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THE QUEST FOR HOLY GRAILS IN LONG-TERM ECOLOGICAL RESEARCH PROGRAMS: POTENTIAL DANGERS AND SOLUTIONS

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Abstract. Long-term Ecological Research programs, LTERs, are necessary to understand processes that occur in time-scales longer than the period of theses, dissertations, and grants from most funding agencies. A basic result of a long-term study is the production long-term time series, but the establishment of general patterns and processes require data integration between many long-term studies and networks. These two main targets became like Holy Grails in LTERs, objectives on their own, many times dissociated from the questions they should provide answers. I discuss the advantages and potential pitfalls of these targets becoming Holy Grails in LTER, and Long-Term Socio-Ecological Research as a potential new Holy Grail.

Keywords: data management; long-term ecological research; research goal;

INTRODUCTION

Ecosystems, communities, populations, individuals, all have aspects that change relatively fast in response to environmental changes, such as algal blooms in response to eutrophication, species composition, population densities, and physiological responses of individuals in general. These changes are fast relative to our perception, a matter of days, months, maybe a few years, also possible to reach conclusions in the time-frame of a phd thesis or the usual grants by funding agencies. Responses beyond that time-frame become harder to perceive and detect, such as changes in temperature and precipitation regimes, but also long-term responses of organisms to habitat loss and fragmentation ("extinction debts", Tilman *et al.* 1994), changes in survival, mortality, and fecundity that are delayed due to maternal effects (Beckerman *et al.* 2002), consequently also changes in fitness of individuals or populations (Legrand *et al.* 2017). Therefore, ecology and environmental sciences in general need studies that last long enough to detect such slow responses, inferred by "slow variables" (Ludwig *et al.* 1978, Carpenter & Turner 2000). Long-term studies are essential to understand and predict long-term effects of environmental changes, and to devise strategies to mitigate the impacts of human activities demands of society (Lindenmayer *et al.* 2012, Reinke *et al.* 2019).

Long term programs (LTER) vary in objectives and characteristics, but in all there is an emphasis on obtaining long time series of the phenomena of interest. Obviously, a long time series is a necessary basic data for long-term studies, and frequently the most valued result, becoming almost a holy grail in long-term studies. Originally, in Christian traditions, the holy grail was the cup that Jesus drunk from in the Last Super, but after medieval literature the term Holy Grail is often used "to denote an elusive object or goal that is sought after for its great significance" ("Holy Grail" 2017). This definition fits perfectly for time series in long-term studies. They are an elusive object or goal because of the many difficulties involved in obtaining long-term funding, regular sampling, especially over more than a decade. A great significance is also attributed to long time series as only they would reveal long-term responses biodiversity processes and components. Similar significance is attributed to the (i) integration of data, not only between sites within an LTER network, but also between networks regionally and globally, and (ii) to the inclusion of human societies as part of the system.

In this short essay I discuss how Holy Grails can be beneficial to the development of a field of study, but also the main danger involved: the quest for the "graal" becomes the main objective, because when found it will reveal unforeseen trends, patterns, and goals. The questions or objectives of study become secondary, or presumed to be revealed once the grail is obtained.

THE GRAIL OF LONG TIME SERIES

A main advantage of having time series as a Holy Grail is making a clear target of an LTER, separating it from short term studies, and avoiding the risk of LTER sites becoming a collection of short term studies succeeding themselves along time. In addition to long-term funding, long time series require continuous maintenance of equipment and infrastructure. Like weather stations continuously recording climatic variables on a site, long-term studies needed tools that continuously record target variables, such as key atmospheric and soil key nutrients, pollutants, but also species and composition, population abundances, densities and demographic parameters. In this regard, a site of Long-Term Ecological Research, LTER, is frequently described as an observatory of natural phenomena that otherwise would go undetected or would be difficult to estimate (Scholes *et al.* 2012, Mirtl *et al.* 2018). An LTER site could be seen as huge and complex station that register biodiversity processes along time, similarly to a weather station. Besides long-term funding, appropriate tools are necessary to detect the slow-response phenomena investigated in long-term studies, tools that need to be functioning regularly over long time periods. Within this context of many difficulties the final result becomes especially prized, contributing to a valorization of long time series. Indeed, time series of only 10 data points may take 10 years to obtain, if each data point is one year.

A potential pitfall with such value put on long time series is to forget that specific questions require not only long time series, but also time series of the appropriate organism or process of interest. For example, a study of amphibian and reptile population trends across Europe, encompassing 843 time series of 17 species, considering only times series > 4 years, concluded that 54% of the time series were declining, and the major effect size was attributed to climate change. However, when the two commonest species were excluded, habitat loss became the main determinant of negative trends (Falaschi *et al.* 2019). Climate change certainly was a component of the overall negative trend, but its importance relative to habitat loss depends on the group of species considered, all species or excluding the two commonest, and more influential. Considering all time series equally may not provide the best answer depending on the question of interest.

In addition, the time series provided by LTERs for different groups of organisms and processes are not random samples, but biased to some degree, hence any research question needs to carefully consider potential sources of bias. Most LTERs suffer from site-selection bias, the selection of study sites where species of interest are most abundant (Pechmann *et al.* 1991, Palmer 1993, Fournier *et al.* 2019). This selection already create a bias towards the detection of negative trends because future population abundances tend to be on average lower than the starting value (Figure 1). Although recognized as an important bias, is has been rarely addressed in studies analyzing long-term trends in time series (Fournier *et al.* 2019).

These and other bias involved in most time series have already been pointed out as important in the accurate and robust detection of long-term trends of population abundances, especially negative ones (Didham *et al.* 2020). It may seen challenging to account even for just a few of these sources of bias in the detection trends in long time series, in addition to potential confounding, uncontrolled factors. The detection of negative trends of population abundances in time series of many taxa in central Europe associated with their thermal preference is an example that it is possible (Bowler *et al.* 2017). Potential confusing factors and sources of bias related to more common or less variable species were included in the statistical modelling, and their effects accounted for.

THE GRAIL OF DATA INTEGRATION

Returning to the metaphor of a weather station, only one station is only a data point, even if composed a long time series. It does allow inferences and forecasts for a region or large geographic area. A network of weather stations is necessary to describe weather variation over large spatial scales. Similarly, only one LTER site does not allow generalization or inferences of patterns to larger geographic areas; a network of LTERs is necessary for that. Many countries have developed their own network of LTER sites. The International LTER network was founded in 1993, with the objective of helping to integrate efforts and data from mostly national LTERs worldwide (Parr 2013, Vanderbilt & Gaiser 2017, Mirtl *et al.* 2018). Clearly, it is a challenge to integrate the data of this variety of LTER networks worldwide (Mirtl *et al.* 2018). In addition to LTER networks, countries frequently have initiatives of long-term monitoring, generally associated with the development management actions to preserve biodiversity and ecosystem services. Taking Brazil as an example, a variety of monitoring networks coexist (Roque *et al.* 2018), in addition to the Brazilian LTER network (Programa PELD - CNPq) established as early as 1993 (Barbosa 2013). Many of these monitoring networks and the LTER in Brazil date comprise long time series, but with a variety of methods, effort, criteria of site-selection, and objectives (Tabarelli *et al.* 2013, Roque *et al.* 2018).

In this scenario, data integration becomes a challenge, a complex process, and the search for integration becomes an objective on its own (König *et al.* 2019). To obtain resources and infrastructure to integrate data from this variety of networks a convincing justification is necessary, generally a promise of revelation of more robust and general pattens, and answers not yet possible to be obtained. As in the search for long time series, the questions and objectives may become secondary, and the search for data integration becomes another Holy Grail. Because the challenge and difficulties involved, data integration as a Holy Grail is clearly defined and valued. Data integration is a fundamental step for more robust and general questions of all kinds, theoretical or applied, but it is still a step towards the answers to questions, which frequently vary the with the spatial scale of interest or application (König *et al.* 2019).

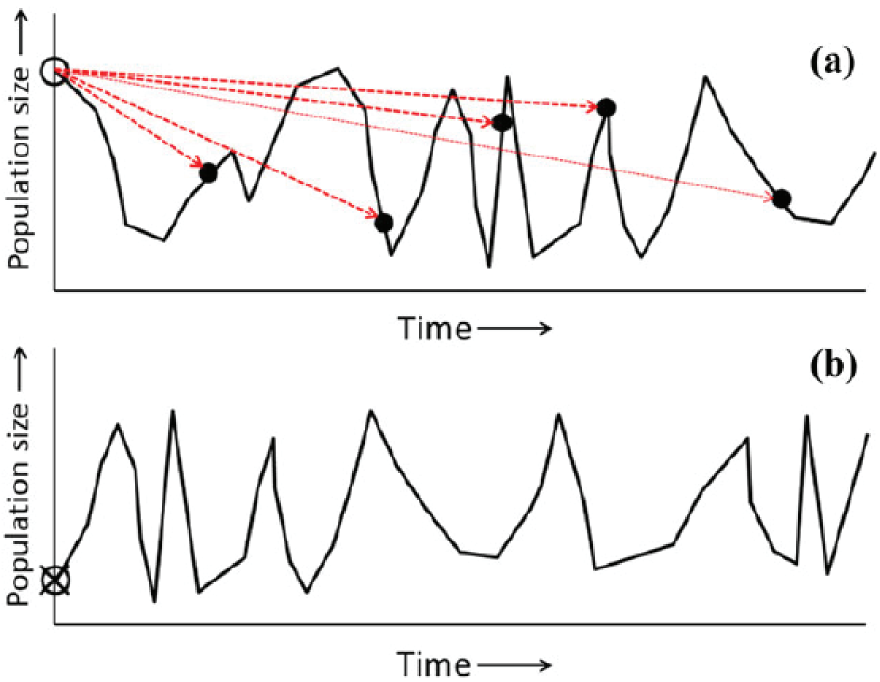

Figure 1. Time-series data for two hypothetical populations of the same species with independent population fluctuations. At time zero, a researcher chooses either populations to begin a long-term study monitoring population density. Researchers may be more likely to choose the population that begins (a) at high density (open circle) than the one that begins (b) at low density (circle with X). Given the choice of the population in (a), for nearly any study end point (closed circles), the inferred population trend is a decline (dashed arrows) (Fournier *et al.* 2019, reprinted with permission).

A potential piftall here is to forget the potential sources of sampling bias in an LTER network, and integration of data from many networks may amplify these bias LTER sites, are not randomly, haphazardly, or uniformly distributed. More frequently they are located in protected areas (Mirtl *et al.* 2018), which already introduces bias in the environments represented, for instance, plant physiognomies that are more widespread will tend to be more represented in network. Also, sites will tend to be closer to research institutions; as these institutions are concentrated in certain areas, LTER sites tend to be concentrated as well. Finally, within a site not all species of a taxomic group may be regularly sampled, and even if all species are sampled, the most abundant or accessible are the ones that will have more consistent time series. At least some of these bias, if not all, are inherent and unavoidable in any long-term study, and in the time series available from LTER networks. LTER networks are not part of a single, top-down study, with planned sampling design.

Users of an integrated dataset need to consider that different questions, their domain of application, and data resolution necessary may require to filter data in the set that are appropriate for the questions of interest (König *et al.* 2019, figure 2). Also, it is necessary to evaluate and minimize potential sources of bias, such as the ones described previously. Data could be filtered a priori, before that statistical modeling of the questions of interest, but this could involve considerable reduction in sample size. Alternatively the nature of the bias could estimated and incorporated in the modelling framework, similarly to what is done for spatial sampling bias in Species Distribution Modeling (Fourcade *et al.* 2014, Stolar & Nielsen 2015), or in population dynamics (Kohyama *et al.* 2018).

LTSER: A NEW GRAIL?

A more recent candidate for a Holy Grail in long-term studies maybe the inclusion of human societies as part of the system under study, even changing the well-established LTER acronym to LTSER, Long-Term Socio-Ecological Research (Singh *et al.* 2012). The tone and frequent justification of this change is framework is not just to broaden the comprehension of the system, but also because actions and strategies to interfere, for conservation of processes and services, need to include humans. LTSERs could provide insights, means, and knowledge for a "sustainability transition" (Singh *et al.* 2012). The inclusion of socio-ecological is becoming another

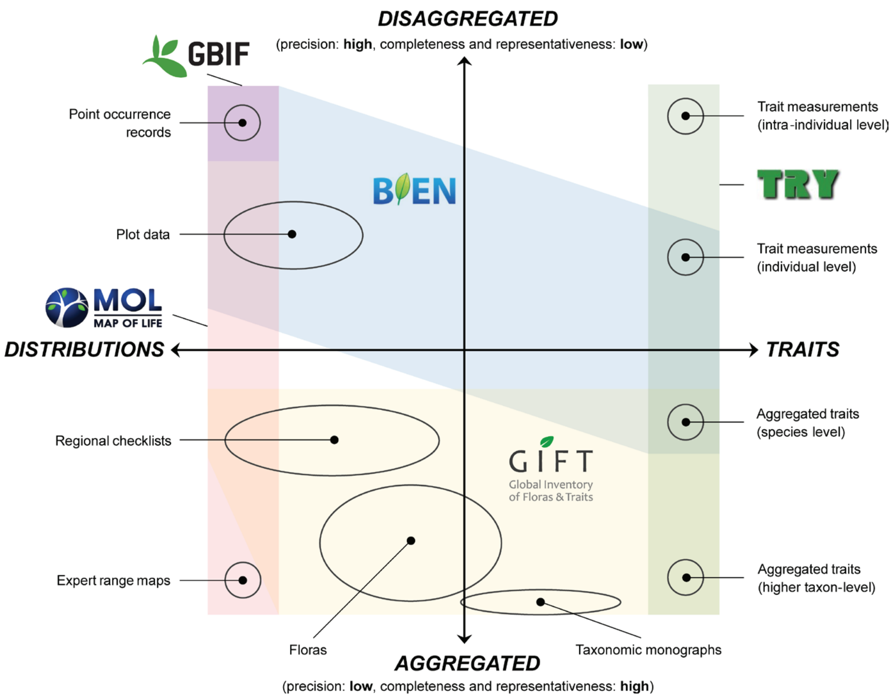

Figure 2. Selected biodiversity data types, arranged according to their primary domain (species distributions versus functional traits) and informational resolution (disaggregated versus aggregated). Projects that integrate global plant diversity data are often domain-specific or focus on the disaggregated end of the data spectrum (modified from König *et al.* 2019) https://doi.org/10.1371/journal.pbio.3000183.g001

“elusive object or goal that is sought after for its great significance”, another Holy Grail. A whole new set of questions and approaches are involved in the passage from LTER to LTSER (Dick *et al.* 2018), such that the object or goal in LTSER studies may be even more elusive than the search for long time series and data integration. Still, it becomes and objective of its own, worth pursuing and potentially leading to the even more elusive goal of sustainability.

In conclusion, Holy Grails as a metaphor represent consolidated, valued and justified objectives that orient and guide future research efforts. Long time series and data integration are such consolidated Holy Grails, and we should pursue them. The same may applies to the more recent endeavor of including human societies as part our systems of study. However, we should not forget that these are steps to answer scientific and management questions, that should always guide our steps and study designs.

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