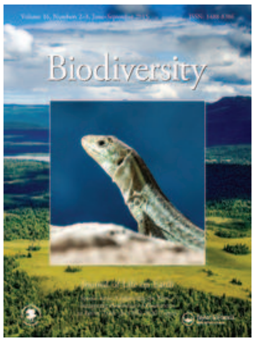

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Challenges and opportunities for the Bolivian Biodiversity Observation Network

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Pragmatic methods to assess the status of biodiversity at multiple scales are required to support conservation decision-making. At the intersection of several major biogeographic zones, Bolivia has extraordinary potential to develop a monitoring strategy aligned with the objectives of the Group on Earth Observations Biodiversity Observation Network (GEO BON). Bolivia, a GEO Observer since 2005, is already working on the adequacy of national earth observations towards the objectives of the Global Earth Observation System of Systems (GEOSS). However, biodiversity is still an underrepresented component in this initiative. The integration of biodiversity into Bolivia's GEO framework would confirm the need for a country level biodiversity monitoring strategy, fundamental to assess the progress towards the 2020 Aichi targets. Here we analyse and discuss two aspects of the process of developing such a strategy: (1) identification of taxonomic, temporal and spatial coverage of biodiversity data to detect both availability and gaps; and (2) evaluation of issues related to the acquisition, integration and analyses of multi-scale and multi-temporal biodiversity datasets. Our efforts resulted in the most comprehensive biodiversity database for the country of Bolivia, containing 648,534 records

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for 27,534 species referenced in time and space that account for 92.5% of the species previously reported for the country. We capitalise this information into recommendations for the implementation of the Bolivian Biodiversity Observation Network that will help ensure that biodiversity is sustained as the country continues on its path of development.

Keywords: Bolivia; biodiversity; big data integration; monitoring; baseline; GEO BON

Introduction

In the last two decades, aided by increased connectivity and easy access to data capturing devices and analytical tools, societies are witnessing a change in the paradigm on how to deal with information. We are rapidly moving from data control schemes to more collaboration, integration and sharing (Wallis, Rolando, and Borgman 2013). Within the biodiversity community, there is a plethora of initiatives dedicated to collecting data on multiple dimensions of biodiversity and at different spatial scales and resolutions such as the Living Planet Index (Collen et al. 2009), the Map of Life (Jetz, McPherson, and Guralnick 2012) and the PREDICTS database (Hudson et al. 2014). More data could lead to improved knowledge on how biodiversity is distributed in space and how it is changing over time; both components are essential for better informed policy-making and more accurate scenarios for conservation and management (Pereira et al. 2010; Schmeller et al. 2015).

However, quantity does not mean quality (Maldonado et al. 2015). One of the main problems is that not all biodiversity data was collected using a sampling design appropriate for monitoring in space and time. For instance, in the last global biodiversity assessment (Tittensor et al. 2014) only 55 out of 163 potential indicators were selected to measure progress towards conservation targets. Spatial coverage and availability of temporal series were amongst five criteria used to determine the indicator's suitability to measure change and/or response to change (Tittensor et al. 2014). Thus urgent harmonisation and standardisation of methods, protocols and quality control measures are needed (Pereira et al. 2013). However, while ontological alignment (i.e. correspondence among concepts) is a priority in data rich regions, this is not as important in data deficient regions where a baseline for monitoring change might not even exist. Incidentally, data deficient regions also happen to occur not only in areas of high conservation value but also in areas where the highest degrees of degradation occur (Collen et al. 2008; Pereira, Navarro, and Martins 2012), making the strategies to define monitoring priorities even more urgent (Hardisty and Roberts 2013).

The country of Bolivia, at the heart of South America, is a perfect example where high levels of biodiversity, deficient information and high degrees of degradation overlap. Baseline information even for the most well-known and charismatic species data is lacking (Vié, Hilton-Taylor, and Stuart 2009). For example, from the 389 mammalian species described for Bolivia, 106 species have stable populations while 84 species are declining (Tarifa and Aguirre 2009). Yet, for the remaining 199 mammalian species, the status of their populations is unknown since there is simply not enough information to estimate or infer a trend (Peñaranda and Simonetti 2015). Similarly, for the 266 species of amphibians reported for Bolivia, available data on possible threats or declines is mostly anecdotal, and long-term well-funded programmes that monitor populations and putative declines are nonexistent (De la Riva and Reichle 2014).

One of the most pressing environmental concerns of Bolivia is deforestation for large-scale mechanised agriculture, small-scale agriculture and cattle ranching (Killeen et al. 2007; Müller et al. 2012). Although deforestation rates were considered moderate for decades, relative to other countries in the region, the situation has changed dramatically in the first decade of the twenty-first century. Independently of whether we look at the lower estimates (0.49%; FAO 2010) or the higher estimates of deforestation (0.66%; Cuéllar et al. 2012), Bolivia is currently placed in the top 10 list of countries with the highest annual rates of forest loss in the world (FAO 2010), with potentially dramatic consequences for biodiversity (Pinto-Ledezma and Rivero Mamani 2014). Thus, establishing monitoring schemes in, for instance, deforested and control areas would be an essential step towards the assessment of consequences of human-induced land-use change for biodiversity in the country.

To provide a baseline against which to measure biodiversity change in countries with similar co-occurring conditions to Bolivia, centralisation, systematisation, archiving and curation of biodiversity data is urgently needed. The Essential Biodiversity Variables framework concept proposed by Pereira et al. (2013) provides an attractive framework for the development of national and sub-national initiatives. These monitoring initiatives can provide the knowledge base to assess the targets for 2020 set by the Convention on Biological Diversity (CBD).

As the first step towards building a monitoring scheme for biodiversity in Bolivia, we evaluate two key aspects in establishing a baseline: first, the identification of taxonomic, temporal and spatial data availability to detect both data gaps and opportunities for long-term monitoring; and second, the evaluation of issues related to the acquisition, integration and analyses of multi-scale biodiversity datasets. We capitalise this information into recommendations for the implementation of the Bolivian Biodiversity

Observation Network, consistent with the essential biodiversity variables framework.

Methods

Biodiversity observation: data acquisition and integration

We evaluated the taxonomic, spatial and temporal coverage of biodiversity observations in Bolivia from the year 1789 until 2015. We used, as the main sources of information on species occurrence, data derived from specimens hosted in natural history museums and herbaria located inside and outside Bolivia (i.e. Herbario Nacional de Bolivia (LPB) and Colección Boliviana de Fauna (CBF) – Universidad Mayor de San Andres, Museo de Historia Natural Noel Kempff Mercado (MHNNKM) – Universidad Autónoma Gabriel Rene Moreno, Missouri Botanical Garden (MOBOT), California Academy of Sciences (CAS), Museum of Vertebrate Zoology at Berkeley (MVZ), Smithsonian Institution National Museum of Natural History (NMNH), Museum National d'Histoire Naturelle de Paris (MNHN), Global Biodiversity Information Facility (GBIF)); we also included expert observations databases from other research institutions (e.g. Instituto Boliviano de Investigación Forestal (IBIF), Wildlife Conservation Society (WCS) and NatureServe). Biodiversity observations that fulfilled the following criteria: (1) terrestrial macrobiotic organisms identified at the species level, (2) with georeferenced occurrence information precise to minutes in latitude and longitude and (3) that contained information about the date of the collection event, were integrated into a single database using PostgreSQL, an open-source database software.

Once all the records were integrated into the database, we applied a series of consistent quality control routines on the data. These included a verification of the types of input values and alignment of fields to controlled vocabularies and standards (i.e. Darwin Core; Wieczorek et al. 2012). We also checked the taxonomic accuracy and redundancy of the database by aligning the scientific identification of each record against a reference taxonomic backbone. For plants we used the Taxonomic Name Resolution Service v.3.2. (TNRS; Boyle et al. 2013) and for animals and fungi we used the Integrated Taxonomic Information System database (ITIS 2010). After applying this systematic quality checks, we replaced synonymies by most current taxonomy and removed the invalid records from the database. We then transformed all the geographic coordinates to decimal degrees and using PostGIS, a spatial database extender, and we imported the database into a Geographic Information System (ArcGIS v.10.2).

Then, we checked if the coordinates of each record were aligned with the country (IDE-EPB 2015): we applied a buffer to the country boundaries and removed all records that fell at distances larger than 2.5 km of the official international boundary of the country.

Taxonomic data coverage

From the integrated database, we first counted the number of species in taxonomic groups from which we were able to find previously published accounts (i.e. fish, amphibians, reptiles, birds, mammals, bryophytes and vascular plants) and then compared the results against our numbers. Secondly, using a national ecoregional classification based on Ibisch and Merida (2013), which provides a more tailored and accurate representation for Bolivia than the global classification from Olson and Dinerstein (2002), we counted the number of records and species that occur within each ecoregion. Based on the results of these analyses we calculated the ratio of the number of records to the number of species, and reported averaged values per ecoregion for animals and plants. A ratio close to one is an indicator that more species in the group are known from one single record.

Spatial and temporal data coverage

We created a grid of 5 × 5 km^2, and counted the number of unique species that occur in each cell. We defined the spatial resolution of the grid based on the average error estimate of the retrospectively georeferenced observations (~2.5 km) using the point-radius method developed by Wieczorek, Guo, and Hijmans (2004), a well know and accepted method that has been incorporated in protocols, geospatial guidelines and software (e.g. BioGeomancer, SpeciesGeoCoder, ModEco). We also counted the number of unique years represented in each 25 km^2 cell, to understand the temporal distribution of the data across space. Finally, to evaluate the distribution of records across time in our database, we plotted the number of records and the number of species collected for each year. In order to compare national and regional patterns, we repeated these exercises at the ecoregion level.

Results

From a total of 965,896 biodiversity observations, our data integration efforts resulted in a database referenced at the taxonomic, spatial and temporal level that contains 648,534 records from 27,534 species for the country of Bolivia (Figure 1), From this database, 93.7% of the records were obtained from vouchered specimens from natural history museums and herbaria and the remaining 6.3% of the records were originated from direct expert observations. Also, 55.4% of the records were obtained from institutions hosted outside Bolivia and 44.6% from institutions hosted inside the country.

Our database contains 92.5% of the total number of species reported for Bolivia when compared with

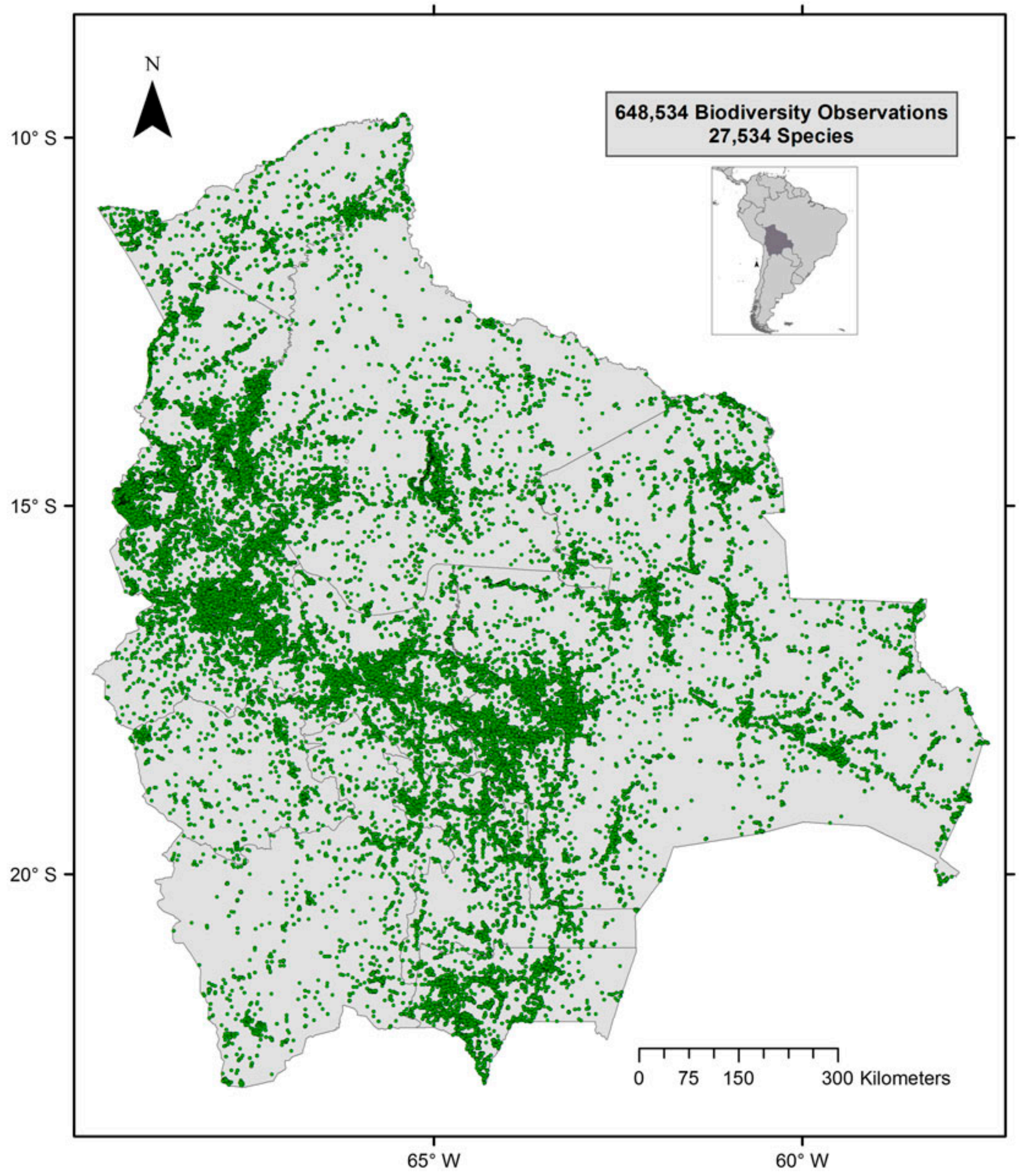

Figure 1. Georeferenced biodiversity observations for Bolivia, compiled from records in local and international natural history museums, herbaria and direct observations reported by experts.

species accounts and checklists from previous studies (Figure 2) and 95.8% of the species included in the IUCN Red List of Threatened Species (Categories: CR, EN and VU), providing a good coverage of the number of species for the most well-known taxonomic groups including amphibians, birds and mammals. Our results also indicate that 34.5% of all the records fall within a protected area with an IUCN protection status, which indicates that biodiversity observations have been sampled slightly more inside protected areas given that 25% of the total area of the country is under protection.

Using ratios, we found that in average plants have 10 times less records per species than animals (Table 1). For animals, the ecoregion with the lowest number of records relative to the number of species was the *Prepuna*, with an average of two records per species; the larger number of records relative to the number of species were from *Sudoeste de la Amazonia* and *Gran Chaco* with an average of 21.3 and 22.7 records per species, respectively (Table 1). For plants, the ecoregions with the lowest number of records relative to species were *Lago Titicaca*, *Prepuna* and *Puna Sureña*, with an average of 1.6, 2.2 and 2.7 records per species,

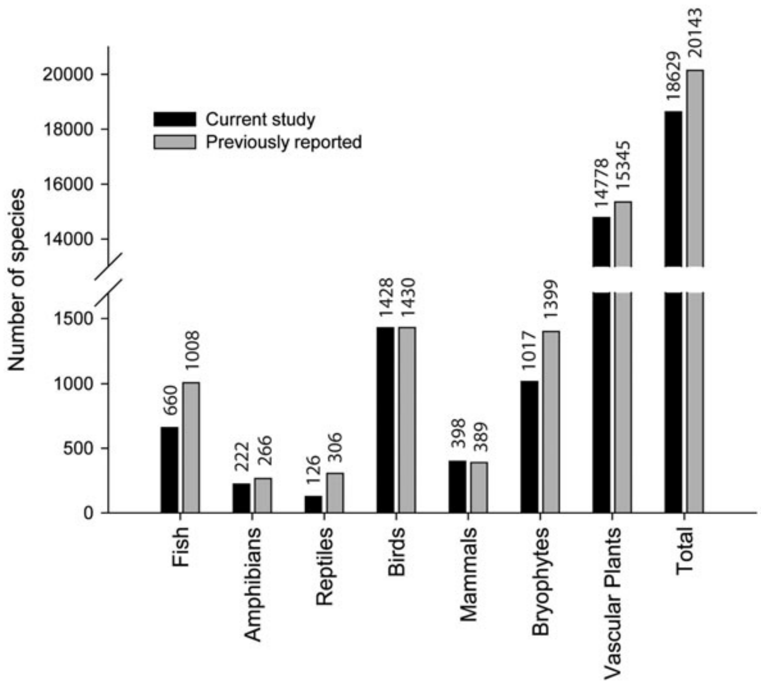

Figure 2. Taxonomic representativity. Number of species from the integrated database (black) compared to number of species in previous studies (grey) from well-known taxonomic groups: fish (J. Sarmiento pers. com.), amphibians (De la Riva and Reichle 2014), reptiles (Aguirre, Aguayo, and Balderrama 2009), birds (S. Herzog pers. com.), mammals (Peñaranda and Simonetti 2015), bryophytes (Churchill, Sanjines-Asturizaga, and Aldana 2009) and vascular plants (Jørgensen, Nee, and Beck 2015).

Table 1. Number of records vs. number of species.

		Plants			Animals			
Code	Ecoregion	Records	Species	Ratio	Records	Species	Ratio	Area sampled (%)
PUSU	Puna Sur	3092	1128	2.74	4645	312	14.89	8.54
PREP	Prepuna	660	289	2.28	108	53	2.04	12.3
GRCH	Gran Chaco	9682	3169	3.06	31,523	1388	22.71	15.37
SAIN	Sabanas Inundables	11,073	3335	3.32	34,110	2251	15.15	15.59
BSCH	Bosque Seco Chiquitano	11,630	3139	3.71	17,213	1306	13.18	15.61
CERR	Cerrado	14,310	4212	3.40	14,189	1352	10.49	15.68
SAMZ	Sudoeste de la Amazonia	126,373	9387	13.46	85,877	4026	21.33	22.24
PUNO	Puna Norte	21,088	4104	5.14	11,366	701	16.21	24.83
LGTK	Lago Titicaca	527	323	1.63	1650	168	9.82	27.89
CHSE	Chaco Serrano	7151	2222	3.22	9984	908	11.00	32.04
BTBO	Bosque Tucumano Boliviano	17,435	3821	4.56	9112	1077	8.46	39.65
YUNG	Yungas	112,198	10,466	10.69	33,915	2203	15.39	43.16
BSIN	Bosques Secos Interandinos	36,574	6639	5.51	23,049	1476	15.62	46.15

Notes: Number of records, species and the ratio between them, calculated per ecoregion for animals and plants. Ratio values larger than one indicate multiple records for a particular species.

respectively; and the largest number of records relative to species were from *Yungas* and *Sudoeste de la Amazonia*, with an average of 10 and 13 records per species, respectively (Table 1).

From a species richness perspective, at the resolution of 25 km^2, the number of species recorded per pixel ranged from 1 to 1278 with a mean of 27 species (Figure 3). The highest numbers of species were recorded in *Yungas* (Figures 3 and 4). From a spatial perspective the ecoregions that were better sampled are: *Bosques Secos Interandinos* (46.1% of the total area sampled), *Yungas* (43.1%) and *Bosque Tucumano Boliviano* (39.6%; Table 1 and Figure 4). Conversely the ecoregions that were least sampled were *Puna Sureña* (8.5%), *Prepuna* (12.3%) and *Gran Chaco* (15.3%; Table 1 and Figure 4).

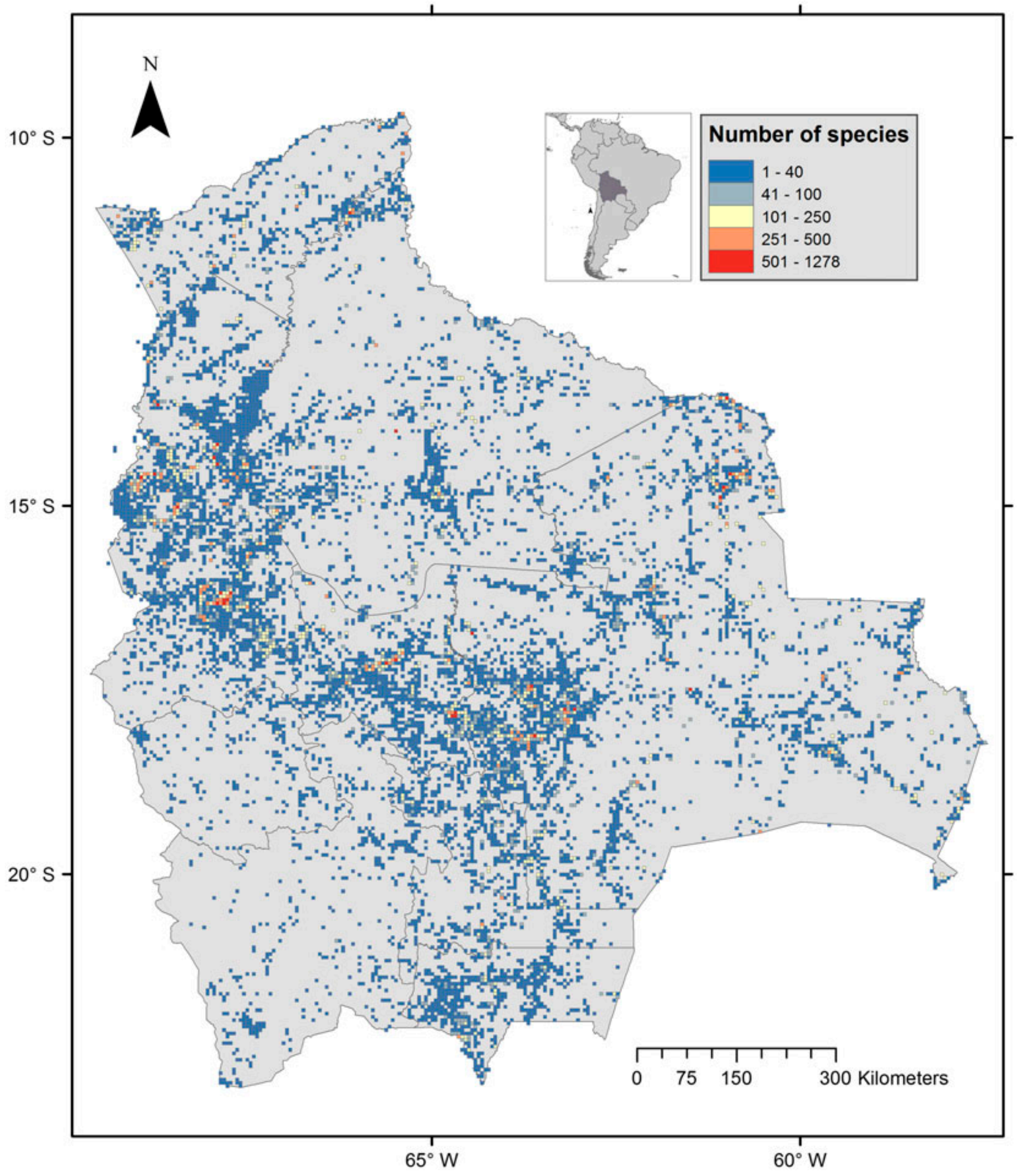

Figure 3. Number of unique species calculated based on a grid of 5 × 5 km^2.

The number of non-consecutive years recorded in each pixel range from 1 to 90 with a mean value of 3 years (Figure 5). The ecoregions with more years recorded are: *Bosques Secos Interandinos* and *Sudoeste de la Amazonia* (Figure 5). The oldest record in our database was collected in the *Gran Chaco* ecoregion in the year 1789 (Figure 6). Ecoregions where collection efforts started early in time are *Gran Chaco*, *Bosque Seco Interandino* and *Sudoeste de la Amazonia*; whereas more recent collection efforts are from the *Prepuna* and *Chaco Serrano*. In general, for all ecoregions, the sampling effort increased in the late 1970s with a marked peak in the number of records and species between 1995 and 2005 (Figure 6).

Discussion

When investigating biodiversity response to global change and human pressure, it is important to make a distinction between 'biodiversity loss' and 'biodiversity alterations' (Pereira, Navarro, and Martins 2012). Determining a baseline and monitoring changes are essential to distinguish the spatial scale of extinction (i.e. from local to global), to identify potential range shifts, and to

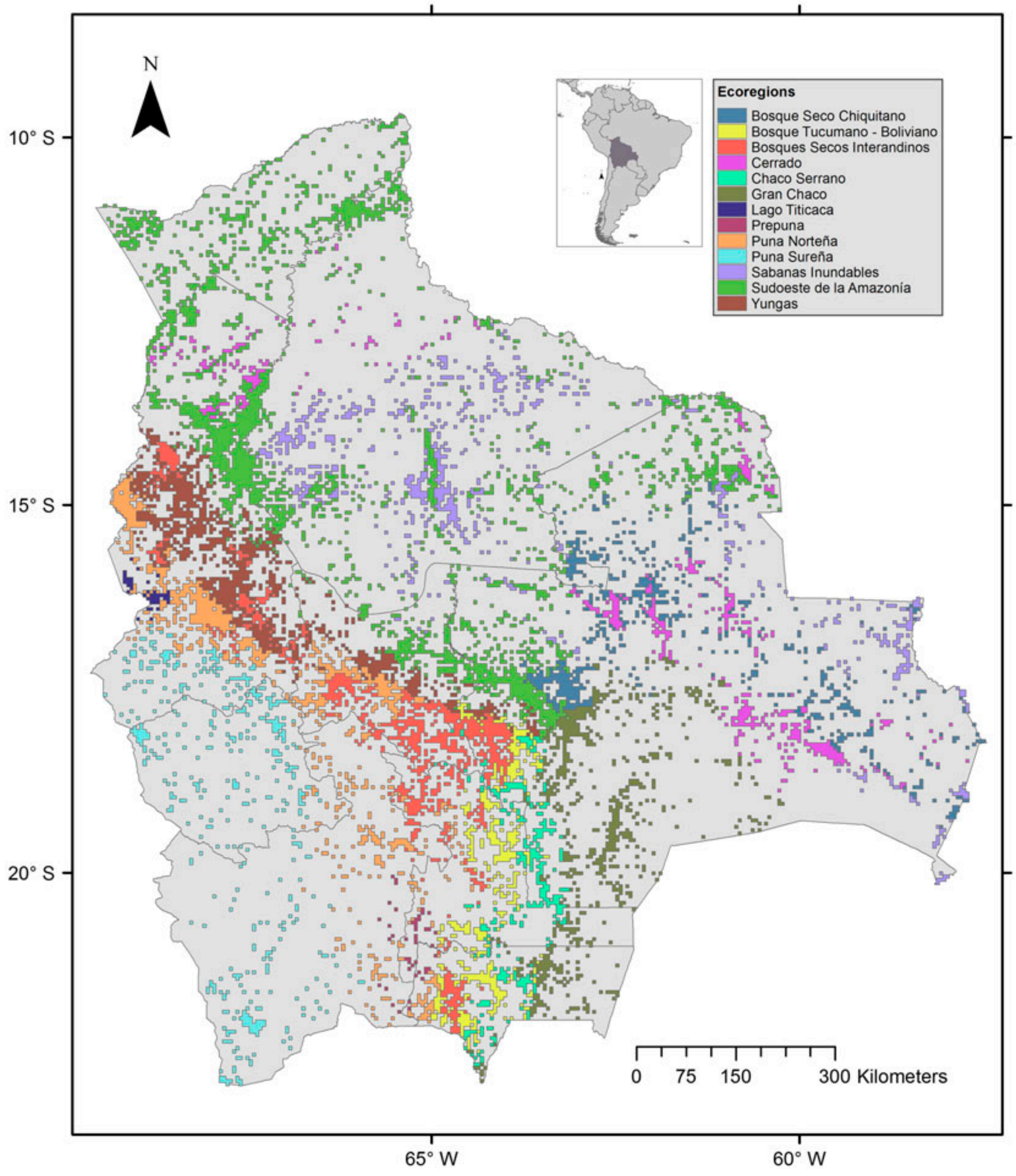

Figure 4. Spatial coverage of biodiversity observations per ecoregion based on a grid of 5 × 5 km^2.

measure changes in communities. In this paper, we provide a state of the art regarding Bolivia's knowledge on biodiversity data and show how collaborative initiatives can help to overcome major resource limitations, and move forward with the creation of a baseline that can serve as the foundation for a biodiversity monitoring strategy in Bolivia.

Our results, by no means are complete. Specific taxonomic groups where our database falls short when compared with previous species accounts are fish, reptiles and bryophytes (Figure 2). As a consequence, this database will require to be constantly and dynamically updated as new information becomes available if the goal is that it serves as a reference against which biodiversity loss and alterations could be monitored. Along these lines, taxonomically accurate and spatially well-distributed data collected at short time intervals are essential to produce reliable scenarios of biodiversity change (Fernandez 2013) that can be used to inform issues such as climate change, food security and public health.

Several limitations preclude biodiversity data integration in Bolivia. They can be grouped under four main non-exclusive categories: dispersion, availability, completeness and alignment. Data dispersion means that

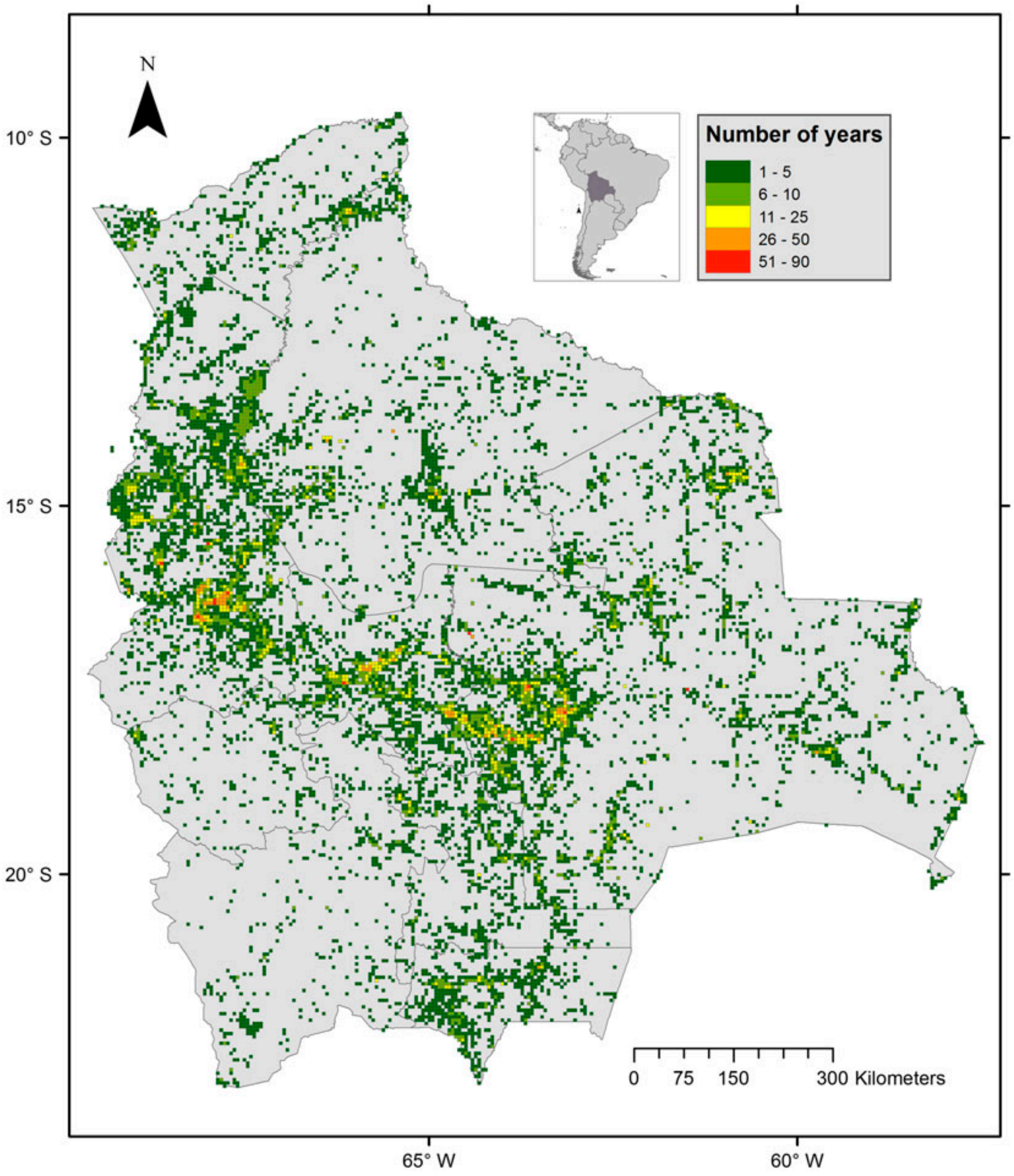

Figure 5. Temporal data coverage of biodiversity observations, calculated based on the number of non-contiguous years represented in each 5 × 5 km^2 cell.

information is dispersed across multiple researchers and research institutions, each with different data standards and data sharing policies. Data availability is related to how much of the biodiversity information is actually readily available for smooth integration into a database system. In most of the cases this is proportional to the amount of information that has been digitised in a museum or herbarium. However, not all the information available in digital form is complete. Old specimens without GPS coordinates are a good example of this, requiring additional work to retrospectively georeference the textual descriptions of the places where they were collected. Finally, if the data is in one place, available and complete, it might still require considerable amount of ontological alignment due to issues that have to do with changes in the taxonomy, differences in database standards and different reference vocabularies.

Despite the limitations mentioned above, the present effort represents the most comprehensive biodiversity database for the country of Bolivia built with one specific goal in mind: the creation of a baseline that can provide an objective basis for directing future collection efforts that can serve to monitor change. With more than half million records, the present database represents a

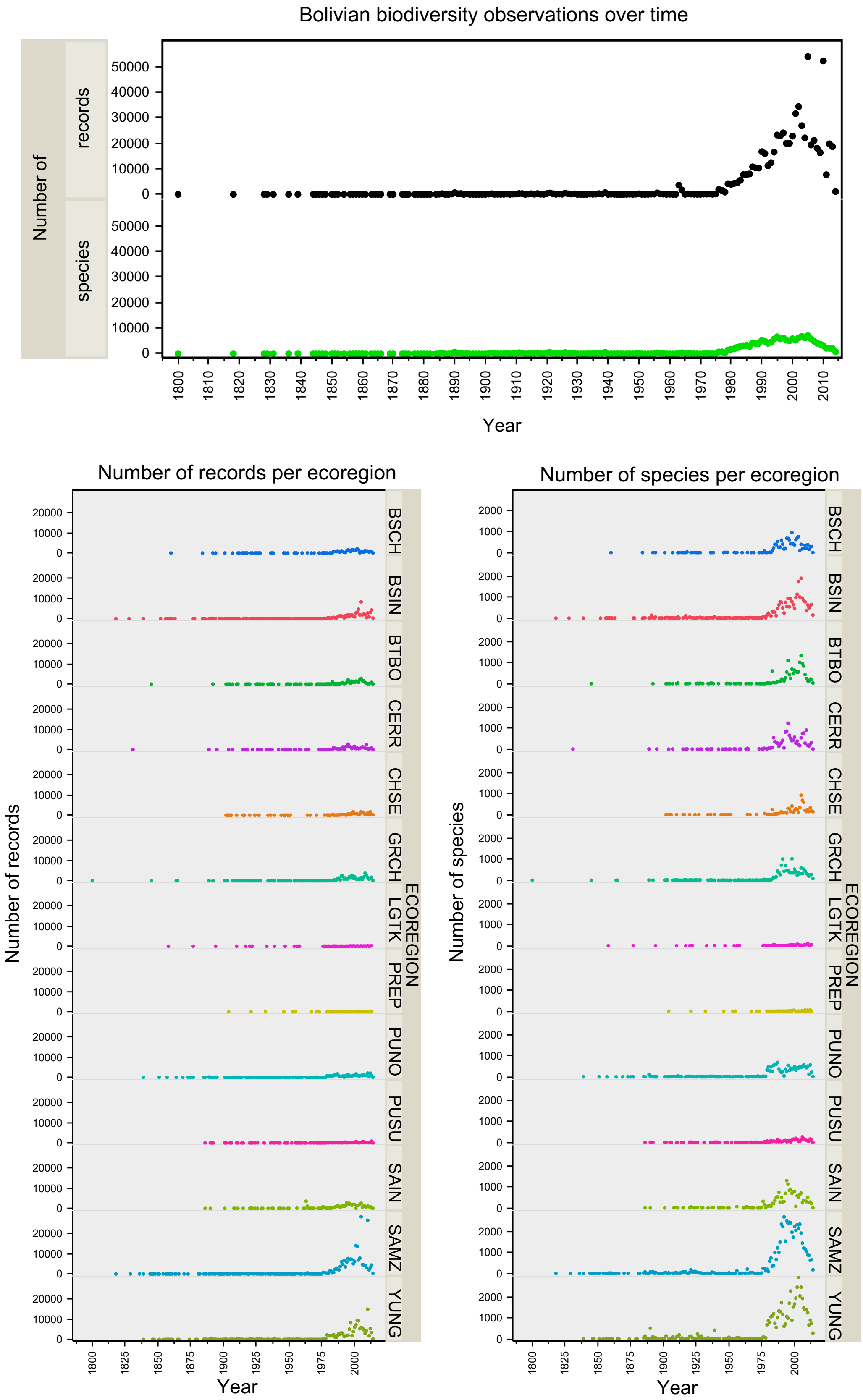

Figure 6. Bolivian biodiversity observations over time. Top panel: total number of records and species over time. Bottom-left and -right panel: number of records and species, respectively, per ecoregion over time.

good approximation of the state of knowledge of biodiversity in Bolivia, corresponding to 92.5% of the species reported in the literature. In this sense, the high representativity of our results provides a good foundation to integrate, analyze and interpret the information in taxonomic, spatial and temporal dimensions.

Taxonomic dimension

Biodiversity research in Bolivia is unevenly distributed across the tree of life. Traditionally, the focus of biodiversity research has been on highly emblematic and charismatic groups such as mammals and birds (e.g. Butchart et al. 2005; Collen et al. 2009). Much less effort has been placed in other groups such as reptiles, amphibians, plants and insects; and the present database for Bolivia is not the exception. The main reason behind this is the lack of financial, technical and human resources enhanced by a worldwide downward trend in available funding for natural history assessments. Biodiversity institutions in Bolivia, despite some isolated efforts, do not have yet a working coordinated strategy and a stable source of funding that allows the long-term storage, maintenance, curation and expansion of biodiversity data holdings and inventories. Infrastructure and technology devoted to the collection and identification of specimens in general is either insufficient or extremely limited and with serious problems in maintenance in the best of the cases. Moreover there are almost no incentives for training local taxonomists in these underrepresented groups, which is worsen by the lack of employment opportunities for young biodiversity researchers inside the country. Finally the lack of a clear national strategy reverberates in the absence of an evaluation mechanism towards a national monitoring strategy that includes these taxonomically underrepresented groups (MMAyA 2014).

Spatial dimension

Current knowledge on biodiversity in Bolivia is spatially biased. With still vast unexplored regions, the scarcity in number of records for the: *Gran Chaco*, *Bosque Seco Chiquitano* and *Sabanas Inundables del Norte* ecoregions (Figure 4) might be attributed to the low accessibility and low human population density of these areas (Ibisch, Chive, et al. 2003; Larrea-Alcázar et al. 2011); for the *Puna Sureña* this might also be explained by the intrinsic low diversity of this ecoregion (Table 1). The relatively high number of records in time and space in the *Yungas* and *Bosques Secos Interandinos* ecoregions might be the result of the research focus that these two regions have received over the years (Ibisch, Gerkmann, et al. 2003). Particularly, the highly diverse *Yungas* ecoregion is also one of the most threatened areas in Bolivia (Kessler 2001), highlighting the importance and opportunity to focus conservation as well as monitoring efforts in the area. Our results also indicate that the *Sudoeste de la Amazonia* and the *Yungas* ecoregions include high levels of biodiversity, which is in line with previous estimates where the two ecoregions and the transition between them are listed as high priority ecosystems due to the high species diversity and high number of endemics, respectively (Araujo et al. 2010; Moraes R. et al. 2014; Müller et al. 2003; Young 2007).

Temporal dimension

Data collection efforts in Bolivia have not been continuous and data shows that there has been a steady decline in the last decade. Our analysis revealed two periods of time where there was a considerable increase in the number of biodiversity observations collected per year. The first one corresponds to the establishment of the Instituto de Ecología in the late 1970s, a pioneer institution in the field of ecology and systematics in Bolivia (Baudoin and España 1997; Ibisch 2003a), followed closely by other research oriented universities and institutions. The second increase (between 1995 and 2005) coincides with the adoption of the CBD by Bolivia in 1994, and the endorsement of the National Strategy for the Conservation of Biodiversity in 2002 (MMAyA 2014). Also as a result of the international funding community focus on biodiversity and biodiversity research, this decade was characterised by high financial support from national and international institutions (FAN 2009). The observed decrease in collection efforts in the last decade might be attributed to two interlinked elements: first, the change of direction and focus in governmental policies from biodiversity to management; and second, the decrease in previously available funding opportunities for biodiversity research in the country.

Biodiversity as a key for development

Bolivia acknowledges the importance of biodiversity for its development. For example, in Bolivia's Poverty Reduction Strategy (IMF 2001), it is stated that 'biodiversity could come to represent an increase of about 10% in the Gross Domestic Product (GDP), if activities are developed in ethnic and ecotourism, mitigation of climate change and biodiversity services relating to biotechnology, ecological products, and others' (IMF 2001). More recently, the country has defined five major axis of action regarding biodiversity, including linking conservation with both human development and economic potential, while highlighting the need to establish, *inter alia*, 'legal, institutional, and political conditions to implement a sustainable model of biodiversity development' (MMAyA 2014). However, realising the full potential of biodiversity for development requires knowledge on the status and trends.

Bolivia identified several limitations to the conservation of biodiversity in its National Biodiversity Strategy and Action Plan (MDSP 2001), being the most important the 'lack of scientific knowledge on natural regeneration, growth rates, population viabilities', the 'absence of a definition of priorities for scientific investigation resulting from a lack of coordination between academics for *in situ* and *ex situ* conservation' and an 'insufficient and deficient transfer of technology' (MDSP 2001). Since then, and as shown in the results, the sampling and monitoring effort, and thus knowledge, have stalled with some exceptions: (1) the Madidi Project, which is a collaboration among the Missouri Botanical Garden (MBG) and the Herbario Nacional de Bolivia (LPB), since 2002 it has been monitoring 50 permanent plots of 1 ha in the *Yungas* ecoregion over an elevation gradient of ~3000 m; (2) the Instituto Boliviano de Investigación Forestal (IBIF), a network of permanent plots distributed across the *Sudoeste de la Amazonia* and *Bosque Seco Chiquitano* ecoregions also generating biodiversity information since 2002; and (3) the Global Observation Research Initiative in Alpine Environments (GLORIA) monitoring the *Puna* with permanent plots since 2006, along an elevational gradient of 1000 m.

To date, no harmonised observation system that delivers regular and timely data on biodiversity change exists in Bolivia that supports all levels of governance, management and decision-making. Despite the progress in biodiversity data integration and mobilisation ((e.g. Centro Geoespacial para la Biodiversidad de Bolivia (CGB; Perotto-Baldivieso et al. 2012)), Centro Digital de Recursos Naturales de Bolivia (CDRNB), it is still difficult for research institutions or even country level research infrastructures to develop, implement and maintain the platforms required to retrieve, share and leverage data investments through collaboration, integration and harmonisation. Only with the establishment of a well-funded national biodiversity monitoring strategy that can leverage individual efforts into a true collaboration and data sharing infrastructure, Bolivia will be able to take full advantage of the new data-intensive science that results from information integration needed to inform urgent pressing issues such as global change.

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