years, they are often used in the analysis of changes across time (Pettorelli et al., 2014). Radar sensors collect data on the structure of the landscape and are important in tropical regions as radars are not affected by clouds to the extent that multispectral sensors are, providing an alternative and a complement via fusion techniques to multispectral and hyperspectral imagery (Schulte to Bühne & Pettorelli, 2018). Light Detection And Ranging (LiDAR) data provides accurate information on the 3D structure of the vegetation, information that is often used in biomass assessments and to understand how this structure mediates the presence and distribution of other organisms (e.g. lianas, birds, mammals) (Acebes et al., 2021). LiDAR has been used in combination with hyperspectral, demonstrating the potential of both sensors for biodiversity monitoring, yet it is still a costly combination even in UAV-borne systems due to the price of the equipment and the computer processing power required for data processing (Almeida et al., 2021). Finally, hyperspectral sensors collect data of hundreds of spectral bands, often at high resolution, thereby providing information on the chemical composition of the sensed object, valuable in studies of invasive species, species traits and functional diversity (Asner & Martin, 2016).

In this review, we identified a wide range of remote sensing products used for biodiversity monitoring. This results in an equally wide range of spatiotemporal scales of analysis (S1.1 and 1.2) crucial in the case of LAC, where ecosystems range from highly diverse forests with tree species of 30 metres in diameter to equally diverse montane grasslands with mosses of less than a centimetre, all affected at various degrees from land transformation, invasive species and degradation. Almost half of the studies use Landsat imagery (38.1%, 37 articles), alone or in combination with other sensors (12.4%, 12 articles). In the case of Sentinel, one study has used Sentinel-1 (Fagua et al, 2021) and four studies have used Sentinel-2 (Tables S2.1 and S2.2). This has to do with the marked tendency to use satellite data to set up the proxy by which drivers of biodiversity (e.g. land cover, productivity) are collected (Figure 3) or use spectral indices like NDVI (Normalized Difference Vegetation Index) to predict biodiversity spatial patterns. For example, authors used Landsat to explore changes in biodiversity in relation to land use change, fragmentation, fire and other anthropogenic pressures (see Table S2.2

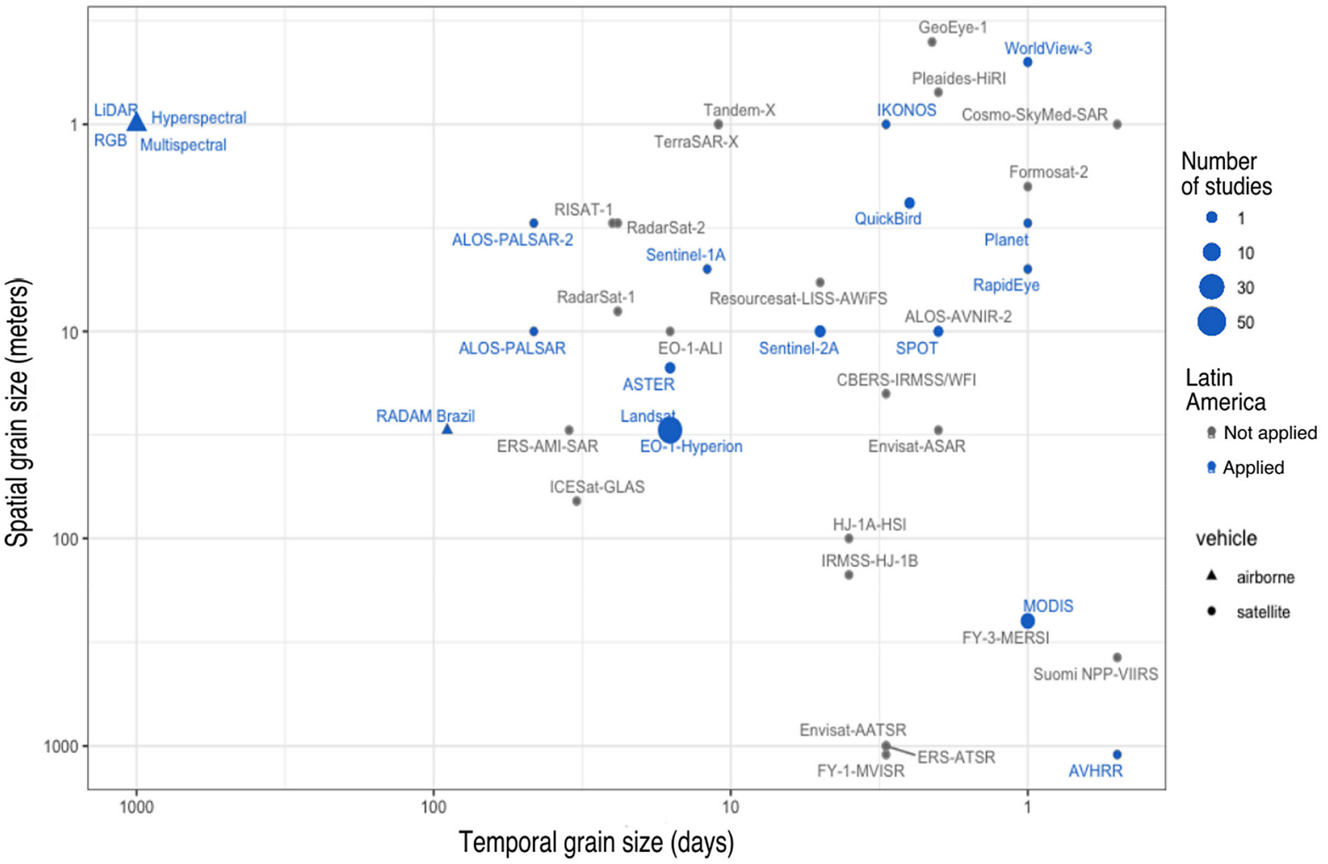


FIGURE 3 Log–log plot of the remote sensing sensors across varying spatial and temporal grain sizes and the application in biodiversity studies in Latin America and the Caribbean. Modified from (Anderson, 2018).

and Figure S4.2). There was, however, a smaller percentage of the studies using Landsat to measure biodiversity directly (9.2%, 9 articles) and just two articles using Landsat in combination with other metrics (see Table S1 and Figure S4.1). Larger scales (>5 km) and lower resolution studies utilized MODIS (10.3%, 10 articles), combined with ground-based metrics to develop indicators of biodiversity for plants and birds (Table and Figure S1). Airborne approaches include the use of LiDAR (19.6%, 19 articles) to assess forest structure, a proxy of bird species richness (Coddington et al., 2023), alone or in combination with hyperspectral data, via spectral composition, heterogeneity or diversity, as direct estimates of plant diversity (Table S2.2 and Figure S4.2) demonstrating the potential of hyperspectral data for biodiversity monitoring in this highly diverse region (Asner, 2008).

On the spatial dimension, resolution ranges from 0.02 m/pixel, to explore biodiversity in restored forests using UAV-borne LiDAR and hyperspectral data (Almeida et al., 2021), to 1000 m/pixel, using MODIS data to study changes in tree phenology as proxies of tree species richness from a time series using stacked species distribution models (Cord et al., 2014). In terms of spatial extent, studies range from areas of 0.003 km^2 up to 2,000,000 km^2, with the majority of the studies distributed across a range of 5 to 70,000 km^2 (73%). On the temporal dimension, half of the studies (54%) do not include a temporal component, and among those that perform temporal analysis, studies range from 0.5 to 60 years, with more than 60% below 2 years and only 13% above 30 years in temporal extent, with annual or decadal temporal resolutions (Tables S2.1 and S2.2). Despite the variation in spatiotemporal approaches and ecosystems studied in the LAC region, our findings suggest potential untapped opportunities for incorporating novel data sources, technologies, and analytical methods to enhance biodiversity research and conservation efforts involved in a comprehensive and integrated approach to biodiversity monitoring in the LAC region. By embracing a broader range of spatiotemporal resolutions and exploring underutilized products, researchers and conservationists can gain a more comprehensive understanding of the region's biodiversity trends, distribution patterns and ecosystem status. The inclusion of such diverse datasets can aid in identifying emerging threats, evaluating conservation strategies and ultimately promoting more effective biodiversity conservation in the LAC region. However, to ensure that the research needs and specific challenges of biodiversity monitoring in LAC are tackled, we need to integrate scientific knowledge in policies and decision-making.

Eleven large terrestrial ecoregions are home to the biodiversity found in LAC (Olson et al., 2001). Despite the fact that only half of the LAC ecoregions are forests, in terms of both ecoregion type and area (54.6%), we found that 80% of the studies published focused on

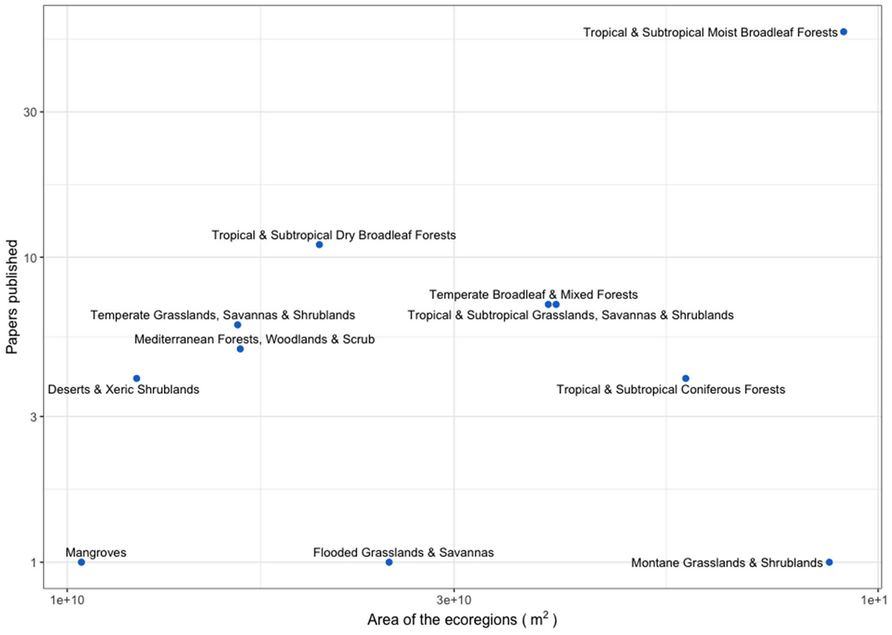


FIGURE 4 Number of papers published in relation to ecoregion area size. Ecoregions area size from Olson et al., 2001.

these areas, with 53% of them specifically set at tropical and subtropical moist broadleaf forest (Figure 4). As a consequence, not only the applications of remote sensing for biodiversity are limited in all LAC ecoregions (Figure 3), but there are little to no advances in the case of remote sensing in biodiversity monitoring in grasslands, wetlands and shrublands (Figure 4).

There is little to no overlap among sensors and ecoregions (Figures S4.1 and S4.2), due to the small number of studies, i.e., in the tropical moist broadleaf forest a wide range of satellite and airborne sensors have been tested (27 sensor types, Tables S2.1 and S2.2), while for other ecoregions of similar size like the tropical montane grassland and shrubland, there is only one study published (Campos et al., 2020). These variations demonstrate the versatility and complexity of approaches to understand and manage biodiversity, even though there is still a significant number of products that have not been fully utilized for biodiversity monitoring in the region (Figure 3).

2.3 | Biodiversity indicators and the applications of remote sensing

The EBVs include multiple dimensions of biodiversity some of which can be assessed using remote sensing metrics (Pettorelli et al., 2016; Skidmore et al., 2021). The research in this area focuses on measuring populations and/or community composition directly by means of species identification or spectral measurements (Brabant et al., 2019; Chrysafis et al., 2020; McCarthy et al., 2021; Peng et al., 2019). It also involves the use of remote sensing-derived metrics as proxy of ecosystem structure and function (Ahuatzin et al., 2019; Asner, 2015; Bastos et al., 2016; Paruelo et al., 2004), or the use of remote sensing products to provide context on the effect of disturbances on ecosystem structure/function (Aguirre-Gutiérrez et al., 2017; Balkenhol et al., 2013; Treitler et al., 2016). In LAC, we found studies that use remote sensing products for all of these approaches but found many especially focused on plant diversity indicators for direct metrics (Table S2.1), and a smaller percentage using remote sensing to contextualize or as a proxy of diversity of other organisms (Figure 5, Table S2.2).

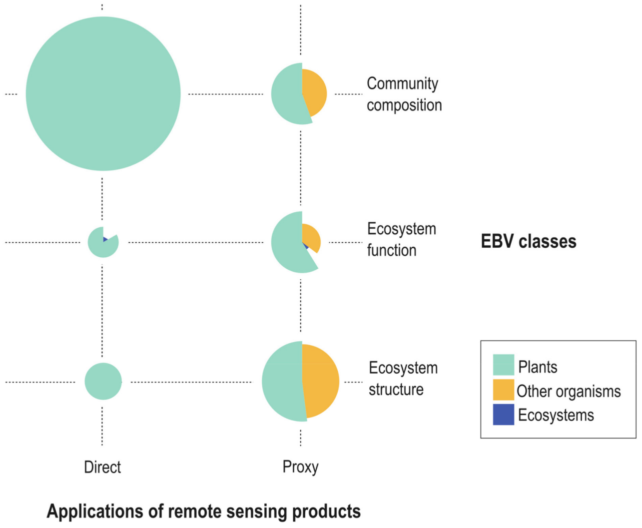


FIGURE 5 Distribution of publications in relation to the applications of remote sensing products and the EBV classes. Pie chart size corresponds to the number of publications per combination of applications and EBV classes. Pie charts represent the fraction of the publications devoted to plants, ecosystems or other organisms. Applications were categorized as direct, if the RS product was directly used to quantify an indicator of biodiversity (e.g. spectral diversity); or proxy, if the RS product was used to derive metrics that correlate with diversity indicators and the attribution of changes over time and/or space (e.g. non-plant species diversity, forest cover).

Given the relevance of species distribution models (SDMs) for biodiversity monitoring, it is important to state that only publications that included remote sensing were retained for this review (for a review on SDMs in LAC see Urbina-Cardona et al., 2019). While SDMs are typically associated with (modelled) climate data, the use of remote sensing is increasing with the publications from Brazilian case-studies (Brown et al., 2020; Paz et al., 2021), the local advances in remote sensing for plant biodiversity (Cavender-Bares et al., 2022) and the development of online tools that facilitate the use of remote sensing and foster capacity building, such as Wallace (Kass et al., 2018). In addition, there are several cases demonstrating how hyperspectral data have already enhanced biodiversity monitoring, offering finer spectral resolution and enabling more detailed characterization of ecosystems and species (Asner & Martin, 2009). The use of LiDAR and/or hyperspectral at high resolution and over large extents results in high dimension datasets that require significant computer power and processing algorithms able to identify patterns, like spectral diversity or spectral signatures of functional groups or species. In this sense, artificial intelligence (AI) approaches have proven its potential to identify/classify species with high accuracy in both highly diverse forests (Baldeck et al., 2015) and montane grasslands (Garzon-Lopez & Lasso, 2020). The incursion of deep learning or neural networks AI algorithms together with the advances in the capabilities of new or planned satellite missions with hyperspectral and LiDAR sensors at higher resolution (Aschbacher & Pérez, 2010; Coppo et al., 2017) open up a myriad of possibilities to monitor biodiversity at multiple spatio-temporal scales (Asner & Martin, 2016; Rossi & Gholizadeh, 2023; Sadeh et al., 2021; Wu et al., 2023), and at the same time call for a renewed interest in ground data to calibrate and validate the remote sensing based assessments. The challenge remains as to how to ensure access to these technologies and expertise across the LAC ecoregions, as well as to implement ecoregion-wide protocols for data collection and facilitate the implementation of such new technologies as standardized and integrative approaches to monitoring.

2.4 | Research networks and collaborations

Collaboration in biodiversity monitoring using remote sensing is essential for LAC's sustainable future. By working together, stakeholders from various socio-cultural and ecological backgrounds can leverage the power of technology, scientific expertise and local knowledge to develop diverse, tailored and robust monitoring and conservation strategies that preserve the region's extraordinary biodiversity for generations to come. As stated in the KM-GBF (CBD, 2023), the implementation of all parts of the framework, including monitoring and reporting on biodiversity, depends on the advances in capacity building and technical and scientific cooperation throughout all the steps of development of the monitoring framework. In a pluralistic setting, local stakeholders can work together to address the specific challenges of biodiversity monitoring in the region to improve preservation and sustainable management of the rich and diverse ecosystems found in this part of the world. A major feature of the application of remote sensing products for biodiversity monitoring is the development of networks of researchers and institutions that allow for an effective integration of methods and coordination of efforts, and facilitate collaborations with researchers and institutions of high-income countries that ensure effective coordination and standardization (Navarro et al., 2017).

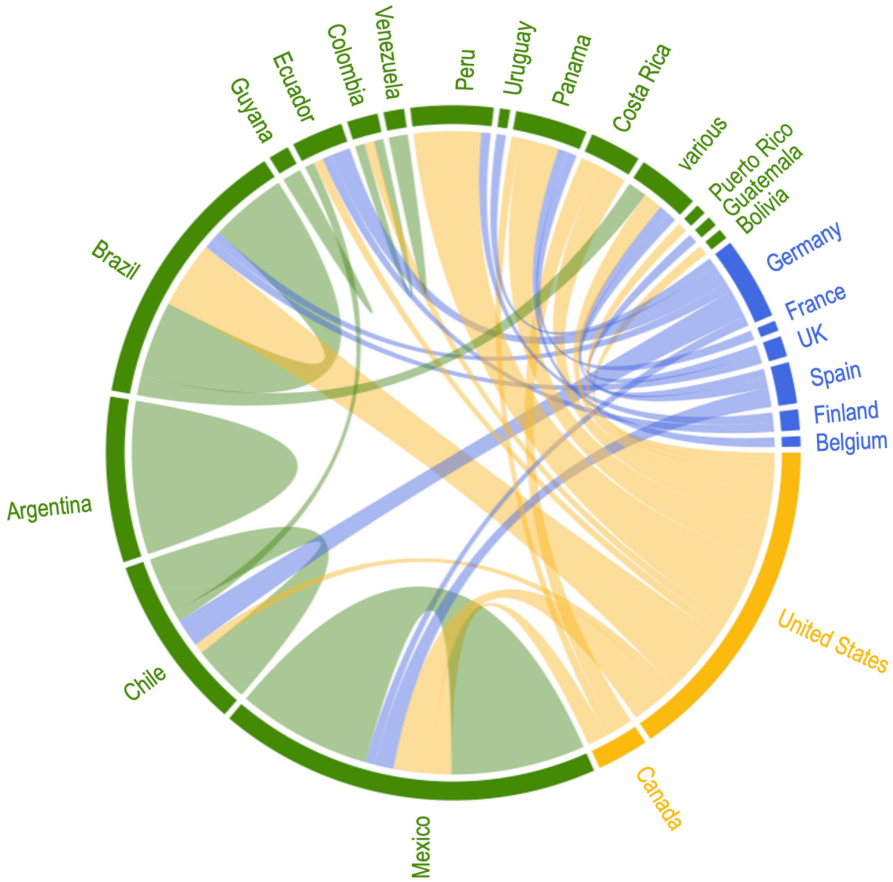
In our review, most research in LAC consisted of scattered efforts connected to collaborators (i.e. leading authors and co-authors) either in the United States (34.6%) or in the European Union (19.2%) with no linkages identified within the region. In this context, the countries with higher number of publications within LAC, after the United States and those in the European Union, are Mexico (15.5%), Brazil (8.7%) and Argentina (7.8%). Argentina is a unique case for the region (Figure 6), with all the publications authored by local researchers and connected to CONICET (in Spanish Consejo Nacional de Investigaciones Científicas y Técnicas), a state organization dedicated to promote and fund science and technology in Argentina that recognizes the role of local scientific journals and promote incentives for researchers which promotes the creation and continuation of research lines as well as the access to less costly per-reviewed publication outlets (Beigel & Digiampietri, 2023). In terms of the areas where the studies take place, however, most of the studies have been performed in Mexico (26.2%), Brazil (14.6%) and Chile (11.6%) (Figure 6), which are also countries in the top three on investments in research and innovation in the region according to UNESCO (UNESCO, 2021).

Using a social network analysis on the collaboration among the authors included in our review, we identified nine isolated clusters of collaborators. Each cluster was led by an author or institution that connected the members inside each cluster. Six of those clusters were distributed among leading authors in the United States, Canada, Spain and the United Kingdom, while only three have leading authors located within LAC. The first node is represented by the work in the tropical dry forests of Yucatan (Mexico) from 2005 to 2019 (e.g. Hernandez-Stefanoni et al., 2011, 2014) the studies at the temperate forests of Chile from 2015 to 2017 (e.g. Ceballos et al., 2015; Lopatin et al., 2016) and the publications about the tropical forests of Panama from 2008 to 2015 connected to the Smithsonian Tropical Research Institute (e.g. Chust et al., 2006; Somers et al., 2015) (Tables S2.1 and S2.2).

3 | NEXT STEPS, CAVEATS AND WAYS FORWARD

LAC is home to some of the world's most diverse and abundant ecosystems, including tropical rainforests, dry forests, grasslands and wetlands. These ecosystems support a wealth of biodiversity, including numerous endemic species, that are important for both ecological and cultural reasons. The recognition of the importance of such biodiversity for the livelihoods of society in and outside the

FIGURE 6 Map of collaborations across countries. Collaborations between countries are depicted as lines connecting countries of study (in yellow) with countries of affiliation of researchers (all colours), and line thickness correlates with the number of collaborations between the countries. Collaborations are defined on the basis of the countries of affiliations of co-authors of a single publication.



region, and for its intrinsic and unique values "Living in harmony with Nature", highlights the relevance of harnessing the expertise and strengthening the connections across biodiversity realms and infrastructures. In this review, we have identified four areas of attention in the application of remote sensing for biodiversity monitoring in Latin America and the Caribbean, namely (1) alignment between remote sensing data resolution and ecoregion structure; (2) investment in research, institutions and capacity building within the region to advance in ground surveys, ensure access and to foster the use of RS data; (3) decolonized practices that promote access to publishing outlets and pluralistic participation among countries that facilitate exchange of experiences and capacity building; and (4) development of networks within and across regions to advance in ground surveys, ensure access and to foster the use of remote sensing data.

3.1 | Alignment between remote sensing data features and LAC ecosystem structure

Biodiversity monitoring in highly diverse and heterogeneous ecosystems posits a number of challenges for remote sensing data collection, processing and interpretation. On the one hand, the smallest spatial resolution in freely available satellite-borne imagery imposes a limit to the sampling design (Gamon et al., 2020; Rocchini et al., 2021). On the other hand, the operational (ecological) definition of population and community, critical in biodiversity monitoring, depends on species size and spatial distribution, as well as the diversity of ecological phenomena (Rocchini et al., 2015). Together, these conditions result in a mismatch in the minimum sampling scale available and the scale at which species diversity should be accurately measured, for example in the attribution of the proxies/drivers of biodiversity, a feature that is affected by the scale of sampling as shown in the case of tropical trees (Garzon-Lopez et al., 2014), and is expected to have an influence in the case of small sized-species like the grasslands and savannas covering the majority of the land surface of LAC (Figure 4). Such mismatch in other regions has been tackled with the development of approaches using high-resolution UAV-borne imagery, laboratory spectrometry and AI-based computational techniques to process the big data files resulting from the gain in spatial and spectral resolution (Lausch et al., 2020). The advancement in the application of these technologies, or the development of new ones, requires exploration of its potential in LAC ecosystems, as well as capacity building in their use for biodiversity assessments. LAC-based publications on this topic have been increasing slowly and mostly in forest ecosystems, with few examples in grasslands (e.g. cerrado, and paramo) (Figures S4.1 and S4.2). Therefore, the relevance and urgency of fostering such research should not be underestimated. Governments, societal stakeholders and researchers can support these advancements by exploring synergies between biodiversity monitoring, precision farming (Velusamy et al., 2022) and urban planning (Lee et al., 2021), among other areas of application.

3.2 | Investment in research, institutions and capacity building within the region

Biodiversity encompasses a wide range of definitions and values for different stakeholders (IPBES, 2022). As such, it is often complex to understand how to invest in biodiversity monitoring. This points to the importance of creating bridges between governments, institutions and societal actors to identify what needs to be known and how, for each ecosystem and local community context. In this review, we have identified an overall limited investment in biodiversity monitoring, especially noticeable in the case of grassland ecosystems, and mangroves, with the majority of publications led by non-local authors. This signals sources of funding external to LAC for those publications. Additionally, there are a number of satellite sensors available that are not utilized or underutilized for biodiversity monitoring (Figure 3), partially due to its limited availability in terms of coverage or costs. This is relevant for biodiversity monitoring, given the multiple dimensions and scales it encompasses, and the need for multiple sensor types to assess it.

Local capacity-building in remote sensing tools and applications provides the context on which stakeholders can work towards the development of roadmaps for biodiversity monitoring. Such roadmaps can clearly identify stakeholders, ecosystems and connections among them. They can inform further investments in research and institutions in a decentralized manner, in order to harness local expertise and ensure co-creation practices for biodiversity monitoring (Mistry & Berardi, 2016). While not specific for biodiversity monitoring, the Argentinian Space Agency (CONAE, https://www.argentina.gob.ar/ciencia/conae) together with different universities from Argentina offers basic and advanced remote sensing courses, diplomas, MSc and PhD programs that are open to all LAC countries. This is a clear example of long-term investment in capacity building and networking in remote sensing applications within the region, in a limited resources context.

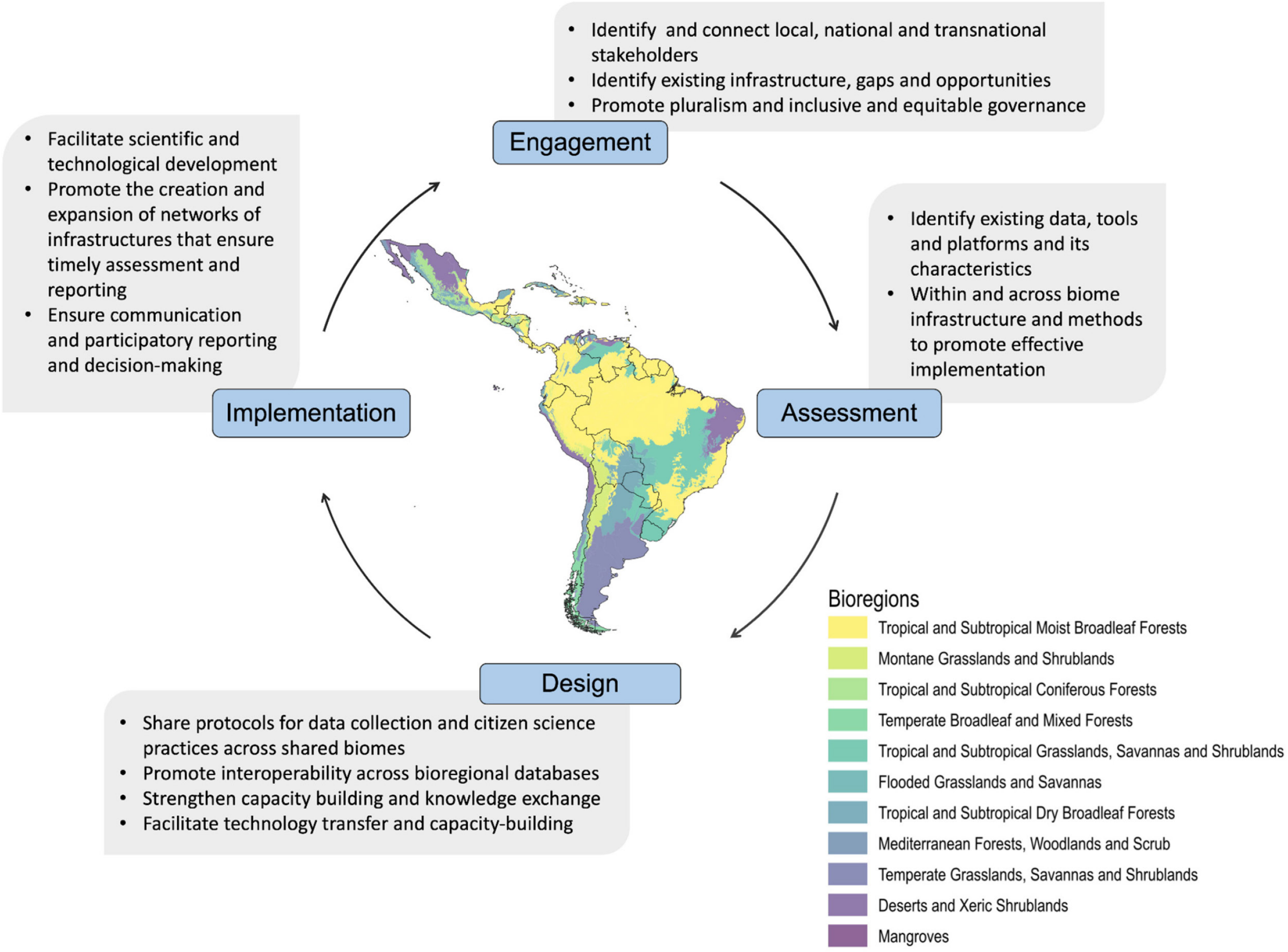
3.3 | Decolonized practices that promote access to publishing outlets and pluralistic participation

LAC not only hosts 60% of the world's biodiversity; it also has an enormous potential in terms of human capital, a capital that is often not included due to its diversity in terms of languages and knowledge systems. Scientists from LAC countries as well as scientists in the Global South face a number of cumulative barriers to carry out research. These include but are not limited to language, lack of funding, poor infrastructure, low salaries, etc. For example, the first eight global IPBES assessments had 96% of the references cited in English (Lynch et al., 2021), yet a revision that included all languages found 35% of references in other languages that were excluded (Amano et al., 2016). Limited financial resources also hinder scientific advancement, namely costs in terms of time and money are 45% higher when publishing for non-native English speakers (Amano et al., 2023) and there are large disparities in income and publication fees between low- and high-income countries (Williams et al., 2023). Such conditions have detrimental impacts on performance in the lab and in the field not only affecting the scope of their research but also limiting their access and attendance to international journals and events. The latter being great opportunities for networking and establishing collaborations. Additionally, many LAC countries face difficult macroeconomic conditions that complicate the development of research activities even further. The already small grants vanish in a matter of months with unfavourable exchange rates and inflation higher than 100% per year in countries like Argentina. Furthermore, while open access policies have allowed LAC scientists to access more published literature than ever before, it also reinforced existing inequalities as it is virtually impossible for them to pay the high APC with their degraded funding or monthly wages of much less than one-half (in the best cases) of usual open access fees. Last but not least, biodiversity monitoring and local communities suffer from colonialist practices identified also in the review, and practices like "helicopter science" reduce the involvement with local communities (e.g. co-creation, knowledge exchange) and reinforce existing inequalities (Baker et al., 2019; Valenzuela-Toro & Viglino, 2021) by excluding their expertise, values, agency and governance of the ecosystems.

Despite these barriers, there is a growing number of local researchers who advance the use of new technologies, and a myriad of local communities with diverse and long-standing knowledge and values around biodiversity (IPBES, 2022; Pascual et al., 2021; Pratson et al., 2023). If we are to develop global (for all) effective biodiversity monitoring, this can only happen via pluralistic approaches that promote capacity building, access to resources and anticolonial practices. In the case of LAC, this is accomplished by creating and strengthening LAC-based researchers and stakeholders' networks and the development of monitoring schemes that not only rely on one type of evidence but are open to pluralistic knowledge on biodiversity (see Trisos et al., 2021). The result will be schemes that can robustly inform global assessments, and at the same time, support the governance of local communities.

3.4 | Development of within and among countries networks that facilitate exchange of knowledge and experiences

At the global scale, GEO-BON serves as an international consortium dedicated to standardizing the acquisition, coordination, and delivery of biodiversity observations for all countries, aligning with the goals of the Convention on Biological Diversity as expressed in the Global Biodiversity Framework. To fulfil the commitments of this international agreement, it is essential to collect reliable biodiversity data to monitor and report on national progress. However, bridging the technical and infrastructure gaps between countries remains a crucial challenge that requires attention. A notable example of a regional network is the MapBiomas project, which originated in Brazil with technical support from Google but received funding



- Identify and connect local, national and transnational stakeholders
- Identify existing infrastructure, gaps and opportunities
- Promote pluralism and inclusive and equitable governance

- Identify existing data, tools and platforms and its characteristics
- Within and across biome infrastructure and methods to promote effective implementation

- Share protocols for data collection and citizen science practices across shared biomes
- Promote interoperability across bioregional databases
- Strengthen capacity building and knowledge exchange
- Facilitate technology transfer and capacity-building

- Facilitate scientific and technological development
- Promote the creation and expansion of networks of infrastructures that ensure timely assessment and reporting
- Ensure communication and participatory reporting and decision-making

FIGURE 7 Conceptual diagram of the general steps identified by GEOBON (Gonzalez et al., 2023), and the ways in which a LAC network would accelerate the implementation of such multilevel framework for biodiversity monitoring. At the centre of the steps is the map of LAC with its countries (black boundaries) and the bioregions in colour.

from various institutions. MapBiomas produced annual land cover maps for Brazil from 1985 to 2021. Furthermore, this initiative is expanding to include other countries such as Peru, Chile, Paraguay, Argentina, Bolivia and more, with the ultimate goal of creating a standardized annual land cover map for Latin America fostering local capacities using the initial experience of Brazil.

There is slow progress and disconnection among researchers and other stakeholders within LAC regarding the use of remote sensing for biodiversity monitoring. This results in a mismatch in the local agenda for biodiversity monitoring at multiple levels (e.g. communities, regions, countries), the global biodiversity monitoring priorities and tools, and the agency and resources available for local researchers. Such mismatch is not only identified in the appropriation of technologies like remote sensing but also in the biases in ground biodiversity data collection. One clear example, related to the uneven distribution of resources resulting in increasing inequalities, is the case of citizen science mobile apps that have largely increased the number of biodiversity observations globally, but at the same time, have resulted in higher disparities in the amount of data collected in regions with robust mobile networks compared to regions where mobile networks and data costs limit its applicability (Hughes et al., 2021).

Local networks at multiple levels can promote the local appropriation of remote sensing data and methods, and ground-based biodiversity data and monitoring, and build robust assessments based on shared expertise at the local and regional levels. A LAC network has the potential to accelerate implementation at every step of the development of Biodiversity Observation Networks (Navarro et al., 2017, Figure 7) and join forces in a global unified network (Kühl et al., 2020), but must be prioritized and developed to ensure robustness, participation and interoperability in multiple contexts, and informed by the local expertise and needs (Escobar, 1998).

4 | CONCLUSIONS

It cannot be stressed enough that Latin America and the Caribbean is a diverse and heterogeneous region with biodiversity and climate change threats that vary from one ecosystem and social setting to another. In this review we have explored the state-of-the-art remote sensing for biodiversity monitoring in LAC and identified its potential and challenges in the region, as well as the gaps to be bridged in order to overcome them.

Incorporating LAC into the global effort of biodiversity monitoring is essential for a comprehensive understanding of biodiversity patterns and trends on earth, but this effort has to prioritize the local. We suggest that, in order to further promote and implement the use of remote sensing for biodiversity monitoring in the region, it is critical for global organizations, local governments and societal stakeholders to tackle these gaps and opportunities from a local perspective. The aim is to use remote sensing as a tool that mediates in the creation of capacities, networks and infrastructures in the local context to ultimately answer the questions of what needs to be known and how, at the scales and operational levels that ultimately result in sustainable management and conservation of biodiversity.

ACKNOWLEDGEMENTS

We acknowledge the contributions of the Latin-American researchers that are represented in this study. We thank Prof. Anne Beaulieu for the insights and comments on the manuscript.

FUNDING INFORMATION

Open Access funding enabled by University of Groningen.

CONFLICT OF INTEREST STATEMENT

None.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supporting material of this article.

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BIOSKETCH

The research team consists of ecologists with ample expertise in remote sensing applications on areas of disease, landscape, biodiversity and fire ecology from various countries in Latin America and Europe, and with shared interests in biodiversity monitoring and conservation.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Garzon-Lopez, C. X., Miranda, A., Moya, D., & Andreo, V. (2024). Remote sensing biodiversity monitoring in Latin America: Emerging need for sustained local research and regional collaboration to achieve global goals. *Global Ecology and Biogeography*, *33*, e13804. https://doi.org/10.1111/geb.13804