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TOPICAL REVIEW

Environmental research infrastructures are not (yet) ready to address ecosystem conservation challenge

Francisco J Bonet-García[1,*], **Francisco Pando**[2], **María Suárez-Muñoz**[1] and **Javier Cabello**[3]

[1] Department of Botany, Ecology and Plant Physiology, Faculty of Science, University of Córdoba, Córdoba, Spain
[2] Real Jardín Botánico, CSIC, Madrid, Spain
[3] Department of Biology and Geology, Andalusian Center for Monitoring and Assessment Global Change (CAESCG) University of Almería, Almería, Spain
[*] Author to whom any correspondence should be addressed.

E-mail: fjbonet@uco.es

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Abstract

Research infrastructures (RIs) are tools intended to be a fundamental pillar in producing knowledge regarding the functioning of Earth's vital systems. However, it is unclear to what extent these instruments can help to deal with global biodiversity challenges. This paper presents the first assessment of the alignment between the services provided by environmental RIs, and the knowledge requested to address three specific Global Challenges concerning biodiversity loss at a global level: threatened species, alien species and ecosystem conservation. We characterized the specific needs and Subchallenges behind each Global Challenge. We also collected the services provided by 44 relevant environmental RIs in a standardized form. Then, we assessed to what extent those services are useful to address the challenges' needs. Our results show that RIs, as a whole, are better suited to respond to species-related challenges than to challenges involving whole ecosystems. Nevertheless, the overlap among challenges' needs is quite significant. Nearly half of the identified needs are shared between the 'threatened species' and the 'ecosystem conservation' challenges. Most of the assessed RIs work with multiple Earth System's compartments at the same time (e.g. terrestrial + marine, terrestrial + freshwater, etc). Regarding the spatial extent of the studied RIs, most of the ecosystem-based RIs focus on the country scale, while most of the RIs specialized in species-related challenges work at a global scale. Considering the needs required to address the studied challenges, we have found that the RIs assessed in this study do not cover several of them. These gaps comprise complex data combinations that the studied RIs do not provide. Most of these gaps can be attributed to the 'ecosystem conservation' challenge. We consider that RIs were generally built to support pure basic research, which hampers their contribution to combat biodiversity loss. Because of the urgency to address global biodiversity challenges, we suggest adding new functionalities to make RIs work as problem-oriented facilities.

1. Introduction

One of the most outstanding responses provided by science to address *Global Challenges* (Ommen 2006) is the concept of research infrastructure (RI). RIs are any institution, initiative, organization or project which develops, supports and maintains equipment, services, computational resources or domain tools for the benefit of the community at large, beyond the entity's scope, and provides them indefinitely or for an extended period. RIs are enablers for cutting-edge science that respond to societal and scientific challenges (UK Economic and Social Research Council 2020). The European Union (EU) is likely the political entity that is working with the concept of RI more comprehensively (European Commission 2010). But countries outside Europe (e.g. USA, Japan, South Africa, Australia, and China) are also leading the creation of long-term infrastructures providing services to scientists. In addition to the immediate utility of RIs as service providers, the role of RIs in science and society goes beyond the mere provision of services.

They play a fundamental role in making the scientific system more robust, efficient, adaptable, and modern. Training, community articulation, citizen science-oriented activities and outreach, and prototyping are critical contributions of RIs. RIs initiatives in the environmental field have grown significantly in the last decades (e.g. Tzovaras 2016), playing a pivotal role in addressing issues like biodiversity decline, climate change, ocean acidification, sea level rise, and overpopulation. All of them are *Global Challenges* that transcend the spatial and temporal scales of current human activities and that need to be addressed beyond the boundaries of individual scientific disciplines.

Species loss is one of the *Global Challenges* that humanity is facing during this century (Haque Rahman 2019). Current extinction rates are higher than expected from fossil records (Barnosky *et al* 2011, Ceballos *et al* 2015). Moreover, only 2.5% of all known species have been assessed globally under the IUCN system (Stuart *et al* 2010), an extremely low figure, considering that between 16%–33% of all species of vertebrates are globally threatened or endangered and that threats are even greater for tropical regions (Dirzo 2014). Dealing with this issue involves tackling aspects ranging from the urgent protection of critically endangered species to minimizing the drivers underlying biodiversity loss. One of these drivers is the impact of invasive species, which may have far-reaching and harmful effects on the environment and natural resources in the long-term (Scalera *et al* 2012). Besides the ethical reasons calling for efforts to halt this loss of natural heritage, biodiversity enables ecosystems to provide services that humans are dependent on (Worm *et al* 2006, Cardinale *et al* 2012). Nevertheless, to ensure ecosystem services provision, the maintenance of the structure and the function of natural systems arises as an additional challenge. In the coming decades, humanity will have to deal with these interlinked biodiversity loss challenges to sustain the Earth system (Chapin *et al* 2011).

It is hardly disputable that addressing the abovementioned challenges requires the maintenance of an efficient global network of RIs that supports multiple services based on the most up-to-date scientific knowledge. In this paper, we will assess to what extent the current plethora of RIs is ready to address the three main *Global Challenges* related to biodiversity loss: threatened species, invasive species, and ecosystem conservation. The overarching objective of this article is to identify and describe how RIs worldwide are contributing—or could contribute- to addressing biodiversity loss challenges. To fulfil this objective, we first describe the various cross-cutting capabilities needed to address these challenges. Then, we characterize the services provided by the most relevant RIs worldwide. Finally, we assess the degree of alignment between the required capabilities and the services provided by RIs. This manuscript shows the most relevant recommendations derived from the COOP+ project (www.coop-plus.eu/) regarding the performance of RIs as service providers to address biodiversity loss-related Global Challenges. The RIs considered in this article do not constitute an exhaustive list of all environment-related RIs in the world since the resulting list would be too long to manage. Besides, the separation between what is an RI and what is not is not clear-cut. Thus, we restricted ourselves to the most used, well-known RIs. With this approach, we aim to analyze the selected RIs and draw general conclusions on the potential and limitations of RIs in their contribution to addressing biodiversity loss challenges.

2. Methodology

In this study, we aimed to assess the alignment between the *needs* to address biodiversity challenges to the *services* of existing RIs (figure 1). Moreover, we analyzed the interdependence among RIs in providing their *services*. To avoid confusion with common use terms, italics highlight technical terms such as *Global Challenge, Subchallenge, services, needs* and *ways*.

2.1. Characterization of biodiversity loss Global Challenges and needs

We first selected three *Global Challenges* strongly connected to halting biodiversity loss: threatened species, invasive species, and ecosystem conservation (including restoration). These challenges were prioritized among other challenges through workshops and meetings organized within the COOP+ project (Cooperation of Research Infrastructures to address Global Challenges in the environmental field). This project aimed to reinforce the cooperation threads among environmental European RIs and their international counterparts. To characterize these *Global Challenges*, we followed a ‘problem-oriented’ methodology focusing on defining and structuring the problem into several pieces (Bardwell 1991). The breakdown process helps anchor the general description of the challenge to concrete requirements or tasks. Thus, we defined a three-level hierarchy of elements: each *Global Challenge* was broken down into a series of *Subchallenges,* for which we have identified and described the required cross-cutting capabilities or *needs* (i.e., information, data access and interoperability mechanisms, data analysis and visualization, tools and training). The Jaccard similarity index (Jaccard 1912) was used to assess the similarity among *Global Challenges* in terms of their *needs*.

2.2. Characterization of RIs and their services

A selection of relevant RIs was performed with the following premises: (1) focus on biodiversity and the environment, (2) offer *services* to scientific communities, (3) *services* offered permanently

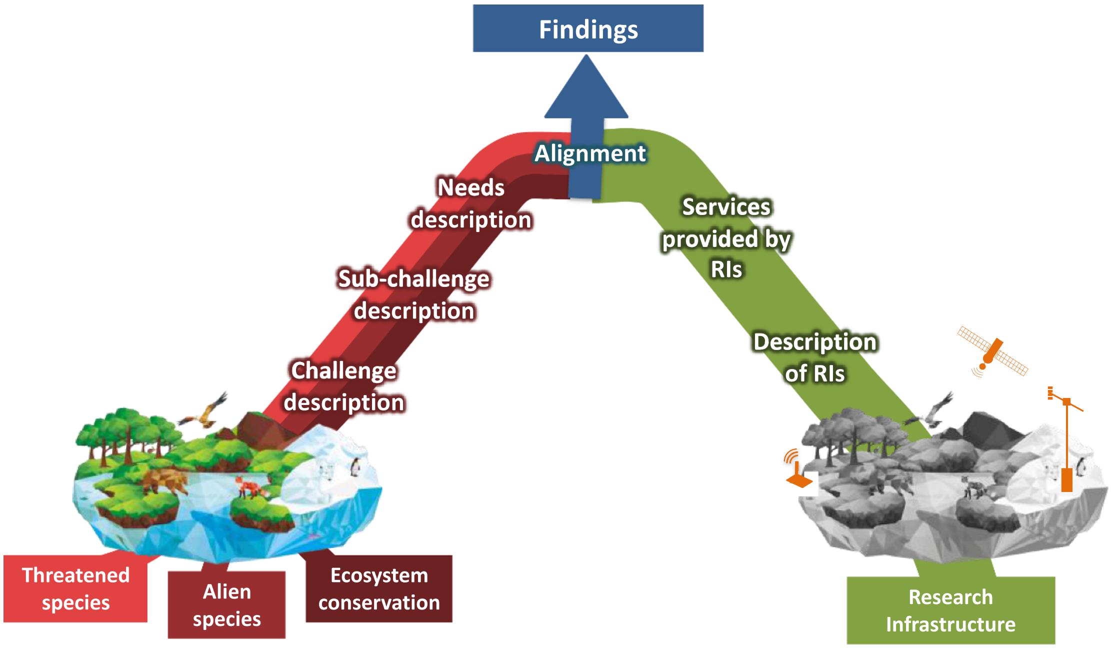

Figure 1. Schematic description of the proposed methodology. The selected biodiversity Global Challenges are described using a problem-oriented approach through three hierarchical steps: challenge description, Subchallenge description and required needs (i.e., information, data access, interoperability mechanisms, capabilities and other requests needed to address the challenge). Research infrastructures are described in parallel using a service provision framework.

(project-like initiatives with well-defined ending dates have been avoided. Since the selected biodiversity *Global Challenges* are multidisciplinary, we selected not only 'pure' biodiversity RIs but also other ones that could provide abiotic information or cyberinfrastructure *services.* Considering these premises, we compiled a comprehensive list of RIs using the following sources: (1) MERIL portal (Mapping of the European Research Infrastructure Landscape https://portal.meril.eu/meril/), an EU-funded project aiming to map all the existing RIs in Europe; (2) COOPEUS (www.coopeus.eu) and COOP+ (www.coop-plus.eu) European projects; (3) US NSF (National Science Foundation) reports, which provided valuable information regarding the RI initiatives in USA (U.S. National Science Foundation 2009); (4) in Australia (National Research Infrastructure for Australia 2018); and (5) in Europe (Group of Senior Officials on Global Research Infrastructures—GSO 2017). The information gathered from these sources was complemented by minor sources and personal communications. Selected RIs were characterized through the variables described in table 1.

Information and data about how RIs operate and the scope and coverage of their services were gathered from the respective RIs websites, reports and catalogues of services. We define RI *services* as resources, processes or structural elements that are provided by RIs such as documented datasets, computational capacity, data storage or facilities to carry out research. We checked the functionality of these services, not considering the mere citation of the service or the plans to implement it as a sign of an actual running service. We used *services* provided by RIs as the key elements to assess how they align with or respond to the *needs* of each Global Challenge. We classified the identified services into the following categories:

- Data services: data products created by RIs can be included in this type
- Supporting services: those services that are needed to create other services or products. E.g. mapping, data hosting, and computational power.
- Outreach services: some RIs can help to disseminate products and other services created by users. E.g. networking, and support to organize meetings.

2.3. Alignment between biodiversity challenges needs and RIsservices

After the mapping of *needs* to address biodiversity *Global Challenges* and *services* provided by RIs, we paired the *services* identified with the *needs* they address (figure 1). We based the alignment between the RIs capabilities and the challenge's requirements on internal discussions and semi-structured interviews with biodiversity experts involved in the COOP+ project (see table 1 in supplementary material for details). The linkages connecting *needs* and *services* to address challenges followed complex paths: different RIs may provide analogous *services, services* may respond to more than one *need, Subchallenges* may share *needs*, and challenges may have some *Subchallenges* in common. We defined the term *way* as 'the combination of a RI service

Table 1. List of variables used to characterize the selected RIs.

Variable	Description
Name	Official name of the RI
Acronym	Acronym of the RI.
Description	Short text describing the most relevant features of the RI.
Thematic domain	Main thematic area or topic: abiotic, biodiversity, biogeochemistry, ecosystem or multi-thematic if the RI is focused on two or more of the above-listed themes, or it is not focused on any specific theme.
Earth system's compartment	Main Earth compartment where the RI focuses: atmosphere, marine, terrestrial, multi-compartment if the RI is focused on two or more of the above-listed compartments, or it is not focused on any specific compartment.
Spatial extent	Maximum spatial coverage of the *services* provided by each RI.
RI type	Type of RI in terms of their core activity: • Species-centered': the taxon is the main entry point to the *services* provided by the RI. Systematic gathering of data points is not a requirement. Data is usually available as points or species web pages. • System-centred': the data unit is a collection of datasets gathered systematically, on spatial and temporal dimensions, on species or other environmental parameters. Data are often presented as spatial layers or multi-thematic databases. • Cyberinfrastructures: these RIs supply facilities to store and analyze data.
Webpage	Official website for each RI.

addressing a *need* to respond to a *Subchallenge* in a *Global Challenge*'. For instance, if a service addresses a *need* identified for two *Subchallenges* and one of these *Subchallenges* is present in two *Global Challenges*, then the RI responds to *Global Challenges* in three *ways* through that service. Thus, the concept of *way* arises when each *need* is linked to one or several *services* provided by RIs. This many-to-many relationship allows us to analyze the extent to which the selected RIs can address biodiversity *Global Challenges*. To identify all *ways*, the main features of RIs, their *services*, and the hierarchy of challenges (*Global Challenges, Subchallenges, needs*), we have built a relational database containing all these elements (figure 1 in supplementary material). This database is based on two entities: *Global Challenges* and RIs. These concepts were linked through tables that contained the list of *Subchallenges* per *Global Challenge*, the list of *needs* per *Subchallenge*, the variables describing each RIs, the services provided by each RI and the interdependency among *Global Challenges* and RIs.

A critical part of our analysis was establishing the *services* that meaningfully contribute to responding to or ameliorating each identified *need*. Through internal discussions in the framework of the COOP+ project and consultations with researchers working on biodiversity loss, we agreed on a proposal for the *need-to-service mapping*. We are aware that the list of connections between *needs* and *services* may not be exhaustive due to the complexity and heterogeneity of specific cases behind each *need*. Nevertheless, we aimed to get a first step towards the deep analysis of RIs *services* alignment with *Global Challenges needs* rather than proposing a closed list of need-services assignments.

2.4. Relationships and interdependencies among RIs in providing services

RIs are rarely self-containing entities that provide their services in isolation. Hence, we also investigated inter-RIs support to provide services. We analyzed how RIs serve other RIs and how RIs rely on other RIs for them to provide their services. To deal with this task, we formalized the RI–RI connections through the concept of *links* according to the following two categories: the first category refers to a situation when an RI provides data to another RI, and the second category refers to a situation when an RI provides methods, tools, ICT, and, in general, all non-data services to another RI.

3. Results

3.1. Biodiversity Global Challenges, Subchallenges and specific needs

We have analyzed the structure of the three selected biodiversity loss challenges following a three-level hierarchy: *Global Challenge, Subchallenges, needs*. We have identified 41 *needs* among the three selected *Global Challenges* (figure 2). Most of them (35) were involved in the 'threatened species' challenge (Th), while 26 involved in the 'ecosystem conservation' challenge (Ec). Finally, 20 *needs* can be attributed to the 'invasive species' challenge (In). The overlapping among challenges' *needs* was quite relevant, both among pairs of challenges and considering all three challenges together. Ten *needs* were shared between the three *Global Challenges* (Th-In-Ec). Among pairs of challenges, 12 *needs* were shared between 'threatened species' and 'ecosystem conservation' (Th-Ec) and 8 between the 'threatened

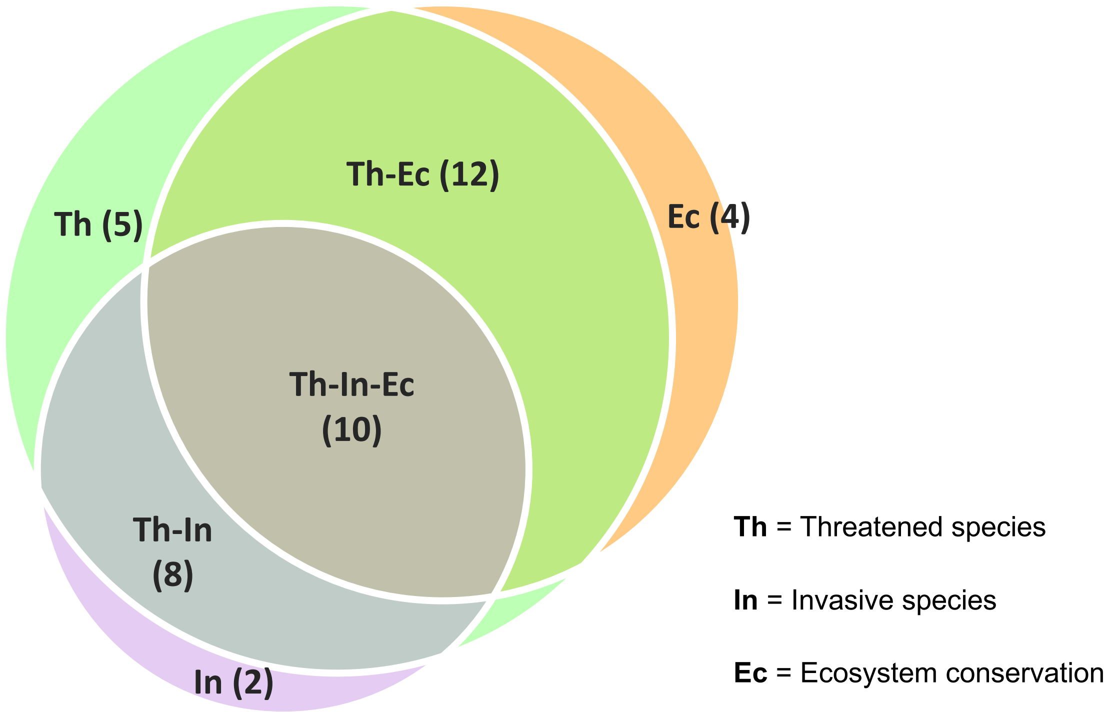

Figure 2. Venn chart showing the overlaps among challenges' needs.

species' and 'invasive species', while the pair 'invasive species' and 'ecosystem conservation' had no *need* in common. The highest similarity among challenges was found between 'ecosystem conservation' and the 'threatened species' according to the Jaccard similarity index. The smallest similarity was found between the 'invasive species' and the 'ecosystem conservation' challenges. The full breakdown of *Challenges, Subchallenges* and *needs* and the Jaccard index comparison is shown in detail in tables 2–5 of the supplementary material.

3.2. Environmental RIs and their services

We have identified and characterized 44 initiatives worldwide that fit into the definition of RI (figure 3). Thirty-one out of them worked on biodiversity or ecosystem thematic areas. Only 4 out of 44 focused on the biogeochemistry domain, and only two worked on the abiotic domain. Eight out of 44 focused their activity on two or more thematic areas. The most frequent case comprises RIs working on ecosystems, using a multi-domain approach at a country level (nine RIs: most national LTER networks,SAEON, CERN, etc).[4] RIs working on biodiversity at the species level using a multi-domain approach at a global extent are also quite common in our list (eight RIs: GBIF, TDWG, IUCN, BHL, CoL, EoL, iNaturalist, IPNI[5]). Interestingly, six RIs were working with a multi-thematic view using a multi-domain approach at a global extent (e.g. NOAA, NASA, GEOSS[6], Copernicus, D4Science, DataOne). On the other end of the distribution, few RIs were focused on abiotic variables or biogeochemistry in any domain at any spatial extent (EMSO, WorldClim, TERENO, ICOS[7]). It was also remarkable that many RIs operating on ecosystems, work on several Earth system domains at any spatial extent. Full details of selected RIs can be found in table 6 of the supplementary material.

We identified a total of 276 *services* among the selected RIs that could be potentially useful in addressing *Global Challenges*. Out of these 276, 58% can be considered data services and 36% supporting services. Finally, 6% off all the identified services can be labelled as outreach services. The complete list of services identified is shown in table 7 of the supplementary material.

[4] LTER: Long Term Ecological Research; SAEON: South African Environmental Observation Network; CERN: European Organization for Nuclear Research.

[5] GBIF: Global Biodiversity Information Facility; TDWG: Taxonomic Databases Working Group; IUCN: International Union for Conservation of Nature; BHL: Biodiversity Heritage Library; CoL: Catalogue of Life; EoL: Encyclopedia of Life; IPNI: International Plant Names Index.

[6] NOAA: National Oceanic and Atmospheric Administration; NASA: National Aeronautics and Space Administration; GEOSS: Global Earth Observation System of Systems.

[7] EMSO: European Multidisciplinary Seafloor and water column Observatory; TERENO: TERrestrial ENvironmental Observatories; ICOS: Integrated Carbon Observation System

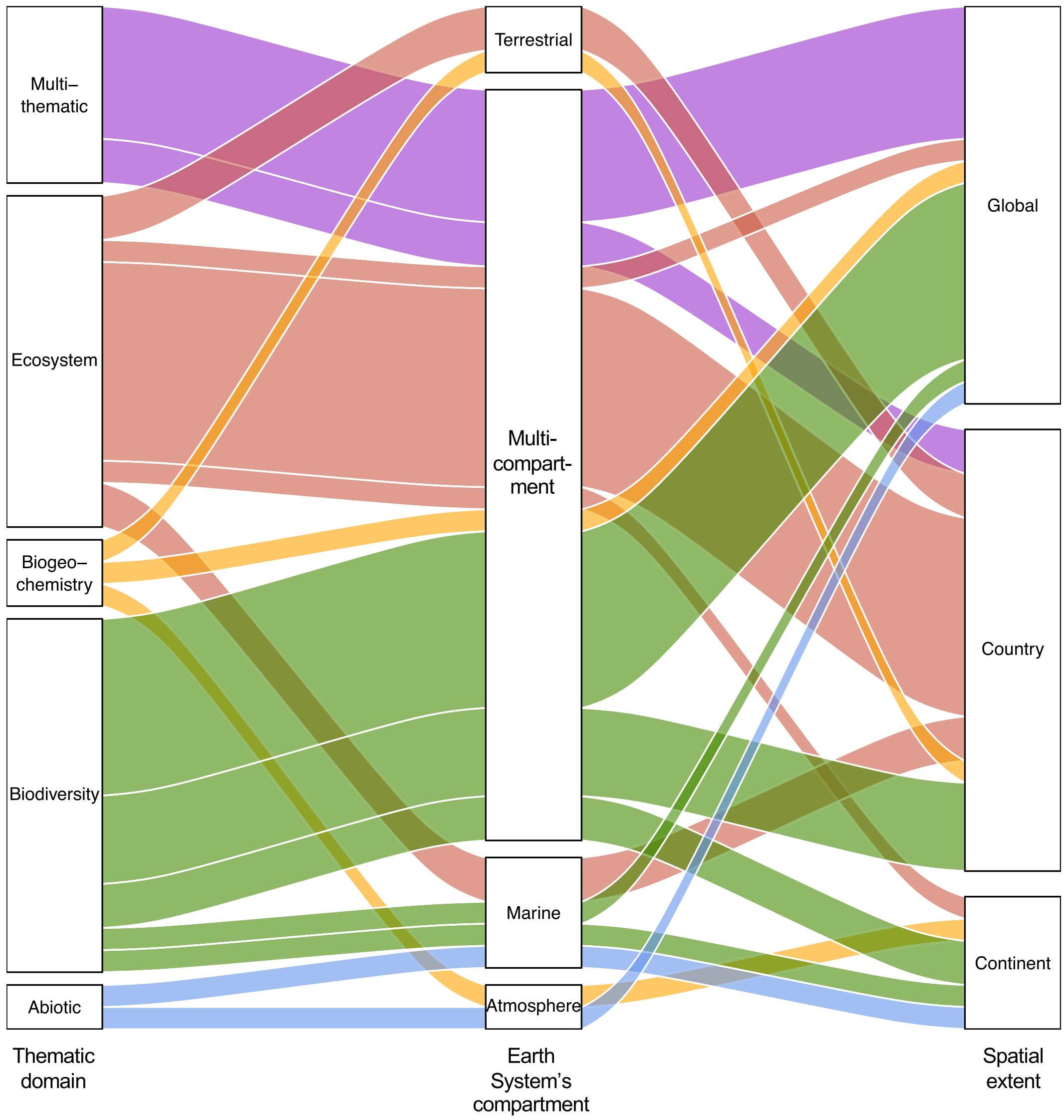

Figure 3. Characterization of selected RIs in terms of their thematic domain, Earth system's compartment and spatial extent.

3.3. Alignment of needs and services

The pairing of *services* provided by RIs and the *needs* of *Global Challenges* results in a network of entities and connections which can be described at two levels: *needs* vs. *services* and *Global Challenges* vs. RIs. Table 2 shows the relationship between *needs* and *services*. Out of 41 *needs*, 7 cannot be addressed by any *service*. These *needs* were mainly related to the ecosystem conservation challenge and its interactions with the other challenges. On the other tail of the distribution, 8 *needs* were 'covered' by more than eight services provided by several RIs. Most of these dealt with *needs* specific to the threatened species challenge.

Figure 4 shows how challenges and RIs broadly relate to each other. Since each challenge was hierarchically linked to several *needs*, and each RI provided several *services*, it was possible to depict the number of *ways* that link challenges with RIs. A total of 745 *ways* were identified. More than half of the mapped *ways* (55%) referred to the threatened species challenge, 26% of the *ways* were related to the ecosystem conservation challenge and only 19% specifically dealt with the invasive species challenge. On the RIs side, many *ways* involve RIs within the cluster of LTER (including national networks, as well as continental initiatives such as LTER Europe). LTER is involved in 23% of the total identified *ways*. CONABIO was the second most relevant RI from this point of view, counting 11% of *ways*. ALA and National Ecological Observatory Network (NEON) provided 10% and 7% of all *ways*, respectively. Furthermore, if we focus on those 'system-centred' RIs that predominantly provide environmental variables data (LTER, SAEON, NEON, TERN, Integrated Marine Observing System (IMOS), TERENO, Ocean Networks Canada (ONC), EMSO and ICOS), we observe that these account for 40% of the identified *ways*. Besides, the cluster of RIs able to provide global products from remote sensing (NOAA, Copernicus

Table 2. Number of RI services identified for each need. The table also indicates Global Challenge to which each service is linked (Th: threatened species, In: invasive species, Ec: ecosystem conservation).

Need	Nr. of services	Global Challenge
Common eScience infrastructure for biodiversity research	19	Th-In-Ec
Time series showing nonnon-climaticiotic data.	16	Th-In-Ec
Datasets describing species abundance	14	Th-In-Ec
Spatial and temporal distribution of taxa	12	Th-In
Datasets describing changes in presence/absence and cover of species (general pool of species)	10	Th-In
Spatial and temporal distribution of past/present climate data	10	Th-In-Ec
Accurate identification of species	9	Th-In
Accurate identification of habitats	9	Th-In-Ec
Introduced ranges of invasive species	7	In
Datasets describing pollution (nitrates, phosphorous, heavy metals, .)	7	Th-Ec
Spatial and temporal distribution of forecasted climate data	7	Th-Ec
Datasets describing functional traits of species	7	Th-In
Classification for habitats and ecosystems	7	Th-In-Ec
Data to describe the degree of (meta)population fragmentation	6	Th
Time series showing age structure and demographic features of target populations	6	Th
Datasets describing changes in phenology (both in the greenness of the canopy and reproductive attributes)	6	Th-Ec
Detecting invasive species	6	Th-In-Ec
Datasets describing changes in structure and composition (shrub encroachment, weed encroachment, falling trees, .)	5	Th-Ec
Ecosystem functioning and time series	5	Th-Ec
Taxonomical backbone for species	5	Th-In
Habitat functioning and time series	5	Th-In-Ec
Identifying potential environmental impacts	5	Th-In-Ec
Habitat structure and time series	5	Th-In-Ec
Datasets describing changes in the presence/absence of key species (pollinators, dispersants, .)	4	Ec
Datasets describing habitat management and conservation	4	Th-Ec
Datasets describing soil erosion/flooding	4	Th-Ec
Habitat distributions and time series	4	Th-In
Datasets describing fires	3	Th-Ec
Ecosystem structure and time series	3	Th-Ec
Data standards (ISO, INSPIRE, W3C, TDWG, etc)	3	Th-In-Ec
Habitat connectivity data and time series	2	Th
Ecosystems distributions and time series	2	Th-Ec
Time series to describe the genetic diversity of (meta)populations	1	Th
Datasets describing the interactions of species	1	Th-In-Ec
Accurate identification of ecosystems	0	Ec
Modelling ecosystem services	0	Ec
Mapping proxy data of ecosystem services	0	Ec
IAS introduction pathways	0	In
Models of eco-evolutionary dynamics	0	Th
Ecosystem connectivity data and time series	0	Th-Ec
Time series showing real 'absence of presence' data	0	Th-In-Ec

and NASA) contribute with 10% of all the identified *ways*. Conversely, those RIs devoted to providing cyberinfrastructures (DataOne, Nectar, LifeWatch, PANGAEA) counts for only 5% of all the identified *ways*. LTER was the biggest single contributor of *ways* for all the Global Challenges. It accounted for 23% of the *ways* regarding the threatened species challenge, 15% of the invasive species and 27% of the ecosystem conservation. CONABIO and ALA are the second and third contributors of *ways* for all Global Challenges (table 8 in supplementary material).

3.4. Relationships and dependencies among RIs

RIs were also analyzed in terms of the interdependence among them. We found that 21 out of the 44 RIs scrutinized were connected through a total of 28 *links*. As shown in figure 5, half of these linkages focus on 'species-centered' RIs (e.g. Catalog of Life, Encyclopedia of Life, GBIF, iDigBio, IPNI, TDWG). It is remarkable the scarcity (18%) of relationships involving 'system-centred' RIs (LTER, NEON, TERN.). Table 9 in the supplementary material shows all the relationships among RIs.

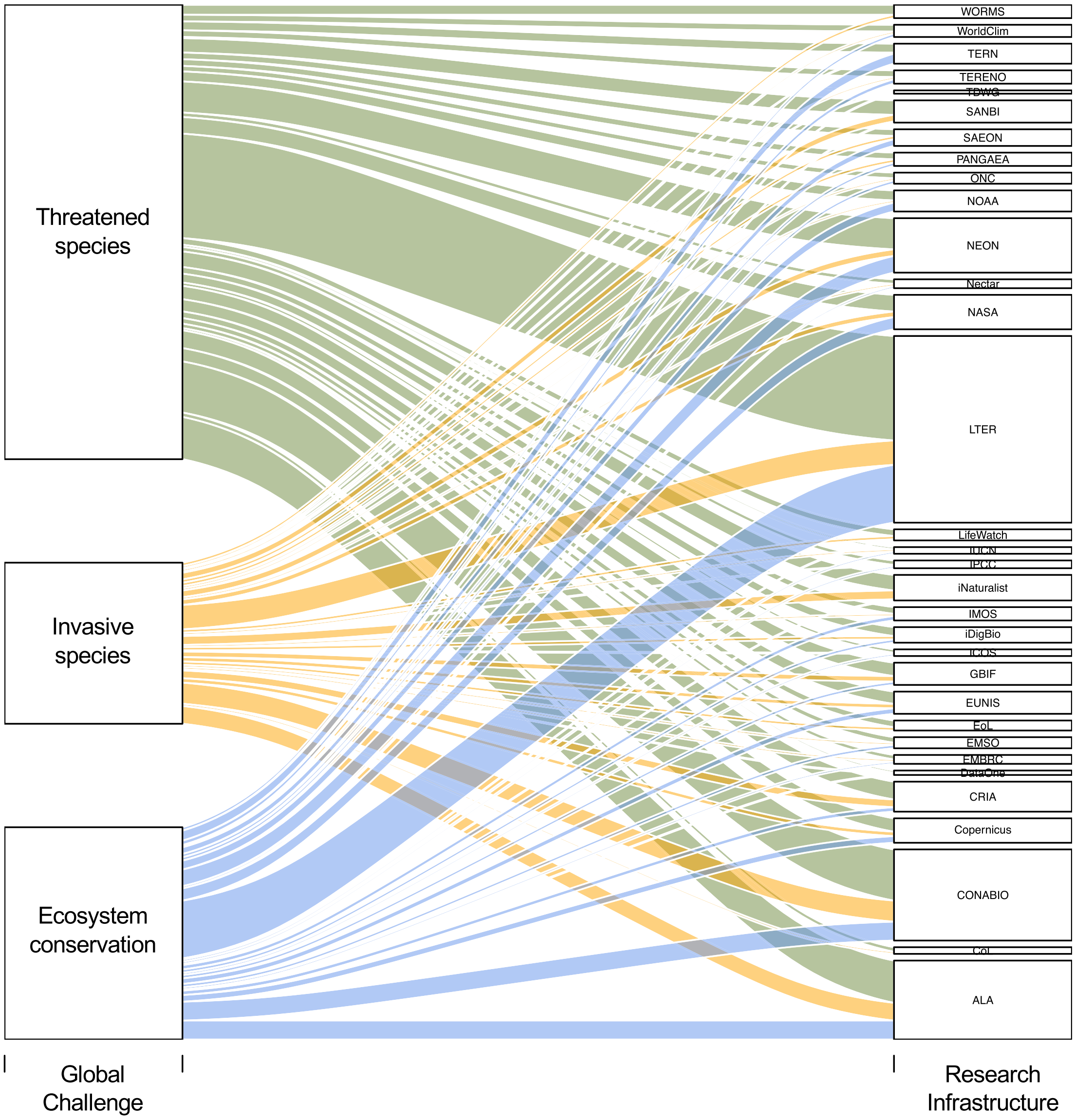

Figure 4. Sankey diagram showing the links between the three selected Global Challenges and the assessed RIs. The width of the lines is proportional to the number of ways (i.e. the combination of a RI service addressing a need required to respond to a Sub-Challenge in a challenge) that connect both concepts.

All 'system-centred' RIs displayed a percentage of *ways* higher than the percentage of *links* with other RIs (figure 6). Nevertheless, 6 out of 12 RIs labelled as 'species-centred' showed a percentage of *ways* smaller than the percentage of *links* with other RIs, but those RIs are national (extending the concept to the EU, in the case of EUNIS) in scope and their services tackle areas beyond 'data-services'. RIs combining 'species-' and 'system-centred' services (EUNIS, SANBI, ALA, CONABIO) provided a mixed pattern. iNaturalist seemed a special case since it is a 'species-centred' global initiative.

4. Discussion

In this study, we obtained insights on the capacity of the identified RI network to address global biodiversity challenges. Our analysis revealed that RIs are not yet fully able to respond to the *needs* impose by these *Global Challenges* worldwide. More in detail, we found that RIs are better suited to respond to species-related challenges than ecosystem-related ones. RIs were built as scientific initiatives to increase our knowledge about Earth System's compartments rather than focusing on environmental challenges such as biodiversity loss. Often their primary goal is pure basic research. Although the outcome of such research can potentially be applied to real-life situations, more work is needed to address complex environmental problems like those described here. To overcome this mismatch between RIs and *Global Challenges*, we suggest adding new functionalities within RIs to make them work as problem-oriented facilities. Such alignment could be done by strengthening the linkages of RIs with policymakers and managers at different spatial scales.

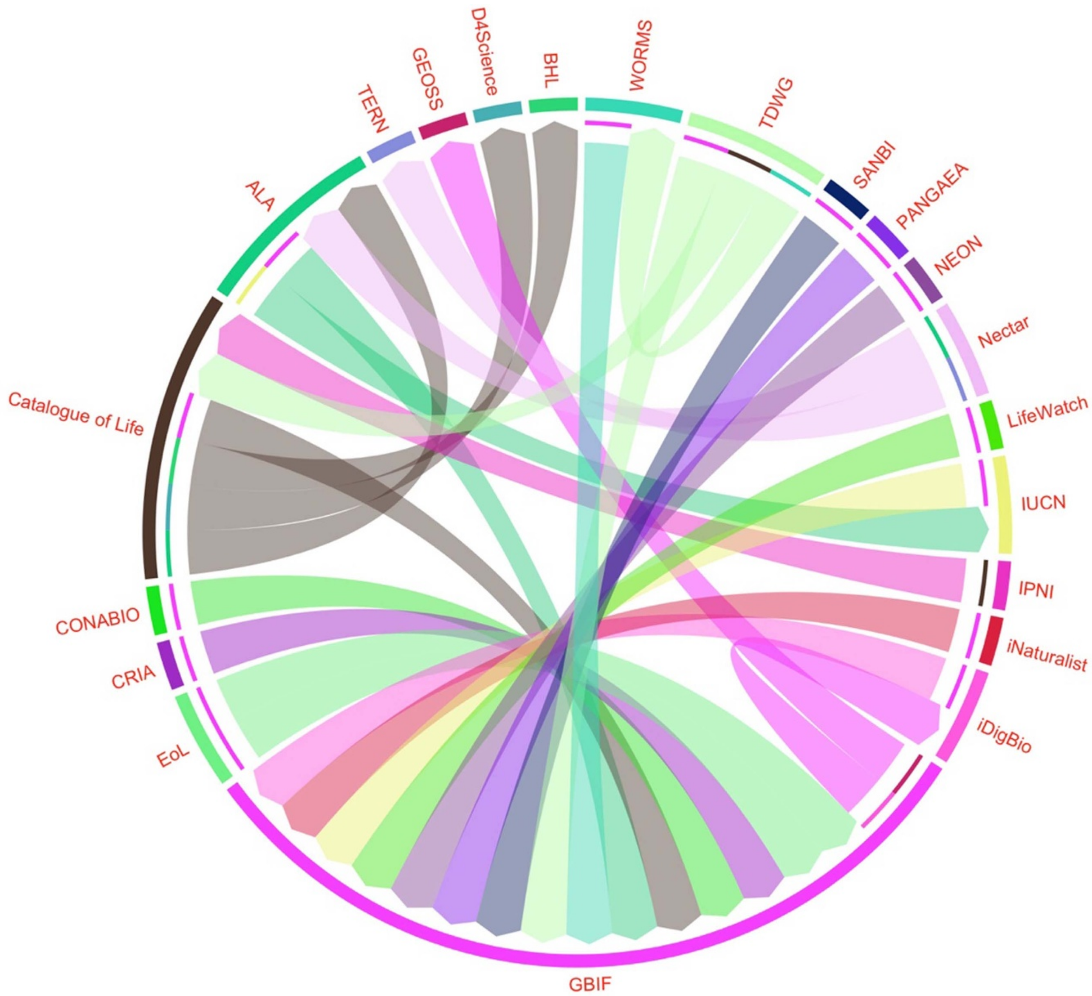

Figure 5. Relationships and interdependencies among RIs. The figure shows 22 out of the 44 studied RIs use other RIs services or whose services are used by other RIs. The inner connectors go from the provider RI to the consumer RI, with color referring to the provider RI.

Delving into the gaps between RIs and biodiversity loss global challenges, we found several *needs* that are not covered by any of the identified *services*. These gaps (figure 4) comprise complex data combinations that RIs do not easily provide. Most of these gaps can be assigned to the ecosystem conservation challenge (e.g. 'Ecosystem connectivity data and time series', 'Modelling ecosystem services', 'Ecosystem distribution and time series'). We consider that the studied RIs are not yet able to provide *services* potentially useful to address the complexity inherent to the conservation of ecosystems in a comprehensive way. This result is consistent with the history of species and ecosystem conservation. Scientists started to be concerned about the conservation status of species, and then their thoughts, methods and results transcended this idea to embrace the concept of ecosystem conservation (van Dykem 2008, Meine 2010, Mace 2014). Nevertheless, there are missing *needs* related to species, as it is the case of time series showing the 'absence of presence' data. This is a particular problem since it is almost impossible to confirm the species' absence (Mackenzie 2005), and therefore it is not easy for RIs to handle this information.

The number of *needs* about more than one challenge is remarkable (see section 3.1). Not surprisingly, the studied Global Challenges share most *needs*, as they are interdependent. They all require a set of *needs* related to a taxonomic background (species or ecosystems). Moreover, some *needs* were related to the structure of the respective biological entity (e.g. spatial distribution patterns) and the characterization of the functioning of the target entity (e.g. species phenology, primary production, etc). Finally, some *needs* point to identifying risks or impacts affecting species or ecosystems. These commonalities between Global Challenges may be the basis for standards and protocols to improve the interoperability and efficiency among RIs. In the case of invasive species, this Global Challenge seems more isolated than the other two, which could be due to its requirement for specific information (Introduction pathways, Introduced ranges, etc).

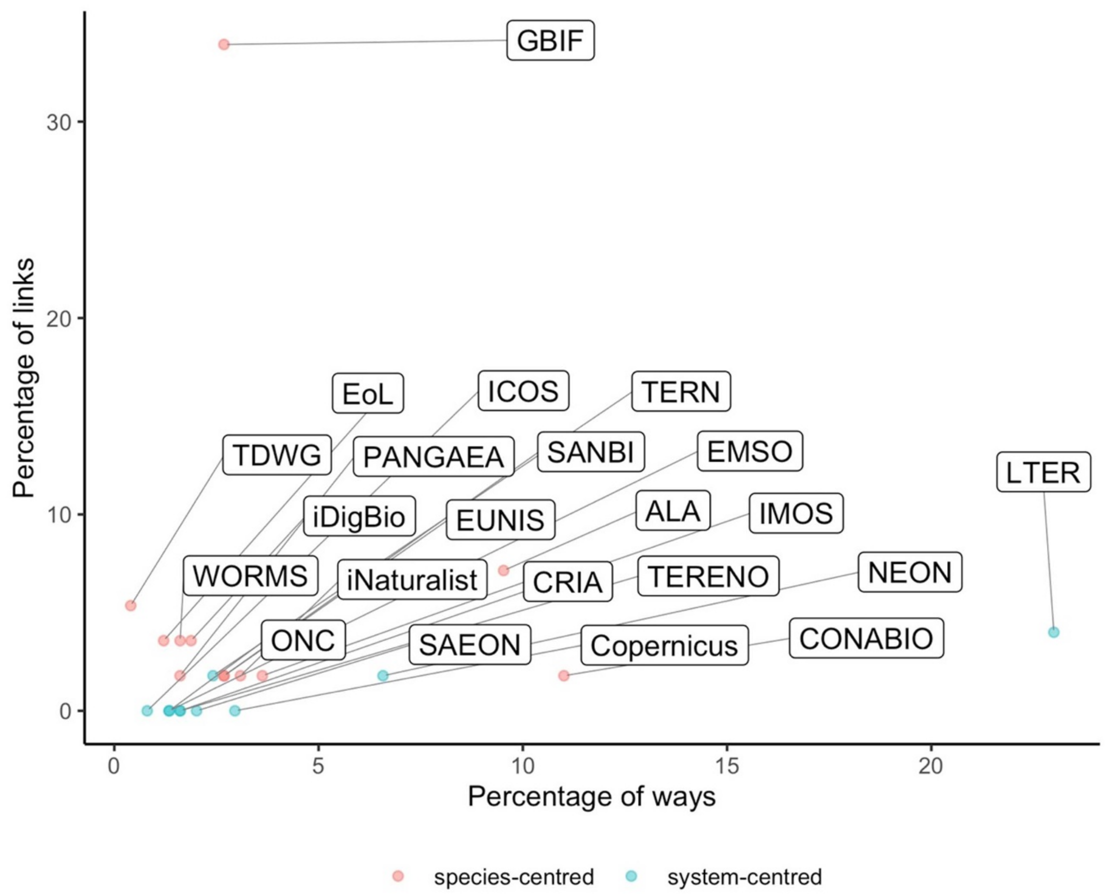

Figure 6. RIs connection with needs and challenges (ways, as described in section 2.3), and links with other RIs (as shown in figure 5). *x*-axis represents the percentage of ways provided by each RI; *y*-axis represents the percentage of links where each RI is involved.

Our findings show that RIs, as a whole, are better suited to respond to species-related challenges than ecosystem-related ones. This is supported by the fact that most identified *ways* refer to the threatened species challenge. Biodiversity RIs have been working on this challenge for many years. Interestingly, the ecosystem conservation challenge also has many *ways* despite being the challenge containing more 'uncovered' *needs*. This can be explained because some of the *needs* of this challenge are also shared with the threatened species challenge.

Most biodiversity (i.e. species-level) RIs focus on the global spatial scale. This could be explained because the species-level approach has a long tradition in conservation science. Building global-scale RIs dealing with ecosystem conservation (system-centered approach) would require, among other things, a sort of classification of ecosystem types (Keith 2015), which is very difficult to create. This could explain why most global initiatives are purely focused on the species-level approach (e.g. GBIF, Encyclopedia of Life, etc), while the initiatives focused on ecosystem research (e.g. LTER, TERN, CERN, etc) tend to be national in scope.

We found that those 'system-centred' RIs that operate at a national level (e.g. LTER, NEON, TERN, CERN, etc) are dominant regarding their capability to provide *ways* (figure 6). These results may be explained by the fact that ecosystem conservation is deeply connected to land use policies, thus being a concern of administrations and governments. Differently, those RIs considered cyberinfrastructures (e.g. DataONE, LifeWatch, Nectar, etc) can provide a few *ways* to address the studied *Global Challenges.* This may be explained because the new techniques and methods provided by these cyberinfrastructures have not yet been adopted by most of the 'system-centred' RIs. This gap reveals as well the still weak interplay among RIs. Since iNaturalist is a citizen science platform serving species occurrences, it is unique among the analyzed RIs, and it does not fit well in any of the RI groups discussed in this paragraph.

The degree of interdependence among RIs is the last component considered in this study. Counting *ways* provides only one perspective of the picture. The analysis of the interdependence among RIs yielded other interesting findings (figure 6). Most of the relationships among RIs involve those considered 'species-centred' RIs (e.g. GBIF, TDWG, EoL, etc). Different patterns were observed between the 'species-centred' RIs and the 'system-centred' ones. The first group seems to render a smaller number of *ways* concerning the second group, whereas the 'species-centred' cluster shows a larger number of connections and much fewer *ways* (figure 6). Two interesting characteristics can be identified in how 'species-centred' RIs interconnect. Firstly, there is a clear specialization in what the different RIs provide and how others use the services of some RIs as input to produce other *services*. The second dimension worth mentioning here is the global character of these interconnections. The mentioned RIs are global players as they constitute global communities and provide *services* at the global level. In contrast, RIs focused on ecosystem monitoring present a different picture: rather than constituting a group of interconnecting RIs, each performing different functions, these RIs constitute a group of fairly similar RIs providing similar *services,* each of them on its respective country or territory, with little integration among them and with the 'species-centred' cluster.

The above-described scenario could be an intrinsic consequence of the connection to the territory of the 'system-centred' RIs, or just an indicator of a fragmented RI landscape. We argue that both explanations are plausible. First, the data gathered on a 'system-centred' RI are intrinsically more applicable and relevant at a local scale. The detailed information collected at this scale must be generalized or simplified for integration with other datasets at scales. For example, a given user looking for the distribution area of a species is not interested in the detailed information collected at a local scale. He/she needs to translate the locally collected data into more generalist information: occurrence data. It is, therefore, necessary to create a conceptual crosswalk to 'reduce the dimensionality' and to scale up the information towards a global scale. This process could be assisted by conceptual frameworks such as the essential biodiversity variables (Pereira *et al* 2013). Besides, this scaling-up process is even more complex when dealing with the ecosystem conservation challenge. Second, it seems that 'system-centred' RIs have paid little attention to making their data interoperable among themselves and with the global data aggregators (Pando and Bonet 2019). They have invested resources in designing harmonized monitoring methods, but their datasets are not yet interoperable. Perhaps cyberinfrastructures (e.g. LifeWatch, NECTAR, DataONE, etc) could play a role in helping 'system-centred' RIs to increase their interoperability.

As mentioned in the Introduction, in this study we do not intended to consider every existing RI. We aimed for a representative analysis of RIs and their connection to Global Challenges' needs, and from that, be able to produce useful recommendations that can be applied in a broad sense.

5. Conclusions

In conclusion, we found that RIs are key players in addressing global biodiversity challenges since they provide unique services. However, we have identified areas where there is still potential for improvement. We elaborate on this idea in the following items:

1. Our results show how environmental RIs are key in providing a scientific base to address three selected *Global Challenges* (threatened species, invasive species and ecosystem conservation). The selected challenges show considerable overlap in their *needs* and, consequently, the type of *services* required to address them. These commonalities may underpin joint development and adoption of standards and protocols to improve interoperability and efficiency among RIs.
2. No single RI can respond by itself to the different *Sub-Challenges* and associated *needs* required to address (the identified) biodiversity Global Challenges. So far, cooperation focuses on methods (standards, procedures), which fall short of what could be achieved by sharing resources, building common action plans, co-locating monitoring sites, etc.
3. There is a plethora of RIs that address the *needs* connecting to biodiversity *Global Challenges* in several *ways*. The coverage RIs provide in this regard is patchy, and gaps and overlaps -or at least parallel approaches- are observed (e.g. between ecology and biodiversity communities).
4. Environmental RIs constitute not just a landscape of entities living together but an actual ecosystem with plenty of interactions and interdependencies. These interactions make RIs, as a whole, more efficient. However, according to the identified *links*, we believe there is plenty of room for building more connections, which could result in more effective performance.
5. Our results show how intermingled *needs* and *Sub-Challenges* are, and thus the relevance for RIs to organize their strategies and activities in a coordinated, collaborative manner; and even to go a step further and to do their planning thinking of users and uses beyond their traditional communities.
6. *Needs* not addressed by any RI correspond in their majority to the Ecosystem conservation challenge. System-based RIs may take advantage of these findings to improve and tune their *services* and interconnections to better address the complexity inherent to the conservation of ecosystems.

Data availability statement

The data that support the findings of this study are available upon request from the authors.

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Author contributions

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ORCID iDs

Francisco J Bonet-García https://orcid.org/0000-0002-4627-1442
Francisco Pando https://orcid.org/0000-0002-6321-9398
María Suárez-Muñoz https://orcid.org/0000-0003-1765-6885
Javier Cabello https://orcid.org/0000-0002-5123-964X

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