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ECOSYSTEMS

# Long-term Ecological Research: Chasing fashions or being prepared for fashion changes?

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**Abstract:** Long-term-ecological-research (LTER) faces many challenges, including the difficulty of obtaining long-term funding, changes in research questions and sampling designs, keeping researchers collecting standardized data for many years, impediments to interactions with local people, and the difficulty of integrating the needs of local decision makers with “big science”. These issues result in a lack of universally accepted guidelines as to how research should be done and integrated among LTER sites. Here we discuss how the RAPELD (standardized field infrastructure system), can help deal with these issues as a complementary technique in LTER studies, allowing comparisons across landscapes and ecosystems and reducing sampling costs. RAPELD uses local surveys to understand broad spatial and temporal patterns while enhancing decision-making and training of researchers, local indigenous groups and traditional communities. Sampling of ecological data can be carried out by different researchers through standardized protocols, resulting in spatial data that can be used to answer temporal questions, and allow new questions to be investigated. Results can also be integrated into existing biodiversity networks. Integrated systems are the most efficient way to save resources, maximize results, and accumulate information that can be used in the face of the unknown unknowns upon which our future depends.

**Key words:** Landscape-scale questions, LTER, PELD, RAPELD, sampling modules, temporal questions.

## INTRODUCTION

There is consensus that long-term ecological research (hereafter LTER) is essential to understand ecosystem processes and inform conservation issues, but there are no universally accepted guidelines as to how such research should be done or integrated among sites. In principle, studies of bacterial colonies or fruit flies in the laboratory over hundreds or thousands of generations could reveal or test important ecological processes. However, most research labeled as LTER is related to the study of landscapes or large ecosystems, which Billick & Price (2010) called “The Ecology of Place”. In this approach the involvement of local people is considered essential (Singh et al. 2013), and the education of local people has been a major focus within the LTER (https://lternet.edu/education-and-training/).

Despite its desirability, LTER is rarely undertaken for the following reasons: (1) it is difficult to obtain guaranteed long-term funding; (2) research fashions change frequently, so the original questions and sampling design may no longer be in vogue; (3) scientific reputations are made on ground-breaking results, so few researchers are willing to spend many years collecting standardized data; (4) it is easier to do reductionist science or work with remote sensing than to interact with local people at the landscape scale; and (5) decision makers require information at a variety of scales that extrapolate far beyond individual research sites, so site-based research is not considered “big science” (Knapp et al. 2012, Alber et al. 2021). There has also been severe criticism of what has been called “monitoring for monitoring’s sake” (Yoccoz et al. 2001), though the critics have not presented alternative systems that account for the major challenges outlined above.

Most monitoring is of individual species or habitats (Magnusson et al. 2013), but there is a strong need for integrated monitoring of biodiversity and ecosystem processes (Bustamante et al. 2016), and there have been many attempts to integrate LTER research sites or create new networks (Craine et al. 2007). Because it is difficult to integrate individual researchers, some states have adopted a top-down approach with all monitoring being done by a dedicated team. Examples of this are the highly successful Alberta Biodiversity Monitoring Institute (ABMI) in the state of Alberta, Canada (Haughland et al. 2010), and the National Ecological Observatory Network (NEON) in the USA (https://www.neonscience.org/). For instance, the NEON program costs around US$ 70 million per year, and its administration is concentrated in a single foundation (https://www.neonscience.org/). Australia´s Land Ecosystem Observatory network (TERN) costs less (almost AU$13 million for 2022-23), but currently has protocols only for rangelands. As with NEON, it is strongly oriented to remote sensing with only limited surveying of most biological groups. At the moment, it only has standardized surveys for ants, but the project administrators recognize the need for surveys of more diverse biodiversity elements that can be implemented by partners with independent funding (https://www.tern.org.au/field-survey-apps-and-protocols/). A top-down approach has many advantages in relation to integration, but it can be difficult to maintain funding, and there is little incentive for new researchers to join the network, especially in developing countries where resources destined to science and people’s access to universities and other research institutions are limited. In addition to the lack of resources, developing countries are those that hold the largest and most remote conserved areas, increasing field costs.

Therefore, in this article we seek to present an integration proposal for the different sampling sites that make up the LTER, as well as solutions for the challenges encountered by researchers in long-term studies.

## RAPELD AS AN INTEGRATION SYSTEM FOR LTER

In 2000, researchers in the LTER (PELD in Portuguese) site “Impactos Antrópicos no Ecossistema de Floresta Tropical (PELD-IAFA)” in Brazil developed the RAPELD system, which was designed to minimize the five problems listed above and provide research infrastructure that could be maintained on a permanent basis (Magnusson et al. 2013). The RAPELD system is a sampling system developed to deal primarily with spatially distributed questions, but which, if inserted in an LTER, is capable of meeting temporal research demands, precisely because of its permanent spatial arrangement. As the RAPELD system is spatially standardized, it allows comparisons across landscapes and ecosystems when appropriate, elevating the importance of local surveys to understand broad spatial and temporal patterns while enhancing decision-making and training of local researchers. It consists of a combination of straight-line trails, systematically distributed plots and stratified plots to capture particular landscape features, such as riparian zones (Magnusson et al. 2013). It was designed to be compatible with conventional plot and transect studies so that results can be integrated into existing biodiversity networks (Rosa et al. 2021).

The PELD-IAFA site is in closed-canopy rainforest, but the RAPELD method was based on previous biodiversity research in a savanna-forest transition near Alter do Chão, PA, Brazil (Fadini et al. 2021). This and related monitoring systems received severe criticism from researchers who considered that monitoring can only be used to inform previously defined questions, a position criticized by Wintle et. al (2010), who emphasized the importance of "allocating monitoring effort in the face of unknown unknowns". The exchanges resulted in several papers defending systematic monitoring (Haughland et al. 2010), but the arguments on both sides were largely academic. Now, more than a decade later, the critics have not produced any LTER systems that are economically viable for developing countries, and data are available to show how the RAPELD system can be used to effectively deal with the five major limitations of LTER research.

Over the past two decades, two basic sampling modules of the RAPELD system have emerged based on consumer preferences that can be inserted in LTER research sites. In places with easy access and usually near consolidated academic institutions, parallel trails, one kilometer apart, form a 5 km x 5 km grid with 30 uniformly distributed plots. Where a more dispersed system is required, the most popular modules consist of two parallel 5 km trails separated by 1 km with 10 uniformly distributed plots and a variable number of stratified plots (Figure 1). In some cases, especially for environmental-impact studies, the number of plots is increased to better define gradients, such as in the studies of the Santo Antônio hydro-electric dam and the effects of the BR101 highway in Sooretama Biological Reserve, where plots were placed each 500 m along the trails (the location and detailed description of these areas can be found in Rosa et al. 2021). Most analyses require at least three of the smaller modules to ensure sufficient replication.

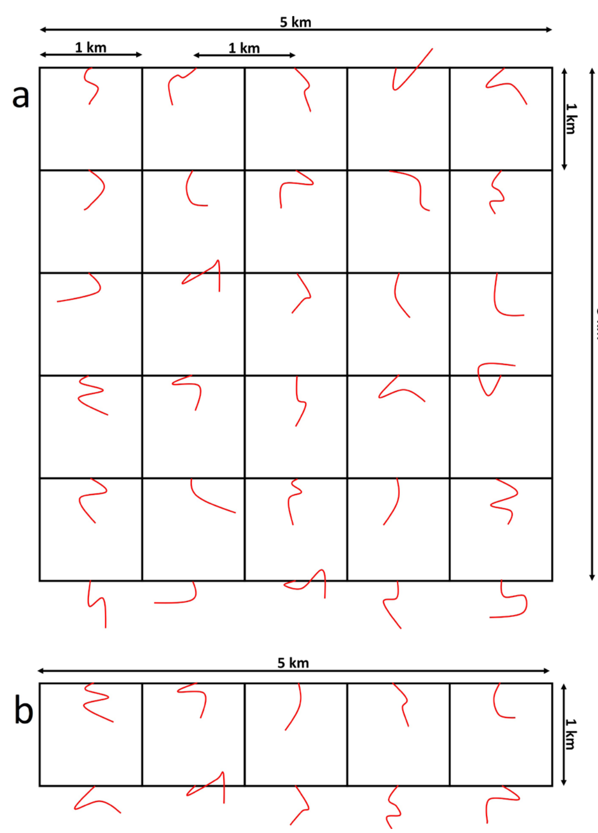


**Figure 1. Grid of 5 km x 5 km (a) and module of 5 km x 1 km (b), the most common configurations in the RAPELD system, showing the 250 m RAPELD plot (in red) uniformly distributed following the contour of the land and, therefore, are not linear.**

Uniformly distributed plots are unconventional because they follow altitudinal contours, which reduces within-plot variability due to water table, soil characteristics and other topographic variables, but they produce results that can be integrated with data from conventional plots (Magnusson et al. 2013). In a few places, below ground features, such as suspended water tables, can lead to within-plot vegetation changes in topographically homogeneous areas, which may be undesirable for questions that require precise measurement of predictor variables that apply to the whole plot. This is a typical case of coastal plains where the topography is homogeneous but the water table depth varies, which alters the physiognomy of the vegetation (Araujo et al. 1998). However, for overall biodiversity surveys, it is important to maintain the basic design, and using subplots within the basic 250 m plot allows fine-scale evaluation of factors determining the limits of vegetation types, or analyses can be focused on phenomena occurring in subplots (e.g. Baccaro et al. 2012). Where there are insufficient plots with homogeneous vegetation or other characteristics, it is easy to supplement the basic design with extra stratified plots. It may be difficult to install RAPELD systems in very steep mountainous areas, though researchers on Ilha Grande Island in the Atlantic Forest have successfully installed plots on a virtual grid without straight-line connecting trails and in the São Joaquim National Park where the location of modules followed the landscape concept (Vianna et al. 2015). The great success of the RAPELD system has been in inducing researchers to investigate all parts of the landscape in proportion to their availability and avoiding “the science of the easy”. Where it is presently technologically impossible to survey some locations, the plot positions at least show which parts of the landscape cannot be included in generalizations based on the data collected.

The system was planned to answer most landscape-scale questions of interest to decision makers in 2000, but it was also designed to allow new questions to be answered. It was formulated for questions about what is happening across landscapes, involving biotic interactions. In this sense it differs from LTER studies that focus only on individual elements in particular places in the landscape. RAPELD was not designed to substitute such directed research, but to give a broader landscape context in which their results can be interpreted for management decisions.

## CHALLENGES FOR LTER

It is difficult to obtain guaranteed long-term funding for good reason. Science needs to be competitive and subsidies to study one question in the long term, assuming that questions will not change, are likely to result in inefficient research (Yoccoz et al. 2001). Most funding agencies are therefore unlikely to commit to monitoring simply for the sake of monitoring and require that all questions are explicit in the proposal. The value of the RAPELD landscape approach is that the same data protocols can be used or updated for many different questions. Some monitoring schemes have dedicated staff (e.g. Haughland et al. 2010; https://www.neonscience.org/), but such systems are too expensive for most funding agencies, and labor laws make long-term contracts difficult. Because the sampling scheme is appropriate for a range of questions, much long-term research is carried out in RAPELD sites by independent students. Although each student has a focus on a different question, the data is comparable for time-series analysis or synthesis, and the overall cost is vastly less than installing independent infrastructure for each question (Magnusson et al. 2013). RAPELD is a system designed to increase the effectiveness and applicability of research in LTER sites (Magnusson et al. 2005), but it can also be used in short-term studies when there is no provision for continued monitoring. This allows the results of those studies to be integrated with parallel studies in LTER sites, greatly increasing the value of the results of rapid surveys and LTER studies (Magnusson et al. 2013).

Most of the longest time series based on RAPELD methodology have been obtained in sites initiated by the Brazilian Research Council (CNPq) or the Brazilian Biodiversity Research Network (PPBio), but funding for LTER from those agencies has to be supplemented from many other funding sources. Within the PPBio, after a new RAPELD site is installed, basic variables (e.g. slope, soil and vegetation characteristics) are made available in a public data repository to be used to answer various questions, enhancing the dynamism and cost-effectiveness of research. However, the use of standard basic variables does not prevent the inclusion of other variables that may be important for specific questions (Rosa et al. 2021). RAPELD is used in many other Brazilian biomes, and even in the arid lands of Argentina, but most of the long-term studies have been undertaken in the Amazon and we will use those to illustrate how different questions can supply the same data while reducing overall costs by several orders of magnitude.

In 2001, a Masters student studied spatial patterns of fish assemblages in 38 RAPELD stream plots distributed across 64 $km^2$ in Reserva Ducke (Mendonça et al. 2005) without including temporal elements. In 2005, another student studied seasonal variation in fish assemblages, focusing on short-term changes but required resampling of the original plots. Subsequently, other students have asked other spatial questions and there is now an 18-year time series for fish assemblages in the reserve (Borba et al. 2021). By studying landscape questions, each student was able to publish in respected journals while accumulating data for the long-term studies, even though LTER was not the principal objective at first.

Landscape sampling of vegetation plots has also been important to generate time series. All vegetation strata can be sampled in RAPELD plots, so plot infrastructure installed for one group can be used for all taxonomic and functional groups, greatly reducing costs and time for individual researchers, especially for graduate students who need to complete their research in short periods with limited budget. Seventy-two uniformly distributed plots installed in Reserva Ducke in 2001 were first used by a Masters student to sample understory plants in the genus *Psychotria*, and the same infrastructure was used to inventory above-ground live biomass in the woody vegetation (Castilho et al. 2006). Monitoring the plots after a two-year interval allowed evaluation of changes in biomass in relation to topographic and edaphic variables, and revealed probable climate by soil interactions (Castilho et al. 2010). Landscape sampling not only allowed investigation of questions that would not be viable in individual plots, the large number of replicates allowed statistically validated conclusions, even though the temporal changes were within the expected sampling error of individual plots.

Bats have been extensively sampled in RAPELD plots (e.g. Pereira et al. 2019) in the Amazon and in the Atlantic forest. Many surveys were financed by environmental impact studies (e.g. Bobrowiec et al. 2022). Recent repeated studies of bat assemblages in RAPELD plots have been financed by institutions interested in surveying landscapes for potential virus threats.

Faria et al. (2008) sampled lizards in spatially standardized plots in Amazonian savanna in

1997 and 1998 to study the medium-term effects of fire extent, data on which had been collected during the previous four years. Souza et al. (2021) used those data in a 21-year study, which also used long-term vegetation and fire data collected independently in the same plots (Lima et al. 2020). The standardized infrastructure permitted the integrated long-term studies of lizard-vegetation interactions, even though this was not the objective of the first studies.

Landscape-scale studies have been carried out for many groups. Even where these have not yet generated long time series, they serve as baselines for future questions, and integrated studies can indicate which groups are indicators of others (Landeiro et al. 2012). Such studies also produce ecosystem-specific baseline data for restoration projects. Long-term funding is much easier to obtain for some biological groups than others, but we need to take advantage of researchers who want to sample any group, even if only for taxonomic or spatial questions, because we do not know which questions or groups will be of the greatest relevance in the future.

Research fashions change frequently, so the original questions may no longer be in vogue. When the vegetation plots were installed in the IAFA site, most studies attributed between-plot variation to soil granulometry (e.g. Castilho et al. 2006). However, sampling the RAPELD plots by many different researchers studying a variety of plant groups showed that distance to the water table was as important, or more important than, soil characteristics (Schietti et al. 2013). This resulted in a paradigm shift, but the same plots and the time series could still be used for the new questions.

Studies of understory plants in uniformly distributed RAPELD plots attributed most of the assemblage variation to edaphic variables and slope. However, uniformly distributed plots sampled few riparian zones, so Drucker et al. (2008) compared the previously collected data to samples from riparian plots and showed that the most distinct habitat for understory herbs in central-Amazonian rainforest is the riparian zone. Guedes et al. (2022) carried out a similar study with understory palms and used environmental data that had been collected in a previous study of leaf-litter frogs (Jorge et al. 2016). Because sampling was spatially standardized, it was possible to take advantage of the old data. Bueno et al. (2012) sampled understory birds in 2009 in the same plots that had been used for vegetation studies and were able to show that the riparian zone was also the most distinct habitat for the birds. Further questions about habitat use by understory birds may not have attracted financing, but Menger et al. (2018) sampled many of the same plots using the same methods as Bueno et al. (2012) with the objective of evaluating gene flow across the landscape. Different taxonomic groups, different questions and different researchers, but all contributing to time series that can be integrated in the future.

Scientific reputations are made on groundbreaking results, so few researchers are willing to spend many years collecting standardized data. In the previous section, we showed that long-term temporal trends can be constructed from data generated by independent researchers studying different spatial factors if the studies are based on spatially-standardized sampling units. Few new discoveries are based purely on theoretical considerations and most breakthroughs come from examination of empirical patterns. Here we highlight some of the most cited studies, often with graduate students as first author, that have resulted from studies that started in RAPELD grids and that were subsequently validated through inclusion of data collected from other regions.

Levis et al. (2017) reported in Science that there are persistent effects of pre-Colombian plant domestication on Amazonian forest composition. The first author carried out floristic inventories in RAPELD grids for her Masters dissertation and integrated this knowledge with data on indigenous use of plants for her Ph.D. thesis, which resulted in her receiving a young-scientist award from the Brazilian Science Foundation (CNPq) and the Best Thesis Award from CAPES, the Brazilian organization responsible for graduate studies.

Sousa et al. (2022) reported in Global Ecology and Biogeography that water-table depth modulates productivity and biomass across Amazonian forests. The first author worked on data curation for RAPELD plots before collecting data on forest structure in RAPELD plots for her Ph.D. thesis. The fact that she collected standardized data and had access to similar data collected by many other researchers enhanced rather than detracted from the importance of the work.

Toledo et al. (2009) used experiments to examine wood decomposition at the landscape scale in RAPELD plots. The first author was a Ph.D. candidate and he subsequently used the long-term data from tree censuses in the same plots to examine factors affecting mortality rates, modes of death and species-trait/mortality-rate relationships (Toledo et al. 2017). The integrated studies could only be undertaken because the data were collected in spatially standardized plots where other researchers were collecting data.

Jorge et al. (2020) published a study in the Journal of Zoological Systematics and Evolutionary Research showing that the Manaus harlequin frog represents one of the most endangered Amazonian taxa. The first author studied the distribution of a frog species in a RAPELD grid for his Masters dissertation, and subsequently extended the study, using standardized sampling units, throughout the species' range for his Ph.D. thesis. What started as simple natural history evolved into an important conservation study.

Many graduate students used spatial replication to study the ecology of the rodent *Necromys lasiurus* in an Amazonian savanna. Although those dissertations and theses initially only resulted in short-term ecological studies, the data were integrated into long-term studies one to two decades later and several of the students were co-authors on important studies of global change (Magnusson et al. 2010). These and the other examples given above show that collecting standardized data at the beginning of a scientific career is not an impediment to development of a strong scientific reputation.

It is easier to do reductionist science or work with remote sensing than to interact with local people at the landscape scale. This is true, but it does not justify the exclusion of local people from the decision-making process (Silvius et al. 2004). Working at landscape scales essentially guarantees that researchers interact with local people and government authorities. Most RAPELD modules are installed on private land or dedicated reserves, and many of the protected areas were created to support local communities (e.g. Extractive and Sustainable Use Reserves) or for specific economic activities (e.g. National Forests). Land use can only be understood in the context of overlapping political and economic territories (Becker 2015).

The involvement of local people as assistants, guides and/or as decision makers should be part of the process of installing field infrastructure for LTER (Magnusson et al. 2013). Indigenous groups and other traditional communities often possess far greater knowledge about local ecosystems than academic researchers. However, there are language and cultural barriers to the exchange of information, and LTER sites are important in promoting long-term communication among different stakeholders. It is only by understanding and promoting communication among diverse territory holders that effective conservation and economic development can be achieved (Becker 2015).

There are some small steps with large effects that can be taken to stimulate interactions between local communities and researchers. Knowledge co-production, such as the generation of policy briefs, field guides, books, pedagogical material, and field courses , is an important first step in citizen science, and these can be used to pass information far beyond the identification of species. Long-term studies are often necessary to produce field guides that are effective in hyper-diverse regions, especially for taxa less studied than birds and mammals. For instance, the IAFA site was location for two Masters dissertations and two Doctoral theses that focused on snakes. These studies accumulated the information necessary to produce the most complete field guide to the snakes of the region currently available (Fraga et al. 2013).

The species guides to snakes and other taxa produced largely in that site are used by many stakeholders, including researchers, tourist guides and the Brazilian army. However, an important characteristic of these guides is that they have introductory texts in accessible language that can be used by secondary students in science fairs and other activities. In fact, sometimes booklets with the equivalent of the introductory text are the best products to influence children and ecotourism guides (e.g. Torralvo et al. 2021).

In some cases, studies in academic sites (e.g. Levis et al. 2017) can lead to directed studies on indigenous lands in collaboration with local groups (e.g. Levis et al. 2018). Whatever communication strategy employed, the most valuable information for indigenous and other traditional groups relates to the landscape from which they draw their sustenance. That is why a landscape approach is the most effective to involve traditional groups, conservation agencies and economic developers in sustainable development of the region.

Decision makers require information at a variety of scales that extrapolate far beyond individual research sites, so site-based research is not considered “big science”. There is no clear definition of what represents “big science”. Sometimes the term is used for studying a single topic in the laboratory (e.g. Isaacson 2021), for studies integrating many different aspects over a limited area (e.g. Landeiro et al. 2012) or data collected in many sites over a large part of the World (e.g. Muscarella et al. 2020). All these uses imply studies that extrapolate physically or conceptually beyond a single study. Below, we will discuss studies undertaken in RAPELD plots that allowed extrapolation to scales relevant to decision makers.

Dominance hierarchies are well known to structure ant assemblages in small-scale experiments. However, using RAPELD plots distributed over more than 700 km, Baccaro et al. (2012) showed that the dominance patterns shown at the scale of meters are imperceptible at the scale of the landscape in Amazonian Forest, and therefore do not have to be taken into account in reserve design. Repeated studies over a small area could not have shown this.

Big science does not always cover a wide geographic area. Sometimes it just breaks conceptual barriers, usually by showing links that were unappreciated before. It is increasingly understood that management problems cannot be resolved with studies of a single or a limited number of species (e.g. Lambrinos 2004). Interactions are ubiquitous in ecology and are often occult (e.g. Barbosa et al. 2023). Documenting interactions among multiple taxa and environmental drivers is a characteristic of papers originating in RAPELD systems. Figure 2 (see the methodology for creating the figure in Supplementary Material - Appendix SI) illustrates the links among biological groups and ecosystem processes that have been studied in RAPELD modules, and many other studies have investigated the links between species within each of these broad groups.

The River Barrier Hypothesis provides a convincing explanation for the diversity of some groups of organisms (Ribas et al. 2012). However, studies of many taxa coincidently in RAPELD plots (e.g. Dambros et al. 2020, Santorelli et al. 2018) showed that most Amazonian taxa do not show strong patterns associated with postulated river barriers. It is generally assumed that flooded-forest (várzea) assemblages are more species poor than terra-firme assemblages, but Rabelo et al. (2021) used landscape sampling in RAPELD plots to show that Nymphalid-butterfly assemblages do not follow this pattern.

Much "big science" is based on consortia of vegetation plots, especially those in the ForestPlots (ForestPlots.net et al. 2021) and the Amazon Tree Diversity Network (ter Steege 2013), and RAPELD plots make up a significant part of these networks. These and other networks help consolidate links between RAPELD sites and other sites throughout the World. RAPELD plots have been used in integrated studies involving researchers from more than 26 countries (Figure 3, see the methodology for creating the figure in the supplementary material).

It is sufficient for a researcher to contribute data from a single plot to become a partner in the vegetation networks. This is obviously a contribution to big science, but the study itself

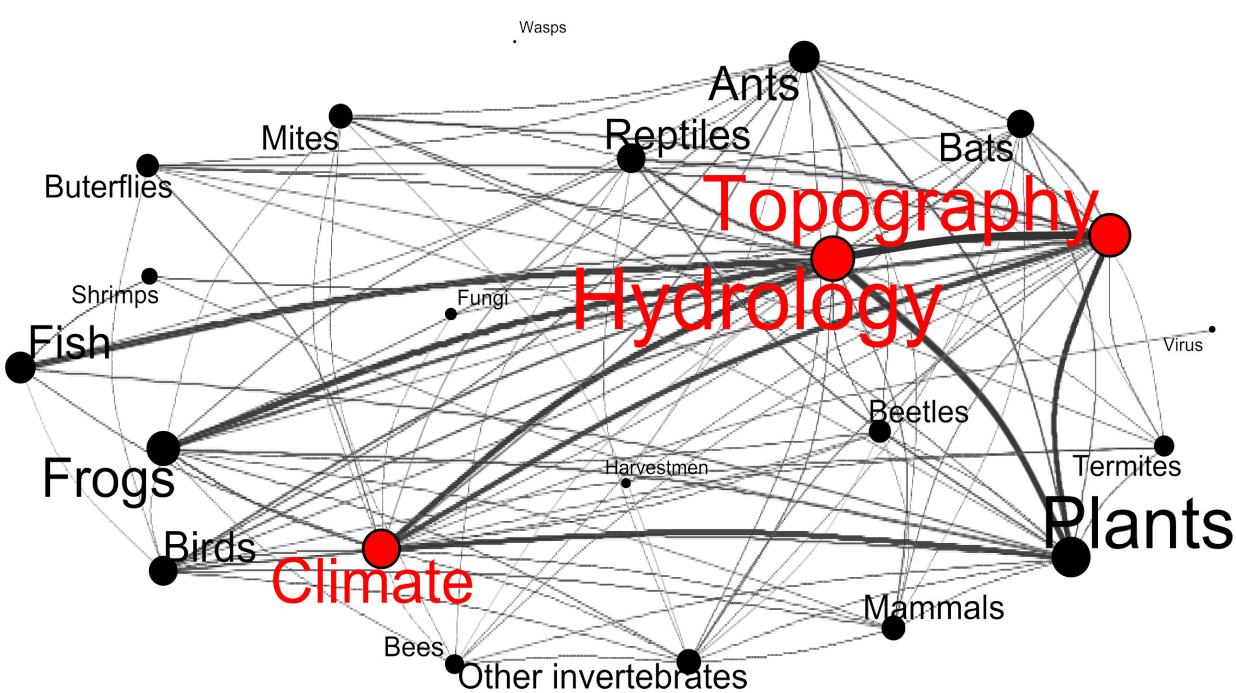


**Figure 2. Interactions among species groups and some non-biological environmental characteristics that have been studied in RAPELD plots. The graph is based on a scientometric study of 100 recent publications and line thickness is proportional to the number of studies that investigated the relationship between the linked variables. This illustrates that RAPELD methodology is useful for integrated research and also indicates the relationships that are in need of more intensive research.**

would not generally be considered big science. Researchers who conduct such isolated research often lack the resources or experience necessary to organize integrative studies. However, researchers who work in RAPELD systems are accustomed to thinking at landscape and larger scales, often integrating results from multiple LTER sites (e.g. dos Santos et al. 2020, Levis et al. 2017, Schietti et al. 2016, Sousa et al. 2022, Stegmann et al. 2019, Zuquim et al. 2012, 2014).

## OTHER CONSIDERATIONS

We have focused on some widely recognized problems with undertaking LTER and shown that they can be minimized by taking a landscape approach. However, there is another reason to study landscapes to detect the effects of land-use and climate changes on biodiversity and socio-economics. Due to our limited life spans, we tend to think of landscapes and ecosystems as relatively stable, but they have not been over the several million years since most species evolved.

The majority of extant species have experienced several glaciations, so they have had to deal with previous climate change. In some cases, glaciers may have displaced species from whole regions, but, in most cases, species have adapted by migrating across local landscapes. To evaluate the effects of environmental changes, it is not sufficient to know whether species have been displaced from individual sample units; we need to know whether they have been extinguished regionally or have just migrated to other places in the local landscape. Landscape elements are not static. What is soybean field today may be forest in a hundred

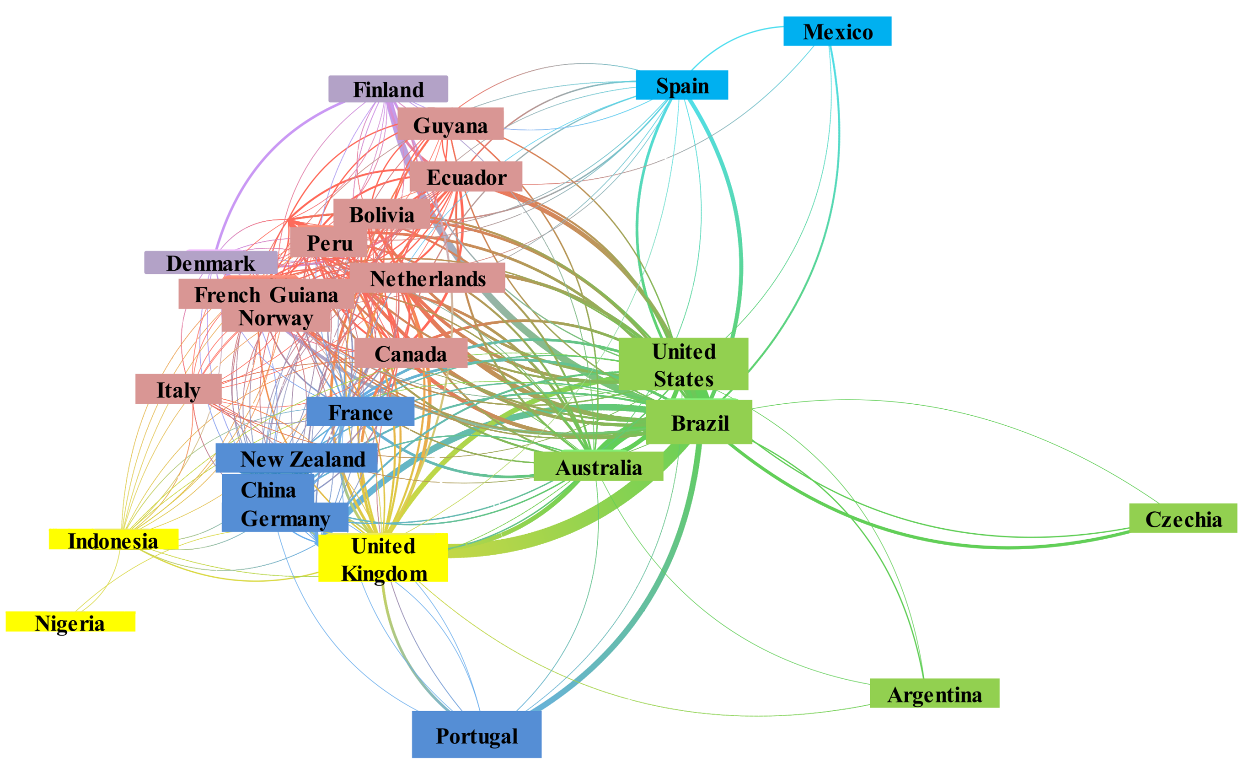


**Figure 3.** International links of the RAPELD system based on a scientometric study of 100 publications. The thickness of lines is proportional to the number of joint authors. There are links to many parts of the World, but the majority of connections are to a limited number of countries, a situation that should change as RAPELD is adopted in more regions.

years, and vice versa. Locations with specific temperatures will not be the same under global warming. Sea level rises will turn some areas with sea-grass beds into reefs or other habitats. To understand the effects of global changes on biodiversity, we will have to follow changes in landscape configurations. For that reason, long-term monitoring should not be only for specific species in specific locations; it must have at least some on-the-ground monitoring of diverse elements across the landscape.

We believe that the RAPELD system has not shown its full potential, but that is not because of the lack of possibilities or because it cannot attend to the needs of a great number of biodiversity stakeholders. Rather, most limitations stem from misguided preconceptions against spatially standardized monitoring, which leads to lack of vision by researchers and funding agencies. In this short letter, we cannot cite the hundreds of studies from RAPELD sites (https://ppbio.inpa.gov.br/public), but we hope that our brief overview has shown that attending to current scientific fashions does not impede the generation of high-quality integrated LTER. Working in an integrated system is the most efficient way to save resources, maximize results, and offers a critical bonus: it accumulates information that can be used in the face of unknown unknowns upon which our future depends.

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## SUPPLEMENTARY MATERIAL

**Appendix SI.**

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