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The next generation of site-based long-term ecological monitoring: Linking essential biodiversity variables and ecosystem integrity

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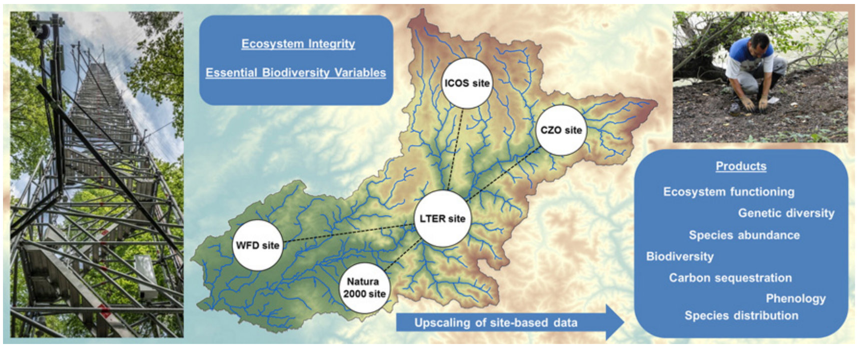
HIGHLIGHTS

- Monitoring changes in biodiversity requires improved standards and frameworks.
- We link the Ecosystem Integrity and Essential Biodiversity Variables frameworks.
- We make recommendations for long-term monitoring variables and instrumentation.
- Site-based long-term monitoring data will become more broadly applicable.
- Co-located monitoring site networks will enable covering all recommended variables.

GRAPHICAL ABSTRACT



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ABSTRACT

Global change effects on biodiversity and human wellbeing call for improved long-term environmental data as a basis for science, policy and decision making, including increased interoperability, multifunctionality, and

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harmonization. Based on the example of two global initiatives, the International Long-Term Ecological Research (ILTER) network and the Group on Earth Observations Biodiversity Observation Network (GEO BON), we propose merging the frameworks behind these initiatives, namely ecosystem integrity and essential biodiversity variables, to serve as an improved guideline for future site-based long-term research and monitoring in terrestrial, freshwater and coastal ecosystems. We derive a list of specific recommendations of what and how to measure at a monitoring site and call for an integration of sites into co-located site networks across individual monitoring initiatives, and centered on ecosystems. This facilitates the generation of linked comprehensive ecosystem monitoring data, supports synergies in the use of costly infrastructures, fosters cross-initiative research and provides a template for collaboration beyond the ILTER and GEO BON communities.

1. Introduction

Global environmental issues, including the impacts of land use, climate change, and biodiversity loss are at the center of humanity's grand challenges (e.g. Sala et al., 2000; Rockström et al., 2009). These challenges are reflected in policies at multiple scales such as the United Nations Conventions on Biological Diversity (CBD) Strategic Plan and Aichi Targets for 2020 (web reference 1). Further, among others, the United Nations Sustainable Development Goals 13 and 15 call for combating climate change and preserving terrestrial ecosystems (web reference 2), and the EU Biodiversity Strategy aims to halt the loss of biodiversity and ecosystem services in the EU and help stop global biodiversity loss by 2020 (web reference 3). To tackle these grand challenges, detecting environmental change at multiple spatial and temporal scales through biotic and abiotic research and monitoring programs is fundamentally important for policymakers, environmental managers and scientists (Parr et al., 2002; Peters et al., 2014). Because long-term data are needed to disentangle change driven by anthropogenic stressors from background noise (Magurran et al., 2010), they are of central value to each of these user communities.

As most existing long-term environmental observation programs have developed from specific scientific questions posed by individual scientists or research groups, these programs are typically decentralized (Marsh and Trenham, 2008; Schmeller et al., 2009), rarely harmonized globally (Scholes et al., 2012) and unevenly distributed geographically (Amano and Sutherland, 2013). This applies to most available networks measuring biotic and abiotic variables simultaneously, with a few exceptions of centrally organized or centrally funded networks and facilities such as the Integrated Carbon Observation System (ICOS), National Ecological Observatory Network (NEON; USA), and Terrestrial Ecosystem Research Network (TERN; Australia), respectively. Furthermore, biodiversity monitoring has historically often been hampered by design flaws (Yoccoz et al., 2001) and available data are strongly biased towards popular taxa such as birds, butterflies and vascular plants (Schmeller et al., 2009). The lack of methodological standardization impairs cross-site comparability and scalability across spatial and temporal scales (Pereira and Cooper, 2006), which is an issue that applies to long-term monitoring as well as almost all kinds of comparative environmental research.

Accordingly, there is common agreement on the necessity to harmonize, coordinate and synthesize long-term environmental data (both biotic and abiotic) to enable comparisons within and between networks, ecosystems, and scales (Hoffmann et al., 2014). Currently, we see parallel developments of data harmonization and integration mechanisms driven by different scientific communities and facilities (e.g. NEON, GEO BON, ILTER, Kissling et al., in press). The maturity of these initiatives varies from informally affiliated scientists that share data to more developed infrastructures with harmonized measurements and automated quality assurance and data integration workflows. However, one step that has been lacking so far is to link the different initiatives, enabling the interoperability of collected data and creation of interfaces between the different approaches embraced by the various communities. One goal of such a development would be the establishment of a co-located network of sites within one ecosystem with shared research and monitoring tasks that provides modular data for flexible and multi-purpose uses. A co-located network of sites could be constituted by a collaboration between, for example, an LTER site, a NATURA 2000 site and a Critical Zone Observatory that are located within the same ecosystem.

Based on the expertise of scientists from different long-term environmental monitoring communities, the objective of this paper is to provide a conceptual framework that serves as an improved guideline for future site-based long-term research and observation. By covering a broad variety of biotic and abiotic variables included in existing frameworks, this new generation of site-based long-term observation would provide a broader suite of ecosystem data, allowing causal interpretation of pressure-state relationships and a more holistic view of ecosystems. Such data could be used for a multitude of purposes from basic science to policy reporting (Bingham et al., 2017).

1.1. GEO BON and ILTER

We selected GEO BON and ILTER as exemplary global networks to demonstrate how the challenges of interoperability and linking underlying frameworks could be met. To investigate long-term changes in ecosystems, ILTER gathers in-situ data, which may feed into other global initiatives and networks, such as GEO BON. However, the frameworks behind ILTER and GEO BON show a range of complementarities but differ considerably. By linking these frameworks, future data generation at monitoring sites could serve the needs of both initiatives by incorporating required measurements at their sites. This is particularly timely as major initiatives and facilities have recently been initiated or adapted that will result in new environmental monitoring infrastructures at large scales (e.g. NEON, eLTER Horizon 2020 project). At this crucial time, more emphasis needs to be placed on a holistic framework focusing on what, how and where to measure to use the limited resources most efficiently.

The ecosystem integrity (EI) framework is based on a comprehensive set of abiotic variables for identifying drivers of biodiversity changes within the context of ecosystem structures and processes (after Müller, 2005). In contrast, GEO BON and the essential biodiversity variables (EBV) framework (Pereira et al., 2013; Schmeller et al., in press-a) are more comprehensive for biotic variables. While a broad variety of biotic variables are currently measured at ILTER sites, a consistent monitoring framework is lacking. Most biotic data collected at ILTER sites are insufficient to fulfill the requirements of the multi-scale EBV framework, which covers the hierarchical levels from genes to ecosystems. Conversely, while EBVs are biological state variables documenting changes in biodiversity, they are not foreseen to explain the underlying causes of change. EBVs are not pressure (e.g. exploitation), benefit (e.g. ecosystem services), or response (e.g. proportion of protected areas) variables but they may be combined with these response variables in subsequent analytical steps (Schmeller et al., in press-a). How this could be done is currently under consideration by the GEO BON network (Cord et al., 2017; Vihervaara et al., 2017; Schmeller et al., in press-a; Turak et al., in press-b).

Therefore, we propose a new, integrated approach linking the EI and EBV frameworks for site-based, long-term ecosystem research and monitoring to be applied in terrestrial, freshwater and coastal ecosystems. This integrated approach will support holistic ecosystem research and simultaneously provide data for biodiversity and ecosystem service reporting purposes. This combined framework is recommended for consideration when setting up new, or further developing existing, long-term research and monitoring sites featuring three clear benefits: 1. Ensure that individual sites or co-located site networks cover the most important features of ecosystems. 2. Promote the comparability and interoperability of data between different sites and monitoring networks. 3. Provide coherent environmental data that allows for causal analyses of basic ecosystem research, environmental monitoring schemes, reporting purposes and decision making at local, regional and global scales (see also Turak et al., in press-a). This integrated approach requires coordinated measurements and infrastructures at monitoring sites and an aggregation of co-located sites to form site networks within an ecosystem.

1.2. LTER, ILTER and the ecosystem integrity (EI) framework

LTER is a general umbrella term for site-based long-term ecological research and monitoring. LTER represents formal national, continental and global in-situ networks of research sites, and also independent long-term research sites and communities. By investigating cause-effect relationships, the LTER community strives to support local to global environmental research and decision making through a better understanding of ecological and socio-ecological processes under global change. ILTER (International LTER) is the global network of national LTER networks linking almost 900 LTER sites covering a broad range of ecosystems (terrestrial, freshwater, marine) in many different biomes globally (Vihervaara et al., 2013; Haase et al., 2016). The novelty of such networks is the ability to collaborate among site-based projects, thus improving data usage for detecting trends and facilitating the analysis of “combined effects” (multiple stressors). LTER sites and national networks have mainly been developed in a bottom-up manner. This entails that sites were established for different research and monitoring purposes potentially resulting in different research foci. These sites cover a wide variety of ecosystem types, plot sizes, infrastructures, and instrumentation, and individual sites measure a wide range of biotic and abiotic variables according to site-specific requirements.

A modified version of the EI framework (Müller et al., 2000; Müller, 2005) has been adopted by the European node of ILTER and has now been recommended for the entire ILTER network as the conceptual framework for indicator selection, data integration and upscaling for individual sites (Fig. 1). The EI framework combines biotic and abiotic aspects of ecosystems with ecosystem structures and processes. Thereby, it differs from the traditional approach of investigating individual components of ecosystems separately (Crabbé et al., 2000). Essentially, EI represents the self-organizing capacity of ecosystems (e.g. during succession or after disturbance) and reflects the idea of sustainability from an ecological perspective (Müller et al., 2000).

The EI framework comprises two primary components, ecosystem structures and ecosystem processes, of the hierarchical EI structure, with five nested secondary components (Fig. 1). Ecosystem structures comprise biotic diversity (e.g. number and identity of selected indicator taxa) and abiotic heterogeneity (e.g. soil type and water content), whereas ecosystem processes comprise energy, matter and water budgets. Budgets can be estimated based on system inputs, storages, outputs and additional state variables. The structural components of EI (biotic diversity and abiotic heterogeneity) essentially describe the state of the system, which can respond to pressures such as climate or land use change, whereas the process components directly reflect states, pressures and changes. This results in 23 basic EI indicators that comprise more specific variables, such as faunal diversity to be indicated by fish, bird or insect diversity, for instance.

1.3. GEO BON and EBVs

Many ecosystem changes, particularly with respect to species or habitats, reflect regionally specific environmental changes, such as those addressed in the newly emerging field of macrosystems ecology (Heffernan et al., 2014). Therefore, to adequately track trends globally and also recognize changes locally and regionally, monitoring data need to be collected at multiple scales in a variety of bioregions (Collen et al., 2011; Heffernan et al., 2014). For this purpose, the Group on Earth Observations (GEO), a voluntary group of government and non-government organizations, launched GEO BON (Scholes et al., 2008). GEO BON was established with the primary goal of harmonization and coordination of initiatives and organizations collecting, maintaining, managing and using data. The overall goal of GEO BON is to facilitate and guide biodiversity monitoring at global, regional and national scales, considering different time scales from physiological to evolutionary responses. By coordinating and harmonizing biodiversity data for more widespread and standardized usage, individual observation data will synergistically contribute to an ever more valuable network level database (Schmeller et al., 2015).

Noss (1990) emphasized that biodiversity is not only the presence of certain species or genes, but also other important aspects of ecosystems such as functional and structural components. Thus, indicators of biodiversity need to be multifaceted and considered at different levels from genes to habitats, but major gaps remain (Feld et al., 2009). As it is unrealistic to measure all aspects of biodiversity, it is essential to prioritize the most important into standardized variables as an additional layer between basic biodiversity observation and aggregated indicators. The EBV framework represents such a layer (Pereira et al., 2013; Brummitt et al., in press; Schmeller et al., in press-a) and is defined as a measurement required for study, reporting, and management of biodiversity change (Pereira et al., 2013). The EBV framework aims to mobilize, standardize and harmonize biodiversity data to document biodiversity change (Fig. 1) and lends itself to cross-realm, large-scale comparability of biodiversity (but see Turak et al., in press-a). EBVs intend to describe change of multiple and critical facets of biodiversity (Schmeller et al., in press-b), including ecosystem functioning. Aggregated EBV data has the potential to facilitate the comparison of key biodiversity features within and among ecosystems and ecosystem types across space and time (Brummitt et al., in press). EBVs based on species occurrence data or derived from remote sensing (O'Connor et al., 2015; Skidmore et al., 2015; Pettorelli et al., 2016; Kissling et al., in press) may be the most straightforward to operationalize, but many others may need adjustments in the data collection to robustly document changes of the biological units over space and time (Schmeller et al., in press-b). While existing long-term monitoring programs cannot necessarily change methodologies to standardize data (Schmeller et al., 2015), EBVs are relevant for a range of monitoring techniques and technological transitions (Pereira et al., 2013).

2. A proposed holistic, conceptual framework for next-generation site-based long-term ecosystem research and monitoring in terrestrial, freshwater and coastal ecosystems

ILTER and GEO BON differ considerably in their structure and purpose, as ILTER pursues a holistic approach to understanding ecosystems and their biotic and abiotic components while EBVs and GEO BON focus on biodiversity in particular. However, both create or work with site-based biodiversity data. While both the EBV and EI framework cover static and dynamic aspects, EBVs are geared towards biotic data (four out of six EBV classes require biotic data only, Fig. 1), whereas EI places more emphasis on the abiotic components (four out of five level-two components require abiotic data only; Fig. 1). Nevertheless,

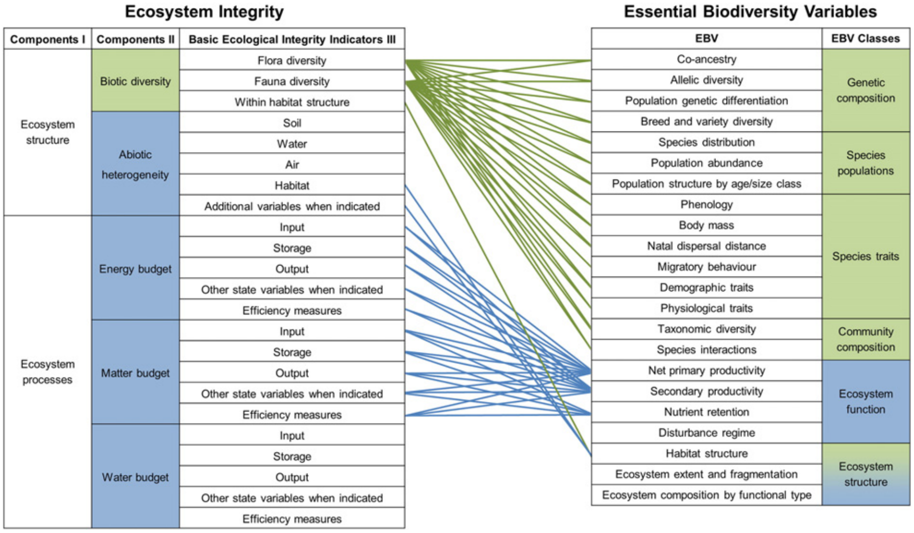

Fig. 1. Ecosystem integrity (EI) and essential biodiversity variables (EBV) frameworks. Lines indicate examples of linkages, differences in resolution and complementarity of EI and EBV frameworks (green color refers to biotic and blue color to abiotic indicators or variables, respectively). Green lines indicate that three biotic EI indicators are relevant for 16 EBVs. Blue lines indicate that four biotic EBVs are relevant for 12 abiotic EI indicators.

while the EI framework comprehensively covers the abiotic variables at monitoring sites, the biotic integrity indicators lack sufficient detail and standardization to be applicable to within- and among-network harmonization (Brown and Williams, 2016). An ideal monitoring site should however be able to provide data suitable for both the EI and EBV frameworks.

To capitalize on the individual strengths of both the EI and EBV frameworks and to enable greater contribution of site-based data to wider global initiatives, we propose to integrate the two frameworks for site-based long-term monitoring. Based on this integration and to operationalize our approach, we provide specific recommendations for what (set of variables) and how (list of measurements and instrumentation) to measure at monitoring sites (Table 1, Fig. 2). These recommendations result from a compilation of intensive discussions among LTER scientists and site managers, reflect realistic observation of site conditions, and were further adjusted towards already existing standards in other monitoring approaches (e.g. ICOS, NEON). We also incorporated GEO BON/EBV experts and key information from the literature on EBVs and EI in our decision making process.

The integration of the EI and EBV frameworks would enable individual monitoring sites or co-located site networks within an ecosystem to capture essential ecosystem structures and processes in a more standardized and comprehensive way. In this manner, we aim to strengthen the biotic component of EI in particular, while simultaneously contributing important biodiversity data to global biodiversity monitoring through GEO BON. The overarching goal of EBVs provides a greater coverage of biotic data and the ability to upscale beyond individual sites.

Variables measured at ILTER sites can be directly merged into EBVs. For instance, ecosystem process components in EI directly link with ecosystem function EBVs (e.g. EI energy budget with EBV net primary productivity, or EI water budget with EBV disturbance regime), and the abiotic heterogeneity EI components feed into ecosystem structure EBVs (Fig. 1). As another example, the flora and fauna diversity indicators of EI provide a high-level abstraction of several EBVs, including: genetic composition (e.g. co-ancestry, allelic diversity); species populations (e.g. species distribution, population abundance); species traits (e.g. phenology, body mass); and community composition (taxonomic diversity, species interactions). Hence, such EBVs can be used to serve as a guideline for more specific biotic measurements eventually feeding these currently very broad EI indicators.

Simultaneously considering the EI and EBV frameworks to ensure the full complement of ecosystem structures and processes and holistic biodiversity measurements, respectively, will allow for upscaling data from monitoring sites to meet the requirements of global networks such as GEO BON. Therefore, rather than replacing aspects of one system with elements of the other, we propose an integrative approach incorporating both EI and EBVs into the design process when establishing or updating a monitoring site. More specifically, besides covering all relevant EI components, site-specific monitoring programs should cross-check with the EBV framework to (1) identify data gaps and (2) achieve a higher level of standardization following work flows as outlined in Kissling et al. (in press).

3. Modular ecosystem monitoring

The proposed approach could be applied for various purposes, such as further developing an already highly instrumented site to ultimately cover all variables of the EI and the EBV frameworks. Alternatively, several existing sites, which differ in their level of instrumentation and may belong to different communities (e.g., Critical Zone Observatories, ICOS, LTER, etc.), operation history and specificity of research questions, could form together a network of co-located sites monitoring the full suite of variables in an ecosystem (Fig. 3). An example of co-location would be a specific ICOS (Integrated Carbon Observation System) site, which provides some abiotic data, linked with nearby ecological (organismal) sampling sites such as Natura 2000 (European network of protected sites). Ortega et al. (2012, 2013) demonstrated how different types of environmental stratification data sources can be used to identify sites that can form ecologically meaningful units in co-located site networks.

Ideally, the co-located sites form a formal consortium with a cooperation treaty or memorandum of understanding providing an overarching strategy outlining which site will measure what, and how the resulting data will jointly be used (including tools for data integration and analysis). Environmental authorities may also be an important partner in such consortia as they often measure a multitude of biotic and abiotic

Table 1
Recommended variables, measurements, and instrumentation for terrestrial, freshwater and coastal environmental monitoring sites considering the ecosystem integrity (EI) and essential biodiversity variables (EBV) framework.

EI components & basic indicators		Recommended variables / observations		Recommended site-based instrumentation and measurements	EBV classes to be informed
Abiotic heterogeneity	Habitats	Habitat / land cover		Habitat mapping, remote sensing	Ecosystem structure
	Soils	Soil moisture content / temperature		Measurement beyond the point scale, e.g., cosmic ray probes, wireless sensor network, e.g., Time Domain Reflectometry probes	
		Soil texture, bulk density, pH, C_{org}		Soil inventory / basic mapping of soil physical and chemical properties	
	Water	Water quality: water temperature, pH, electrical conductivity		Standard water quality probes	
	Air	Air temperature, barometric pressure, incoming shortwave radiation, wind speed / -direction, precipitation, humidity		Standard climate station	
Biotic diversity	Fauna	Abundance and identity	... of birds	Point counts / transects	Genetic composition, species populations, community composition
			… of butterflies	Transect counts	
			… of bees	Combined flight traps	
			… of ground beetles	Pitfall traps	
			… of benthic invertebrates	Multi-Habitat-Sampling	
		Species richness in water and soil		eDNA (environmental DNA; species detection)	
		Terrestrial species diversity		Automated multi-sensor station for monitoring terrestrial species diversity (AMMOD); identification based on DNA metabarcoding	
	Flora	Abundance of vascular plants		Vegetation survey during the phenologically most appropriate time	
	Within-habitat structure	Vertical forest structure (stand height; tree height, tree diameter)		Standard forest inventory / remote sensing	Ecosystem structure
Energy budget		Concentration of CO_2, water vapor, albedo/radiation budget, soil heat flux, climate variables		Eddy-flux covariance station	Ecosystem function
		Leaf Area (Index, LAI)		LAI optical sensor	
		Primary productivity (biomass above ground)		Light Detection And Ranging (LiDAR); use of data from forest inventory	
		Transpiration		SAP-Flow-measurement	
Matter budget		Wet / dry / bulk atmospheric deposition		Deposition samplers	
		Discharge surface water; spectral absorption coefficient; DOC; nutrients		Optical sensors; multiparameter probes	
		Soil water chemistry		Soil water samplers and analysis	
Water budget		Hydrological discharge: discharge, water temperature, pH, electrical conductivity		Standard gauging station including measurements of basic physical variables	
		Groundwater: level, temperature, specific conductivity		Groundwater station	
		Throughfall and stemflow		Throughfall samplers, stemflow collectors	
		Snow depth		Optical sensors	

variables to fulfill legislations like the Water Framework Directive, the Clean Water Act or the Habitats Directive.

Such modularity in ecosystem monitoring allows for a wider use of site-based research and monitoring data and cross-network communication. For example, networks focusing on different questions could simultaneously incorporate data from other networks, in addition to their own collected data. This leads to two complementary layers: the first layer comprises sites that measure few data that fit into a single or few frameworks, but cover (almost) all ecosystem types altogether (e.g. Natura 2000). In the second layer, single sites combine to build a network of co-located sites within an ecosystem that together measure all major components of the EI and EBV frameworks and can thus be used to inform different scientific and political communities. The criteria for co-location of sites may vary depending on the scientific question that is addressed. In particular, the different spatial and temporal scales of patterns and processes under study may require a flexible arrangement of co-located site networks.

4. Discussion

Here, we outlined how to make use of the existing EI and EBV frameworks for future site-based ecosystem research and monitoring.

Fig. 2. Left: Eddy covariance tower measuring energy and trace gas (e.g. CO_2) exchange between the ecosystem and the atmosphere. Right: Flight interception trap for monitoring of flying insects (e.g. bees).

In particular, we recommend a list of variables, methods, and instrumentations that we regard as important for representing the state of ecosystems and biodiversity (Table 1). This list was developed to harmonize measurements across ecosystems and focusses on the requirements of the EI and EBV frameworks. We see this as the first step in the process of harmonization of these frameworks, as we do not provide specific details of how and when to measure such variables, and accept that there are other possible variables that could be included beyond those that are recommended (for EBVs e.g. Schmeller et al., in press-b). The benefit of the merging of these frameworks is that the variables listed are commonly used in ecosystem monitoring.

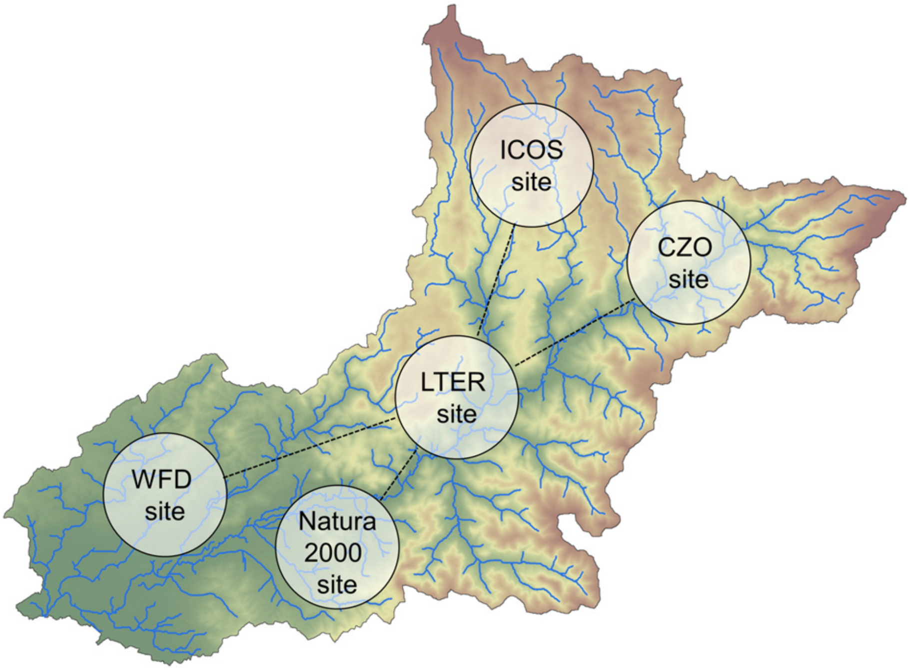

Fig. 3. Example of a co-located site network that altogether is measuring all variables required for EI and EBV frameworks. WFD - Water Framework Directive; ICOS - Integrated Carbon Observation System, CZO – Critical Zone Observatory.

4.1. Real world constraints and potential solutions

We are aware that our list is still challenging for the vast majority of sites. Yet, we believe that some already highly instrumented sites could be further equipped to eventually become "master" sites covering all relevant ecosystem structures and processes (e.g. NEON or TERENO sites). However, many aspects of biodiversity still require skilled labor rather than automated instrumentation. Consequently, instrumentation always needs to be complemented by expert knowledge. For the majority of sites, a more realistic and much cheaper scenario is the formation of co-located site networks within an ecosystem, where a single site does not need to cover all variables and instrumentation.

From the perspective of a monitoring site, this will likely come with various challenges. For example many existing long-term time series use specific methods or instrumentation that are not recommended here and a change in methodology may destroy such time series. Therefore, there will likely be a tradeoff between keeping the method or instrumentation and the continuity of data. For such cases, appropriate statistical tools that address differences in methods can be used to analyze heterogeneous datasets. Harmonization in methods and instrumentation at newly emerging sites or upgraded sites would, nonetheless, be a first major step.

Another important constraint that applies to most sites is a limitation in funding, making the maintenance of existing data challenging and extensions of the monitoring schemes even more so. Yet the disproportionately higher benefits from the option to join a network of co-located sites, access additional data from comparable sites, and embed one's own data in new contexts might help to convince funding agencies to invest in staff and instrumentation that will meet the recommendation presented here (e.g. McDowell, 2015).

Although we promote a higher degree of harmonization of site-based monitoring, we acknowledge that a certain degree of heterogeneity within long-term monitoring sites is vital to allow for flexible responses to new and emerging scientific and policy issues. Moreover, many other site-based monitoring networks similar to ILTER, such as NEON (restricted to USA) and TERN (restricted to Australia), could also contribute to such data harmonization globally in the long term. However, despite this wealth of monitoring networks, several gaps in coverage of ecosystems exist, particularly in remote and undeveloped areas (e.g. large parts of Africa). Therefore, strategies to close these gaps and improved concepts of regionalization (e.g. Proença et al., in press; Pettorelli et al., 2016) are needed.

Finally, the EBV framework remains theoretical for the moment, as no EBV has yet been operationalized. Work flows for "species abundance" and "species distribution" EBVs have been developed (Kissling et al., in press) and will now be tested under real world conditions. Transferability of these workflows to other EBVs is likely, but needs to be tested. Further, discrepancies still remain in the definition of EBVs, which need to be overcome quickly to not overload the framework with too many different views and perceptions (Brummitt et al., in press; Schmeller et al., in press-a). In addition, in the original description of the EBV concept (Pereira et al., 2013) ecosystem function is mentioned as EBV class, while generally EBVs are biological state variables and therefore biotic (Schmeller et al., in press-a). The different budgets in the EI concept are therefore pressures and drivers of biodiversity change as documented by an EBV (see Table 1). They are useful to describe why biodiversity is changing. Finally, too many EBVs might be counterproductive for the usability of the framework and the integration of EI and EBV frameworks. The scientific community must agree on the truly essential variables documenting critical biodiversity change (Schmeller et al., in press-b, for a suggestion of a suite of EBVs) and not to include any kind of biological variable easily measured. A high number of EBVs renders the framework too complex and difficult to integrate in ongoing biodiversity monitoring programs. Further, the EBV framework must also be "backward compatible", meaning if historical data is available integration across time and scale must be possible. Hence, not only future but also past change can be documented and lined up between the EI and EBV frameworks. For the operationalization of the EBV framework, our approach to integrate the EI and EBV frameworks should provide useful directions.

4.2. Benefits from joining forces

Long-term ecological research can inform our understanding of the factors driving changes in biodiversity, the self-organizing capacity of ecosystems, the effects of rare events and disturbances, the impacts of stressors on ecosystem function, and the interactions between short- and long-term trends (Müller et al., 2010; Dodds et al., 2012). However, to enable consistent research and monitoring of ecosystem structures and processes, a consistent framework is needed. Currently, many long-term research initiatives suffer from inconsistencies that do not allow for integrating data among sites and beyond the network. These issues inhibit the ability to tackle society's grand challenges like climate change and greenhouse gas emissions, biodiversity loss and land use change, eutrophication, and pollution, which strongly depends on reliable long-term data. We believe the integration of the EI and EBV frameworks can provide a stimulus for substantial improvements in the availability and interoperability of environmental data that can serve as basis for decision making. This is particularly pertinent as Agenda 21, principle 7 (UNEP Rio declaration) indicates that health and integrity of ecosystems need to be preserved, protected and, where required, restored. A common framework for data integration also facilitates upscaling from local measurements to address global research challenges. To achieve the best benefits from these data, more efficient feedback-loops still need to be established between site-based measurements and local, regional and global requirements for both science and policy (Fig. 4).

Ecosystem research and monitoring need to look beyond developing consistency in methods and data within their respective networks. The end point should be a unified standardization of data between networks, which can be used by different GEO initiatives. This task could be achieved through modularization of monitoring. We need standard modular monitoring data that are flexible enough to be fed into different frameworks and used for different purposes. Therefore, monitoring experts should focus on two aspects: 1) defining the interfaces between the frameworks they use; and 2) defining sets of essential variables (e.g. biodiversity, climatic), harmonizing measurement and reporting methods. We believe that an improved cooperation of ILTER and GEO BON can serve as an example for how to overcome fragmentation in the environmental research and monitoring landscape and also catalyze and structure communication between further networks and initiatives. This cooperation enables common environmental questions to be tackled by the research community and important conservation targets (e.g. CBD) to be addressed by managers and policy-makers (Geijzendorffer et al., 2016).

Finally, our recommendations of variables, measurements, and instrumentation also serve as an important contribution to harmonize field research globally. These recommendations can be used by any researcher (entirely independent from ILTER or GEO BON) doing any kind of ecological field research as a guideline on how to collect environmental data in a standardized manner. Future efforts may also focus on standardizing modelling approaches (site-related as well as for up- and downscaling purposes) and contributions from citizen science to site-based monitoring.

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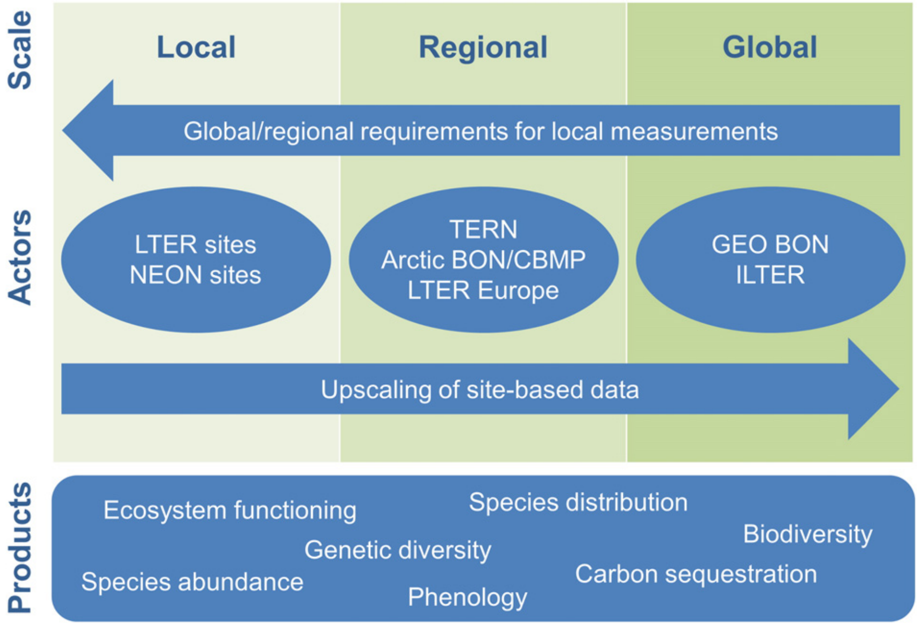

Fig. 4. Feedback-loops of site-based measurements and local, regional and global data requirements and scale independent products. Actors and products: examples are provided only.

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