D01.1 Horizon scanning

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Publishable Executive Summary

Understanding the multiple effects of global change on ecosystems and social systems requires appropriately configured research infrastructures. Rapid biophysical, societal and technological developments may cause unforeseen environmental problems that pose new questions to be addressed and require adjustments of existing research strategies and infrastructures. A horizon scanning was conducted to identify emerging research questions that environmental scientists think need to be considered for future ecosystem research infrastructure development and to prioritize them in a collaborative way. Twenty priority questions that address important gaps in knowledge in ecosystem research were identified. Research questions covered a wide range of topics related to (i) fundamental principles of ecosystem functioning, (ii) the impacts of anthropogenic drivers on ecosystems, (iii) the maintenance of ecosystem services under global change and (iv) advanced methods and technologies that may benefit ecosystem research. From these questions and the explanations of participants a number of key issues relevant for future ecosystem research infrastructure development were derived. First, addressing complex environmental issues requires a further integration of site-based biotic and abiotic measurements. Second, experimental approaches should be combined with long-term observation to improve the understanding of mechanisms underlying ecosystem change. Third, strategies need to be developed to respond flexible to new requirements, e.g. regarding spatial scales, frequencies of measurements, methods, without putting the integrity of existing long-term data series at risk. Fourth, indicators and tools to quantify and value ecosystem services need to be further developed. Finally, emerging data-intensive sampling technologies require new capacities and tools for data integration, processing, storage and analysis.

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Publishable Executive Summary

1. Introduction

A key issue for environmental science and research is to find answers to complex questions that emerge from the grand challenges humanity is facing such as climate change, biodiversity loss and food security (United Nations 2015). Well-developed research infrastructures are needed to investigate the multiple impacts of global change on ecosystems and social systems and how they interact. Understanding the multiple aspects of change requires long term observations over large spatial scales, experiments, comparative studies and sophisticated facilities for computation (Schimel & Keller 2015). The identification of key scientific questions represents a prerequisite for long term investments and the successful establishment of extensive research infrastructures, e.g. NEON (2011); TERN (2013). Nevertheless, many aspects of global change are difficult to predict as rapid biophysical and societal changes and technological developments may have unknown, unforeseen and potentially interactive effects on ecosystems and social systems. Thus, long-term research strategies need to be regularly reviewed to inform the most appropriate adjustment and further development of existing research infrastructures.

The European Long Term Ecological Research Network (LTER-Europe) comprises 25 national networks with a pool of around 400 LTER Sites and 38 LTSER (Long Term Socio-Ecological Research) Platforms. LTER-Europe's objective is to enhance the understanding of ecosystem structures and processes which provide essential services to people in the context of global environmental change. LTER-Europe is part of the global network ILTER. The Critical Zone Observatories (CZO) represent an interdisciplinary research network created to study the chemical, physical, and biological processes that shape the Earth's surface (Lin *et al.* 2011). The CZO program was funded in 2007 by the U.S. National Science Foundation. In Europe, the CZO concept was adopted in 2009 by the EU FP 7 project SoilTrEC. LTER-Europe and the European CZO community collaborate in the EU funded project eLTER (http://www.lter-europe.net/elter) to advance the existing network of LTER sites and LTSER platforms.

Horizon scanning represents a method to detect emerging issues within a given discipline by consulting a large group of individuals (Sutherland *et al.* 2011). It has been widely applied in a range of scientific fields such as conservation (Dicks *et al.* 2013), agriculture (Pretty *et al.* 2010), environmental sciences (Kennicutt *et al.* 2015) and sustainability science (Shackleton *et al.* 2017). The method allows for the consideration of both broad topics, e.g. emerging environmental issues at a global scale (Sutherland *et al.* 2016) as well as very specific ones, e.g. potential threats to Nordic duck populations (Fox *et al.* 2015).

Here we used horizon scanning to capture, classify and prioritise the research questions considered by environmental scientists from across Europe and further afield to be the most pressing, so that these may guide the further development of ecosystem research infrastructures. The focus was especially on research questions that are emerging or otherwise address important gaps in knowledge.

2. Methods

The horizon scanning presented in this work followed a modified Delphi approach as described by Sutherland *et al.* (2015). The core team comprised 30 participants from a range of disciplines (e.g. terrestrial and aquatic ecology, earth science, soil science, forest science, landscape ecology) originating from the LTER and CZO community as well as scientists not linked to either community. From the 30 core team members 16 were directly involved in the eLTER project whereas 14 were not linked in such a way. We included both, managers of ecosystem research infrastructures and scientists as main users in the core team. Due to the wide geographic distribution of participants (26 from Europe, 4 from the U.S.) we did not conduct a workshop but implemented several online surveys following Pretty *et al.* (2010). First, core team members were invited by the leading team to participate in the process. Core team members collected emerging research questions in their personal networks by spreading a link to an online survey that also contained background information on the aims of the exercise and the LTER-network. The task of participants of the survey was to name emerging questions related to ecosystem and socio-ecological research that have not been answered, and/or have hardly been recognized, and that form important gaps in knowledge. Further, they were also asked to provide requirements for future ecosystem research infrastructure development. The survey was restricted to terrestrial, freshwater and transitional waters systems (coasts, estuaries but no marine open sea systems). This, and subsequent online surveys, were built using an internal system located at a secured server at Helmholtz Centre for Environmental Research-UFZ. Participation during all stages was anonymous. There was no possibility to link any of the responses to the origin of participants.

In total, 95 research questions from 55 individuals were collected. Questions were consolidated by members of the leading team which included the deletion of duplicates and language editing. Questions were subsequently grouped according to the following four themes:

(i) Ecosystem structures and processes
(ii) Impact of anthropogenic drivers on ecosystems
(iii) Ecosystem services and socio-ecological systems
(iv) Methods and infrastructures

Consolidated research questions and associated explanations were presented to all core team members for a first scoring. Core team members were asked to rank all questions according to their relevance for future ecosystem research infrastructure development at a scale ranging from 1 (lowest) to 10 (highest relevance). For each question a mean score was calculated. The four highest scored questions per theme were chosen to be discussed by the group, in total 16 questions. Participants were given the opportunity to comment on this selection, to provide further explanations particularly with respect to research infrastructures, and to express their agreement or disagreement. Further, they were asked to name one additional question per theme from the list of lower ranked questions that would deserve further consideration as well and to explain their choice. The highest ranked questions and possible alternatives were further rephrased and consolidated according to the suggestions of the participants. This compilation of research questions was subject to a final ranking using the same scale as described above. The resulting five highest ranked questions for the four themes were included in the list of the 20 most important research questions. These questions were further developed by the coordinating team. Research questions are presented in the results section. A short section of text introduces the problem, specifies the gaps in knowledge and presents consequences for ecosystem research infrastructure development, thereby focusing on the LTER-network.

3. Results

3.1 Research questions focusing on ecosystem structures and processes

3.1.1 To what extent do changes in species diversity and community composition due to global change and disturbance impact on functional diversity and what are the consequences for ecosystem functioning?

Introduction describing the problem and gaps in knowledge

It is generally accepted that ecosystem functioning depends on biodiversity and that species loss can considerably reduce functions such as biomass production or decomposition (Hooper *et al.* 2012; Tilman *et al.* 2014). The relationship between species assemblages and ecosystem functioning has been mainly demonstrated by experimental work whereas less knowledge exists regarding its applicability on real world ecosystems characterized by complex trophic interactions (Tilman *et al.* 2014). Measures of functional diversity have increasingly attracted attention as they can improve understanding of mechanisms underlying ecosystem functioning and the provision of ecosystem services (Cadotte *et al.* 2011) as well as the response of communities to disturbances (Mouillot *et al.* 2013b). Nevertheless, many aspects of the relationship between biodiversity components such as species richness, functional diversity and ecosystem functioning remain unexplored. Key questions that need to be addressed are: (i) To what extent can the functional roles of certain species be compensated by others (functional redundancy, see for example Mouillot *et al.* (2013a))? (ii) Can shifts in functional trait space be used to quantify ecosystem resilience (see also Mori *et al.* (2013)? (iii) Are trends in changes of functional trait space due to specific disturbances consistent across different biomes?

Infrastructure requirements

A basic requirement to address this question is the further development of biodiversity monitoring schemes that representatively cover a wide range of taxa, trophic levels, functional types, habitats and ecosystems. To explore the relationship between species assemblages and ecosystem function a better integration of measurements of biotic and abiotic variables within and across site networks needs to be achieved. Research infrastructures will need to generate data in a consistent manner, to maximise the potential to infer the functionality of species, and aid the development of functional diversity indices. As more trait information becomes available the efforts to compile such information in trait data bases should be advanced. Such data bases should explicitly consider intra-specific trait variability as it may have considerable impact on functional trait structure of communities (Carmona *et al.* 2015).

3.1.2 How can we restore degraded soils in order to improve soil functions and services?

Introduction describing the problem and gaps in knowledge

A significant proportion of the world's soils are considered to be degraded, i.e. their capacity to provide ecosystem services is significantly diminished (FAO and ITPS 2015). Major degradation threats include soil erosion, decline in soil organic matter (SOM), soil contamination, soil sealing, soil compaction, decline in soil biodiversity, soil salinization, landslides and desertification (Kibblewhite *et al.* 2008). Given the fundamental importance of soils in ensuring human wellbeing (Amundson *et al.* 2015) soil protection and restoration has become a major issue in environmental science and policy world-wide. Key strategies to improve soil quality include measures to reduce soil erosion, improvement of carbon sequestration, improvement of micro- and macronutrient availability, promotion of soil biodiversity and enhancement of rhizospheric processes (Lal 2015). There are several ways to implement these strategies. For example, soil organic carbon can be increased by organic amendments, the establishment of perennial grassland or the incorporation of crop residues. The success of such practices may largely depend on local circumstances such as climatic conditions (Ogle *et al.* 2005). Research is needed to develop and identify the most appropriate restoration measures under different environmental and socio-economic settings. The latter is indispensable to design proper implementation strategies that concern the needs of land users and local communities. Further, their implementation at management/ landscape scales requires monitoring to measure success and to prevent failure. It is important to develop tools that quantify soil functions and test them in long term studies that relate soil fertility and soil functions to land use practices and carbon amendments.

Infrastructure requirements

Research on soil restoration requires both experimental and observational studies. As many soil processes are rather slow, a long-term approach is required in either case. Soil monitoring in existing site networks should be extended to areas where restoration measures have been or will be implemented. Experiments need to be conducted to explore mechanisms underlying the successful restoration of soils. These experiments should be placed in existing long-term research sites to benefit from existing observations of multiple environmental parameters. A holistic approach will be particularly important to address potential interactions between climate change and soil restoration. Many soil properties that are subject to restoration show considerable spatial variation that complicate the detection of trends, e.g. soil organic carbon (Saby *et al.* 2008). Thus, for large-scale restoration approaches the application of remote sensing methods may be appropriate, e.g. visible, near-infrared (VNIR) and mid-infrared (MIR) diffuse reflectance spectroscopy (DRS) to measure soil organic carbon (McDowell *et al.* 2012).

3.1.3 What is the magnitude of time lags between changes in biodiversity and ecosystem processes?

Introduction describing the problem and gaps in knowledge

The response of species to natural or anthropogenic drivers often occurs with a delay. (Tilman *et al.* 1994; Devictor *et al.* 2012; Gilbert & Levine 2013), the extent of time lags depending on species traits and the type of disturbance (Hylander & Ehrlen 2013). A recent theoretical framework proposes that effects of change that are transmitted across different organizational levels of biodiversity (e.g., individuals, populations, species, communities) along linked cause-effect relationships experience specific lags at each of these intermediate links (Essl *et al.* 2015b). In this way time lags accumulate at more complex organizational levels such as ecosystems. Consequently, changes in ecosystem functions and services may only become visible long after changes in the underpinning biodiversity components. Such time lags have the potential to alter human sensitivity to the importance of biodiversity change particularly when ecosystem service provision does not seem to be immediately affected (Essl *et al.* 2015a). Therefore a proper quantification of time lags is indispensable to inform policy and biodiversity management.

Infrastructure requirements

The expansion of long term monitoring networks that measure biodiversity at different organizational levels and main drivers using standardized protocols represents a key requirement to appropriately assess time lags (Essl *et al.* 2015a). Efforts to compile historical data should be strengthened to better explain the role of time lags in patterns of contemporary biodiversity. To improve the understanding of mechanisms modulating lagged biodiversity response long-term experimental approaches are needed.

3.1.4 How do multi-species interactions that are relevant for ecosystem services and functioning (e.g. pollination, predator-prey, food webs) vary across space (biomes, habitats etc.) and time?

Introduction describing the problem and gaps in knowledge

The web of biotic interactions between species ultimately determines the structure and functioning of whole ecosystems. These interactions are also key for many ecosystem services, e.g. pollination of wild and crop plants, pest control or nutrient cycling, supporting/habitat services. Recent work has shown that global change can lead to considerable alteration of species interactions across time, with consequences for the quality and quantity of service delivery (Burkle *et al.* 2013; Gray *et al.* 2016). While pairwise interactions among species have been studied widely at local sites, little knowledge exists about how complex interaction networks vary across space and time, and how they might influence future range shifts (Kissling & Schleuning 2015). Hence, biotic interactions are currently widely ignored in forecasting biodiversity changes in relation to climate and land use change, and there is no widely established monitoring system to track changes in species interactions over space and time.

Infrastructure requirements

Long-term species observations within current site networks need to be extended by monitoring and recording a large variety of species interactions. It is crucial to think about which new and cost-effective methods can be established for monitoring biotic interactions. The monitoring should explicitly include above-belowground interactions as this aspect commonly receives less attention.

3.1.5 How is community structure related to landscape level processes?

Introduction describing the problem and gaps in knowledge

The composition of local species communities is determined by changes in species abundances, extinctions and colonisations. These processes are influenced by factors acting over different spatial scales. For example, the effects of particular land management practices often have distinct local consequences for habitat quality (Roberge *et al.* 2008) and may be the most important factor affecting whether or not a species occurs at a particular site. In contrast climate change is acting over even larger spatial scales leading to more uniform responses of species at the landscape level. Similarly, different countries and regions have different land use policies and landscape histories, which also affect species, habitat network functionality and processes (Angelstam *et al.* 2013). The occurrence of a particular species, or life history trait, will under the combined effects of land use change, climate change and other drivers largely depend on its ability to persist in suitable habitats and to reach new habitats. Species traits and landscape configuration play a key role for dispersal and persistence. For many species the relative importance of different drivers and the role of the spatial scale they are acting on are not known.

Infrastructure requirements

Changes in community composition are often recorded at individual sites. To explain them properly, data on potential drivers such as climate, nitrogen deposition, landscape composition and habitat connectivity need to be collected beyond the local scale in catchments, landscapes and regions. For several drivers respective information is already available through for example extrapolation of data collected by meteorological or air quality networks, but this may be at an inappropriate spatial and temporal resolution. Remote sensing may provide an appropriate approach to collect additional primary data or aid the calibration of other sources of information. To cover multiple processes that shape species communities over different spatial scales the implementation of spatially nested sampling designs is necessary.

3.2 Research questions addressing the impact of anthropogenic drivers on ecosystems

3.2.1 How will climate change affect the carbon cycle and what are the consequences for the provision of ecosystem services?

Introduction describing the problem and gaps in knowledge

Climate change is expected to affect carbon budgets of terrestrial systems thereby altering their function as carbon sinks or sources (Ciais *et al.* 2013). The combined effects of climate change and rising CO_2 are generally expected to lead to increased plant productivity and thus a negative feedback on climate change. However, predictions on the strength of the feedback remain uncertain (Ciais *et al.* 2013) because there are a number of mechanisms which have not been fully understood. One source of uncertainty is related to the role of soil organic matter (SOM). Changing climatic conditions, in particular temperature and precipitation patterns, but also extreme events, have the potential to reduce the stability of SOM (Schmidt *et al.* 2011; Reichstein *et al.* 2013). Rising temperatures may lead to increasing decomposition rates and releases of CO_2 and/or fluvial loss as Dissolved Organic Carbon (DOC). Decomposition of SOM further leads to mobilization of nutrients, heavy metals and organic pollutants. These processes may have profound consequences for ecosystem service provision such as carbon sequestration or drinking water, food, feed, fiber and fuel production. Currently, the effects of changes in soil water balances and other factors on SOM decomposition rates of different soil types at the field scale are only poorly understood, as are potential interactions between land use and management and changing climate. Further, there are gaps in knowledge regarding the effects of climate change on soil aggregation and disaggregation processes and their consequences for carbon turnover rates. Research is also needed on the fate of nutrients and toxins released from SOM decomposition and their effects on aquatic ecosystems (clarity, nutrient availability, primary productivity and toxicity). However, such individual aspects should always be considered in relation to the entire carbon cycle.

Infrastructure requirements

Addressing these questions requires research infrastructures to be established along climatic, ecoregion and land use gradients. Observatory plots need to include measurements of soil water stable aggregate composition, SOM content within the various aggregates and SOM composition, in addition to gaseous loss of CO_2 and methane. Climatic parameters, the deposition of dust and pollutants as well as the activity of organisms responsible for organic matter decomposition need to be recorded in parallel. To assess the impact of changes in the delivery of SOM into on aquatic ecosystems observatories should comprise entire catchments which represent different regional contexts to allow for comparative studies. Experiments addressing the efficiency of soil management options aiming at the stabilization of SOM should be placed in long-term observatories. In order to increase their meaningfulness investigations must be carried out in close proximity to existing research infrastructures dedicated to the quantification of carbon and greenhouse gas budgets.

3.2.2 What is the impact of increases in the frequency and intensity of extreme events on ecosystems as compared to gradual long term changes in environmental conditions?

Introduction describing the problem and gaps in knowledge

Models of future climate change predict an increase in frequency and intensity of extreme weather events (Kirtman *et al.* 2013). Extreme events that exceed the typical range of variation can have strong ecological impacts at various levels of organization, from individuals (Pipoly *et al.* 2013), to populations (Roland & Matter 2013), communities (Mouthon & Daufresne 2015) and ecosystems (Allen *et al.* 2010). Extreme events may also affect ecosystem processes, from local disturbances to biogeochemical cycles at the global level (Reichstein *et al.* 2013). Extreme variation in environmental variables can be more important in shaping biological processes than gradual long-term changes (Gutschick & BassiriRad 2003; Zimmermann *et al.* 2009; Thompson *et al.* 2013). Nevertheless, it remains difficult to disentangle effects of short term events from dynamic natural and anthropogenic background processes, especially in naturally dynamic ecosystems such as streams and rivers (Ledger & Milner 2015). Moreover, there are considerable gaps in knowledge regarding the long term impacts of extreme events on species interactions, food webs and complex ecosystems (Woodward *et al.* 2016). Understanding the effects of extreme events is necessary to inform management practices targeted at increasing the resilience of ecosystems and the sustainability of provision of ecosystem services, as well as handle extreme variation in the delivery of provisioning ecosystem services. The issue also applies to extremes not related to climate such as sudden releases of nutrients and pollutants.

Infrastructure requirements

Many observational research infrastructures and monitoring programs are designed to measure long term changes in ecosystems rather than to capture extreme events and their impacts. To improve existing research infrastructures it is first necessary to identify those extreme events which may be most relevant for the system or process under study and hypothesize main impacts. It should then be evaluated whether current instrumentation, frequency and spatial extent of measurements are sufficient to capture the event itself and its impacts. In some situations baseline measurement frequencies may need to be increased, but in many cases it will be necessary to implement adaptive sampling techniques to enable better quantification of episodic behavior. In the latter case it will be necessary to identify thresholds for considering an event as “extreme” (see also Smith (2011)). Considerable efforts are required to develop and implement new technologies that allow for continuous measurements across time and space. Understanding of the mechanisms of ecosystem response to extreme events would benefit from experimental manipulation of key environmental factors in long term observatory plots. Finally, the spatial scale needs to be expanded, such as from sampling points to entire river catchments and landscapes.

3.2.3 How do nutrient cycles change in the long term?

Introduction describing the problem and gaps in knowledge

Nutrient cycles are characterized by complex abiotic and biotic processes that take place in terrestrial, aquatic, and marine systems and in the atmosphere. Yet, they are heavily impacted by anthropogenic activity and are likely to have transgressed the planetary boundaries below which the risk of destabilization of the Earth system is low (Steffen *et al.* 2015). For example, in 2010 anthropogenic production of reactive nitrogen exceeded natural fixation with far reaching consequences for global nitrogen budgets (Fowler *et al.* 2013). Similarly, the phosphorus cycle has been strongly altered, particularly through extensive phosphorus mining for agricultural use (Bouwman *et al.* 2009). Current quantification of global nitrogen budgets and fluxes is subject to large uncertainties (Fowler *et al.* 2013; Shibata *et al.* 2015) and intensified research on a number of issues is thus required. Participants of the horizon scanning exercise highlighted the necessity to better quantify the contributions of artificial nutrient input (fertilizer use, deposition) and natural input through bedrock weathering and soil formation. Considerable gaps in knowledge exist regarding the spatial heterogeneity of artificial nitrogen inputs and the resulting response of different ecosystems (Shibata *et al.* 2015). Nitrogen leaching from terrestrial systems needs to be better quantified as it affects the trophic structure of aquatic ecosystems. Research needs for aquatic ecosystems are related to the storage and denitrification of reactive nitrogen in aquifers, the level of nitrate retention by riparian wetlands, and the character and origin of dissolved organic nitrogen (Durand *et al.* 2011). It is also clear that a deeper understanding of the socio-ecological dimensions of nutrient cycles is required to improve future predictions.

Infrastructure requirements

Monitoring needs to be configured to allow for the best estimates of nutrient fluxes and concentrations across whole catchments. As nutrient cycles are likely influenced by climate change over the long term a set of sites across large (continental) gradients and replicated in different ecosystems with different landscape histories is needed to estimate parameter values related to nutrient cycling (all relevant forms of N and P) and climatic variables. Measurements at site, landscape and regional levels should also include nutrient uptake and release by plants as well as conversion by microorganisms. Monitoring of N-forms in aquatic systems is particularly insufficient in southern and eastern Europe (Durand *et al.* 2011). Given their importance as source of anthropogenic nutrient releases agricultural and urban ecosystems are currently underrepresented in monitoring networks such as the LTER - network (Shibata *et al.* 2015). Any extension of measurements of nutrients and their impacts should link closely to related initiatives such as the Nutrient Network (www.nutnet.org/). Further, measurements on nutrient cycles need a stronger integration with socio-economic issues, such as linking the potential supply and demand of different bundles of ecosystem services among different contexts and stakeholder groups.

3.2.4 How will hydrology and catchment water balances change under different climate scenarios?

Introduction describing the problem and gaps in knowledge

Altered patterns of precipitation and evapotranspiration due to climate change have a significant impact on the hydrologic response of watersheds. Examples include altered patterns of streamflow, changes in frequencies of extreme hydrological events, and altered groundwater recharge (Jimenez Cisneros *et al.* 2014). In addition climate change is expected to increase water demand for irrigation in arid and semi-arid areas. Model predictions on the future development of the global hydrological cycle show an increasing importance of climate change. For example, river flow regimes are predicted to have changed considerably by 2050, the direction and magnitude of change depending on the region (Arnell & Gosling 2013). Flood frequency may change in some regions of the world, with consequences for human populations, energy production, forest and agricultural production (Arnell & Gosling 2016). Groundwater recharge may be affected by climate and soil carbon change, as well as land use and cover change and in many regions (Taylor *et al.* 2013). The predicted changes in hydrology are expected to significantly affect the availability of water resources for human use (Schewe *et al.* 2014). Global hydrological models represent a key requisite to quantify components of the global hydrological cycle. Current models predicting global hydrological change are subject to a number of uncertainties (Döll *et al.* 2016). Major aspects that contribute to uncertainty in model output include insufficient quantification of human water use due to shortage of data, limited knowledge on the response of vegetation and land cover to future climate and levels of carbon dioxide, and uncertainties in climate projections (in particular precipitation). The latter problem has been identified as major limitation for predictions of future river flow regimes (Arnell & Gosling 2013), flood risks (Arnell & Gosling 2016) and groundwater recharge (Taylor *et al.* 2013). Further challenges related to the development and application of global hydrological models refer to the exploration of differences among different models, the consideration of seasonality in water availability and use, and the inclusion of groundwater flows (Döll *et al.* 2016).

Infrastructure requirements

Limited data availability is considered to constrain analysis of ongoing hydrological changes as well as predictions on the development of the hydrological cycle under future climate scenarios. For example a lack of global groundwater data limits the understanding of climate change and climate variability impacts on global groundwater stocks and constrains the development of adaptation strategies (Taylor *et al.* 2013). Additional measurements are needed particularly to make a better use of remote sense data, for example by mapping land use and land cover change. Detection and attribution of changes in freshwater systems are hampered by limited measurements of river discharge and direct measurements of evapotranspiration in many regions of the world (Döll *et al.* 2016). Non-climatic drivers such as anthropogenic water withdrawal and land cover change are expected to strongly affect hydrological parameters. Thus, research infrastructures need to provide data on these issues at multiple spatial scales.

3.2.5 What are the major impacts of alien taxa on natural ecosystems and on society, and what is their magnitude compared to other drivers of global change?

Introduction describing the problem and gaps in knowledge

Invasive alien species represent a major component of global change (Simberloff *et al.* 2013). Yet, their impacts are heavily debated (e.g. Davis *et al.* (2011); Simberloff *et al.* (2011)), and opinions vary from negligible to disastrous. This uncertainty hampers the ability of decision makers to react to increasing numbers of non-native species globally (Vila *et al.* 2010; van Kleunen *et al.* 2015). There has been progress in developing an internationally accepted classification of alien taxa according to their environmental impacts (Blackburn *et al.* 2014; Hawkins *et al.* 2015; McGeoch *et al.* 2015). However, a comparable method for socio-economic impacts is still lacking. Also many aspects of biological invasions are not known as data on the occurrence of alien species, their status and impacts are not collected routinely over large spatial scales (Latombe *et al.* 2016).

Infrastructure requirements

Existing long-term research networks such as LTER sites provide a good opportunity to study the impacts of invasive species on ecosystems and their interactions with other drivers as in many sites a broad range of environmental variables are already measured. However, to capture a broad range of processes related to biological invasion a further development of measurements with greater consideration of invasive species populations across site networks will be necessary. These should include species that pose serious risk for human well-being such as pest species and vectors of diseases. The selection of species and the level of detail of measurements strongly depend on the hypotheses to be tested and the mechanisms under study. Species listed under the European Commission's Regulation on Invasive Alien Species (European Commission 2016) may be a starting point. In any case efforts to establish and further develop a biodiversity monitoring system that comprises complete biological groups (e.g. vascular plants) should be strengthened. Such comprehensive coverage maximizes the potential to analyze processes at community and ecosystem levels. Any action towards implementing monitoring and research on invasive species should fit into global initiatives to establish a monitoring of biological invasions (Latombe *et al.* 2016) and to standardize assessments of their environmental impacts (Hawkins *et al.* 2015). More conceptual work is needed to develop a standardized system to assess the socioeconomic impacts of biological invasions (see also research question 3.3.4).

3.3 Research questions on ecosystem services and socio-ecological systems

3.3.1 How does biodiversity affect the provision of regulating ecosystem services?

Introduction describing the problem and gaps in knowledge

There is a consensus that biodiversity as natural capital strongly determines ecosystem functioning and ecosystem service delivery (Hooper *et al.* 2012; Harrison *et al.* 2014; Tilman *et al.* 2014; Soliveres *et al.* 2016). The link between biodiversity and ecosystem services has been shown to be particularly tight for provisioning services that are based on primary productivity such as wood and fodder production (Cardinale *et al.* 2012). Close relationships have also been proven for some regulating services such as nutrient mineralization and carbon sequestration whereas for others knowledge on the role of biodiversity remains incomplete due to limited data availability and mixed results, e.g. carbon storage or freshwater purification (Cardinale *et al.* 2012). In a recent review Balvanera *et al.* (2014) investigated the link between species richness (focus on plants, algae, fish, detritivores, natural enemies of pest species, microbes) and six ecosystem services. With respect to regulating services they identified the following sources of uncertainties: (i) There is often a mismatch between the ecosystem function measured and the final service provided to societal stakeholders and actors. (ii) Many studies do not consider multiple processes that underlie the provision of a single service, e.g. water purification. (iii) The role of different components of biodiversity (species richness, composition functional diversity) that may simultaneously affect service supply has been insufficiently assessed. (iv) Species richness may exert positive as well as negative effects on ecosystem functions and trade-offs between those effects may determine final service supply. (v) The relationship may be strongly context-dependent with respect to ecosystem management and environmental conditions.

Infrastructure requirements

Assessing the link between biodiversity and the potential supply of ecosystem services vs. the actual delivery of ecosystem services, and the effects of global change on this relationship requires large-scale and long-term studies. These need to include both observational comparative and experimental approaches. Observational studies need to be conducted under representative management conditions (Balvanera *et al.* 2014) that should be performed at management- and policy-relevant scales such as catchments and entire social-ecological systems. Site networks should cover relevant environmental, landscape history and socio-economic gradients. Biodiversity measurements should include a broad range of taxa and life history traits. Recent work suggests that primary producers, above-ground herbivores and soil decomposers are particularly relevant for the provision of multiple ecosystem services (Soliveres *et al.* 2016); however, alternative taxa may be selected depending on the service under study (e.g. pollinators to assess pollination services). Further, the relevant processes that underlie service delivery need to be measured as well as the resulting ecosystem service that is delivered to society. Experimental facilities that should be run alongside long-term monitoring should enable (i) the creation of a range of communities of different taxa with varying levels of diversity and (ii) the manipulation of environmental conditions to simulate global change (e.g. climate, pollution, management).

3.3.2 How can a rising human population be fed in a way that is environmentally sustainable?

Introduction describing the problem and gaps in knowledge

It has been emphasized that global agricultural production must grow to meet the demands of a rising human population, while at the same time reducing its negative environmental impacts (Foley *et al.* 2011). Several approaches for alternative agricultural systems that ensure both aspects have been proposed and/ or implemented at small scales such as diversified farming, sustainable intensification, ecological intensification, agro-ecological farming and organic farming (Bommarco *et al.* 2013; Bender *et al.* 2016; Garibaldi *et al.* 2016). A common feature of alternative approaches is the concerted use and promotion of multiple ecosystem services to reduce external inputs, e.g. of fertilizers and pesticides while they differ in details such as the use of biotechnology or the role of livestock and crop farming. It has been argued that introduction of such practices may lead to a global reduction of agricultural production (Leifeld 2016) and meta-analyses seem to support this argument (Seufert *et al.* 2012). However, large scale and long-term assessments of the overall performance of alternative farming practices are limited. Moreover, many studies focus on direct economic effects, e.g. yield measurements, without taking into account a wider range of potential benefits to the wider society (Garibaldi *et al.* 2016). There are a number of unanswered questions that constrain a realistic assessment of costs and benefits across scales and actors. Open questions remain regarding the development of a range of ecosystem components under alternative management practices (e.g. soil evolution), the resulting consequences for ecosystem service delivery and the implications for society (Bommarco *et al.* 2013; Bender *et al.* 2016; Garibaldi *et al.* 2016). There is a particular need to explore the context-dependency that may determine the success of alternative agricultural approaches and to consider appropriate long time scales.

Infrastructure requirements

Infrastructure development must account for the ecosystem and socio-economic dimensions of this question. Examination of the effects of alternative agricultural approaches on ecosystem structures and functions requires long-term experiments and observations under realistic management conditions. It should be evaluated how existing long-term agricultural experiments (Rasmussen *et al.* 1998; Berti *et al.* 2016) can be included. Essential measurements include biodiversity components and a range of abiotic parameters that underlie the supply of ecosystem services. Abiotic parameters should be suited to the quantification of carbon-, nutrient- and water budgets as well as changes in soil structure. Measurements of biodiversity should explicitly include soil organisms as they are expected to play a key role in sustainable intensification practices (Bender *et al.* 2016), but also species that provide supporting/habitat and cultural services related to the attractiveness of landscapes and regions for recreation and amenity migration. Generally, variable and indicator selection should thus not only focus on the quantification of provisioning services but should include the whole suite of ecosystem services that may benefit the wider community beyond farmers (Garrido *et al.* 2017a; Garrido *et al.* 2017b). Such a holistic approach is necessary to assess the overall socio-economic dimensions of alternative agricultural approaches at multiple levels of governance and spatial scales. It has been shown that the success of alternative approaches is highly context-dependent (Seufert *et al.* 2012). Therefore, assessments need to be conducted at relevant large scales (beyond the farm scale) and consider different environmental and socio -economic contexts. Measurements of benefits and costs from multiple stakeholders' perspectives represent an essential component of such analyses. That requirement is satisfied by LTSER platforms, provided that they cover spatial extents large enough to cover rural-urban gradients and commuting ranges for both amenity and job travels (i.e. in the order of 10,000 km^2).

3.3.3 What are the most promising management options for adaptation of ecosystems to climate change?

Introduction describing the problem and gaps in knowledge

Climate change will strongly affect ecosystems and their capacity to deliver essential ecosystem services (Settele *et al.* 2014), but large regional variation in effects is expected. Losses in overall ecosystem service supply, and changes in demands, due to climate change and associated processes are predicted to exceed gains under low mitigation scenarios (Scholes 2016). Adaptation strategies will need to be developed in order to increase the resilience of ecosystem service supply in the face of climate change. There are often alternative options that may differ in effectiveness and that may have secondary (unintended) effects (Felton *et al.* 2016). Thus research on the wide range of potential adaptation measures is necessary to identify the most appropriate ones with respect to multiple conservation goals. Those adaptation measures that have already been implemented need to be accompanied by monitoring to adjust them in in the case of failure. This is particularly important if uncertainty on the expected outcomes is high and if there is pressure to reach immediate decisions (Gillson *et al.* 2013).

Infrastructure requirements

Depending on the ecosystem and ecosystem services under study long-term management experiments will be required to find out best strategies. Experiments are particularly important if an adaptation strategy has the potential to cause unintended effects in ecosystems. To assess the success of management measures that have already been implemented, long-term monitoring of relevant ecosystem components is necessary. Both experimental and observational infrastructures should ideally cover large spatial scales. It may be necessary to adjust the spatial design of existing research infrastructures in order to capture the appropriate scales, at which management for climate change adaptation takes place. In any case such work requires close collaboration with stakeholders responsible for implementation of adaptation strategies, e.g. agriculture, forestry and water regulation. Measurements at monitoring sites depend on the ecosystem under study and the adaptation strategy to be evaluated. They should include the management target (e.g. ecosystem service or conservation goal) as well as potential ecosystem components that may be subject to unintended effects.

3.3.4 Are ecosystem services provided by introduced species of comparable quality to those provided by native biota and what is the proper currency of valuing positive and negative impacts?

Introduction describing the problem and gaps in knowledge

Invasive alien species strongly impact a wide range of ecosystems and cause significant economic losses (Vila *et al.* 2010). Yet, their effects on ecosystem service provision have been shown to be variable (Pejchar & Mooney 2009; Katsanevakis *et al.* 2014). Even species considered as “worst invaders” can express positive as well as negative effects (McLaughlan *et al.* 2014). Many species, or genetically improved variants, have been deliberately introduced to enhance ecosystem service supply, such as the provision of timber by transforming mixed and deciduous forests to coniferous forest (Woziwoda *et al.* 2014) or the regulation of pests by biocontrol, e.g. Roy *et al.* (2016). Many of them also deliver ecosystem services beyond their intentional role (e.g. pollination services by introduced bees (Dick 2001)). Others provide severe disservices, for example by negatively affecting supporting/habitat services and cultural services. However, current knowledge on the multiple effects of introduced and invasive species on the portfolios of ecosystem services is limited (McLaughlan *et al.* 2014). Research is particularly required into their role in ecosystems degraded by other drivers of global change that do not longer support the original native communities (the “novel ecosystem “ concept, see Hobbs *et al.* (2009)). In such novel ecosystems, invasive alien species may sustain, or aid in re-establishment of pre-disturbance communities, rather than disrupt ecosystem processes essential for ecosystem service supply. Landscape restoration and re-wilding are other concepts the consequences of which need to be understood. However, it still remains to be explored whether the quantity and quality of services meet human demands. Access to local and regional stakeholders in LTSER platforms provides excellent opportunity to map the demand side (e.g., Elbakidze *et al.* (2015)), and to link interrelationships between ecological and socio-economic data.

Infrastructure requirements

Basic infrastructural needs are consistent with those formulated for research question 3.2.5 reviewed above: There is a need to establish comparative studies among LTSER platforms with different levels of introduced vs. native species, and a targeted monitoring system for invasive alien species at multiple spatial scales. Apart from large-scale observation, experiments built on invaded vs. non-invaded plots can help to improve the understanding of mechanisms of service supply and suppression, respectively. To address the research question relevant ecosystem structures and functions that can be used as proxies for estimating the potential supply of ecosystem services need to be included in both observational and experimental work. Further, socio-economic approaches are needed to value service supply by native vs. invasive species from different stakeholder’s perspectives. An important starting point is to map stakeholders in different sectors at multiple levels and to learn about their profiles of perceived benefits (e.g., Garrido *et al.* (2017a); Garrido *et al.* (2017b)). Finally, different approaches to valuation can be made (e.g., Merlo and Croitoru (2005); Hirons *et al.* (2016)).

3.3.5 What arguments for the value of ecosystem services may improve ecosystem management leading to improvements in ecological status?

Introduction describing the problem and gaps in knowledge

To describe ecosystems their composition, structure and function need to be understood. This complexity is captured by the biodiversity concept (e.g., Noss (1990)), which was originally proposed to highlight the intrinsic value of nature. Today, policies aimed at regulating anthropogenic pressures on ecosystems have adopted the concept of ecosystem services (ES) as a metaphor and means of advocacy. The ES concept has launched a large and expanding field of research, which seeks to measure and value human and societal dependence on ecosystems (e.g., Norgaard (2010)). While biodiversity captures the potential supply of ES in terms of what can be derived from species, structures and processes (e.g., Brumelis *et al.* (2011)) the ES concept focuses on the benefits to human well-being in terms of provisioning, regulating, supporting/habitat and cultural dimensions. However, this link is not always straightforward as ecosystems may also incur dis-services; and there are trade-offs among services, stakeholders at different governance levels and spatial scales. In addition, abiotic resources need to be considered, and human investment is often required to realize the potential of biodiversity components to deliver human benefits (e.g., Lele *et al.* (2013)). Merlo and Croitoru (2005) provide a good overview of economic valuation technique of tangible goods and intangible services and values. However, it is still under discussion whether economic arguments actually help to improve ecosystem management and resilience. So far valuation of ecosystem services has been dominated by biophysical assessments and economic valuation approaches (e.g., Nieto-Romero *et al.* (2014)). In contrast, relatively little attention has been devoted to valuation based on stakeholders' perceptions in spite of the fact that a stakeholder perspective is critical to successfully tackle land management issues linked to human well-being (Garrido *et al.* 2017a; Garrido *et al.* 2017b). Hence, qualitative socio-cultural valuation is important to identify the portfolios of ecosystem services demanded by different stakeholder categories at different levels of governance. To conclude, the potential supply and actual demand of ecosystem services need to be mapped as input to landscape planning, management and stewardship (Raudsepp-Hearne *et al.* 2010). Research is needed to understand how values that are based on different stakeholders' perspectives influence decision making in environmental issues.

Infrastructure requirements

Large-scale research infrastructures can help designing social experiments illuminating value formation and decision making. One approach to knowledge production and learning about landscapes as social–ecological systems is to compare multiple social-ecological systems in terms of large spaces and places. Angelstam *et al.* (2013) reviewed the landscape concepts' biophysical, anthropogenic, and intangible dimensions. Based on this they exemplified how the different landscape concepts can be used to derive measurable variables for different sustainability indicators. Hypotheses can then be tested by choosing samples of social-ecological systems located along gradients of the three dimensions of the term landscape across continental scales. This approach can improve collaborative learning about development towards sustainability in social–ecological systems. Similarly, analyses of multiple landscapes improve the understanding of the role of context for governance and management. The suite of LTSER platforms in Europe, as well as other landscape approach concepts such as Biosphere Reserve and Model Forest initiatives, provides good opportunities to implement that approach (Angelstam *et al.* 2017; Elbakidze *et al.* 2017).

3.4 Questions dealing with methods and research infrastructures

3.4.1 How can we detect critical thresholds/ tipping points in ecosystem response?

Introduction describing the problem and gaps in knowledge

Tipping points are defined as critical points where a system abruptly and potentially irreversibly shifts into another state. Abrupt changes of ecosystem characteristics in response to certain drivers have been demonstrated at local and regional levels or for certain ecosystems (e.g. Kosten *et al.* (2012)) whereas the existence of global tipping points is subject to ongoing debate (Barnosky *et al.* 2012; Brook *et al.* 2013; Steffen *et al.* 2015). Non-resilient ecosystem shifts may have profound consequences for ecosystem service supply, e.g. food provision and thus for human wellbeing. Prompt detection of tipping points is vital as the time window for environmental decision making and the implementation of management measures may be short (Biggs *et al.* 2009). Still their identification and definition is often problematic. The likely permanence of an observed change is not always obvious, particularly with respect to naturally dynamic ecosystems where it may take years to assess whether a critical threshold has been reached, since long term trends may be masked by short term dynamics. Furthermore, changes in drivers may cause spatially variable responses, leading to higher complexity over large scales. The application of models to predict tipping points may be appropriate in ecosystems where the link between driver and response can easily be established but in more complex systems this approach may have its limits (deYoung *et al.* 2008). Given continued and increasingly heavy human impacts on ecosystems, development of methods to detect tipping points remains an urgent task (Hughes *et al.* 2013). Long term data series of both drivers and responses are needed to understand the occurrence of resilient vs. non-resilient behavior in ecosystems (Müller *et al.* 2016).

3.4.2 Given the differences in monitoring methods, how can changes in biodiversity be compared among different sites and taxa groups?

Introduction describing the problem and gaps in knowledge

Many research site networks such as LTER sites and LTSER platforms have been established in a bottom-up manner. Selection of methods to measure biodiversity has often been guided by specific purposes, local environmental contexts or different research traditions. Consequently, there is considerable variation in methodologies among sites. This is a circumstance that hampers the comparability of data sets and their analysis across large spatial extents. The harmonization of methods should be a primary goal to address this problem. However, any changes in methodology potentially put the integrity of existing long-term data series at risk. Therefore, the development of statistical tools to integrate and analyze heterogeneous data may be more promising. There are already statistical approaches to integrate and analyze biodiversity data from different sources (Henry *et al.* 2008; Solymos *et al.* 2013; Pagel *et al.* 2014). However, thorough efforts are needed to enable the joint analysis of large data sets arising from the emergence of new methods for biodiversity assessment such as remote sensing, camera trapping or soundscaping (see Schmeller *et al.* (2015) for an overview). Given the rapid development of such techniques methodological heterogeneity will remain a top issue in the future.

3.4.3 How can we reduce uncertainties in climate change projections provided by Earth system models?

Introduction describing the problem and gaps in knowledge

Projections of climate change by global and regional climate models are subject to uncertainties that derive from various sources (Hawkins & Sutton 2009; Foley 2010; Flato *et al.* 2013) such as the treatment of aerosols, convection parameterization, treatment and parameterization of clouds, the emission scenarios or the climate system's internal variability. Other uncertainties arise from the treatment and parameterization of processes that link the climate system and major biochemical cycles such as the carbon cycle (Friedlingstein 2015; Bradford *et al.* 2016). Improving the parameterizations of such processes that are important for climate simulations are key to reduce overall uncertainty. Well instrumented research sites can be used for model development through an optimization in the parameterization and process representations in the land surface schemes of global and regional climate models. In this context however, more emphasis should be put on the harmonization of field methods to enable the use of data from different national observation networks for modeling purposes. For example, weather stations should ideally be operated according to World Meteorological Organization standards.

3.4.4 What current technological developments, in particular open sources technologies, benefit ecosystem research?

Introduction describing the problem and gaps in knowledge

Due to the fact that ecosystem research has to deal with complex challenging problems such as dynamic processes or multiple interactions between different drivers and ecosystem components across spatial and temporal scales, new strategies for a more comprehensive environmental monitoring have to be developed. New technologies that allow for extended measurements in space, at higher frequencies and likely at lower costs, are required to implement such a comprehensive approach. Wireless sensor networks (WDN) that deliver real-time data at high spatial resolution are one example for such technology. WDNs are increasingly applied for monitoring and research purposes, e.g. monitoring of water quality (Blaen *et al.* 2016), forest fire detection (Molina-Pico *et al.* 2016), or tracking of animal movements (Dressler *et al.* 2016). Recent work on urban air pollution demonstrates a satisfying data quality if networks are calibrated using standard measurements (Moltchanov *et al.* 2015). Nevertheless, many open questions remain, e.g. regarding their overall costs, stability, sensitivity, life-time and required effort to manage data (Kumar *et al.* 2015). A similar rapid development of open software products facilitates sampling, management (e.g. GeoNet, http://geonetwork-opensource.org/) and analysis (e.g. R, https://www.r-project.org/) of data derived from such technologies. Given the magnitude of opportunities there needs to be a permanent discussion on how a standard setup for comprehensive environmental monitoring sites should look like. The establishment of sites dedicated to research and development could promote the implementation of emerging technologies into existing research infrastructure networks. The implementation of comprehensive instrumentation as explained above requires new user-specific and easy to use infrastructures such as assistance tools for data provision and data processing. With regard to the variety of existing data sources, data acquisition tools and scales, strategies and methods have to be developed to bring research activities and products from science to a more service oriented level.

3.4.5 How can new high-throughput technologies be used to analyze the links between genetic diversity, functional diversity and ecosystem processes?

Introduction describing the problem and gaps in knowledge

Although there has been much progress in introducing intraspecific genetic variation into the analysis of ecological communities, biotic interactions, and ecosystem functioning there are major gaps regarding knowledge concerning the importance of genetic diversity for patterns and processes at the ecosystem level (Crutsinger 2016). The increasing availability of high-throughput sequencing platforms (Reuter *et al.* 2015) and rapidly advancing genomic methodologies could revolutionize this area of research. These new technologies allow for the acquisition of large amounts of data at increasingly diminishing cost. However, there remain unsolved problems associated with a broad-scale application in ecosystem research. On one hand the level of sequencing error rates is still high for some techniques. On the other hand large capacities for computation are necessary to process and analyze data (Bruford *et al.* 2017). To maximize benefits for ecosystem research considerable investment in infrastructure is needed. Apart from appropriate sampling and lab facilities, sophisticated infrastructures for data management and analysis are needed. Data infrastructures are particularly important to integrate genomic with other data on ecosystem structures and processes. The increasing awareness of genomics in all aspects of biodiversity research has led to the establishment of international initiatives to promote and standardize the approach such as the Genomic Observatory Network (Davies *et al.* 2014) and the Genomic Standards Consortium (http://gensc.org). Any extensions of existing site-based ecosystem research infrastructures should conform to these wider initiatives to ensure the maximum use of data by the scientific community.

4. Discussion

Research questions

From the pool of 95 research questions that were collected in the horizon scanning process 20 priority questions were subject to closer consideration in ecosystem research in the context of research infrastructure development. The topics could roughly be assigned to four overarching themes.

Five priority questions were identified that focus on ecosystem structures and processes without a particular emphasis on anthropogenic drivers. They addressed the role of different dimensions of biodiversity for ecosystem functioning, highlighted the importance of functional traits, and addressed the temporal and spatial dimensions of this relationship. Further questions dealt with the role of processes at the landscape level in shaping local species communities and the change of biotic interactions across time. Another topic was the identification of best strategies to restore degraded soils.

Among the questions dealing with the effects of anthropogenic drivers on ecosystems three of them addressed changes in major biogeochemical cycles (carbon, nutrients and water). The impacts of extreme events and biological invasions on ecosystems were subject of two other questions. Although not always explicitly mentioned, all major drivers of environmental change were covered by this selection.

The maintenance of ecosystem service provision under global change was highlighted as a main issue for future research infrastructure design. Highly scored questions related to this topic addressed the importance of biodiversity for regulating services and the ability of invasive alien species to maintain ecosystem services. Management options for ecosystems in response to major societal challenges were the focus of two other questions, one dealing with the maintenance of provisioning services and food security under alternative agricultural intensification approaches and the other seeking the best adaptation strategies in response to climate change. Social aspects play a key role for implementing the ecosystem service approach in ecosystem management. This aspect was highlighted by a question dealing with valuation approaches.

A significant proportion of submitted questions was directly related to research infrastructure development at both site and landscape (=social-ecological system) levels, methodological problems and emerging technologies that may potentially benefit ecosystem research. Particular emphasis was associated with the problem of methodological heterogeneity that complicates large-scale analyses, the use of earth system models for research infrastructure design, and methods to detect tipping points. Infrastructure requirements arising from the application of new technologies such as high throughput sequencing were addressed by two questions.

The topics covered by this exercise emanated from researchers representing different fields of expertise in natural science disciplines such as soil science, forest science, geochemistry, hydrology as well as landscape ecology, macroecology and sustainability science. The observed high priority of methodological aspects indicates that a large proportion of participants originated from infrastructure management. Other beneficiaries of research infrastructures in terms of both LTER sites and LTSER platforms would have specified knowledge needs differently. For example, while social aspects of ecosystem research did emerge, we suspect that they are under-represented.

Despite a detailed instruction to focus on emerging topics, participants tended to formulate general questions and they also gave them the highest scores. While many problems in ecosystem research are well known, there are, nevertheless, considerable knowledge gaps. This applies both to complex and interacting systems (e.g., trophic interactions), how they are linked (e.g., global climate model and regional consequences), and to large spatial extents (landscapes and regions). The limited availability of long-term data emerged as a main obstacle to address questions related to complex environmental problems. Consequently, participants explained basic infrastructural needs how these limitations can be encountered.

Research infrastructure development

The LT(S)ER research infrastructure includes both LTER sites which focus on biophysical topics and LTSER platforms, which focus on ecological and social research topics, and how they are related to each other (Singh *et al.* 2012). An often mentioned infrastructural need was a better integration of biodiversity measurements, e.g., species, composition, habitats, structure, function and processes, with those on the abiotic environment (questions 3.1.1, 3.1.5, 3.2.1, 3.2.3, 3.2.5, 3.3.1, 3.3.3, 3.3.4). The establishment of many research sites has been driven by specific questions related either to the biotic or the abiotic environment, thus limiting the analysis of complex processes that rely on multiple interactions between ecosystem components. Thus, networks of sites for intensive measurements of the biotic and abiotic environment including anthropogenic drivers need to be extended. This calls for integration of LTER sites and LTSER platforms.

Participants of the horizon scanning highlighted the importance of experimental manipulations to address fundamental questions in ecosystem research. Experiments facilitate the understanding of basic mechanisms, yet they often do not reflect realistic conditions. In contrast, observations and comparative case studies (Flyvbjerg 2011) represent a suitable approach to cover large spatial and temporal scales but the high complexity of natural systems may mask existing patterns. Experiments that are placed in long-term observatory plots may be an appropriate solution to benefit from both approaches. Experimental settings that allow for the consideration of higher biological complexity, such as mesocosms (Stewart *et al.* 2013) are suited to investigate mechanisms at the community and ecosystem level over large spatial scales.

Many long-term research site networks are based on a fixed spatio-temporal observation design. However, the highly dynamic and in many cases unpredictable nature of environmental change, as well as human responses, can only be addressed using flexible monitoring approaches. For example, to evaluate the success of adaptation measures for ecosystem management under climate change (question 3.3.3) the adjustment of the spatial design of site networks will be necessary to coincide with management scales. Investigating the impacts of extreme climatic events (question 3.2.2) may require temporal adjustments, i.e. temporarily increasing the frequency of measurements during episodes. In view of limited resources, strategies need to be developed to adapt established LTER site and LTSER platform networks to newly emerging questions while sustaining the integrity of long-term time series. The problem has also been pointed out in the literature on adaptive monitoring approaches (Lindenmayer & Likens 2009). Similar strategies need to be developed to deal with rapid methodological changes. There will be significant methodological advancements in many fields of ecosystem research. New technologies will provide measurements in higher quantity and quality. This will undoubtedly increase the ability to understand complex processes at spatial scales that could not be addressed before. However, introducing new methods may interrupt long-term data series if they cannot easily be compared with traditional methods, and in some cases may themselves be rapidly superseded by next generation technologies. This emphasizes the importance of research sites maintaining some of the most simple but robust measures of ecosystem properties, such as basic meteorological or hydrochemical measurements that may now have been in place for several decades at least.

Many rapidly developing technologies such as remote sensing, high throughput sequencing or sensor networks produce enormous amounts of data that need to be processed, archived and analyzed. Further, these data need to be integrated to enable research on complex environmental issues. Sophisticated and powerful IT-infrastructures will be indispensable to integrate data from different sources and to create specific datasets that fit user needs.

The quantification of the potential supply of ecosystem services represents a key requirement to address several priority research questions (section 3.3). While some provisioning ecosystem services can be measured directly, e.g. yields, the majority of them need to be quantified using proxies. Numerous ecosystem structures and processes acting at different spatial scales have been considered as useful proxies (Eviner *et al.* 2012; Kandziora *et al.* 2013). Spatial modeling of supporting/habitat services that combines evidence-based knowledge about for example species requirements and land cover data with relevant thematic and spatial resolution is one example. However, many ecosystem services involve human management of ecosystems, especially cultural ecosystem services. This requires integration of biophysical data with knowledge about stakeholders' preferences. Regarding the demand side of ecosystem services, LTSER platforms' stakeholder networks provide opportunities to study ecosystem service demand profiles of stakeholders among sectors and levels of governance (e.g., Garrido *et al.* (2017a); Garrido *et al.* (2017b)). To assess a broad range of ecosystem services, efforts to prioritize and harmonize the corresponding measurements across site and platform networks need to be intensified. Finally, different bundles of ecosystem services' contributions to human well-being (Balvanera *et al.* 2017) need to be captured by developing methods for valuation, including monetary (Merlo & Croitoru 2005).

This horizon scanning exercise revealed 20 questions that highlight major gaps in knowledge in ecosystem research and point at methodological developments considered as important for ecosystem research infrastructure development. The outcome will support managers of site networks in evaluating and adjusting research infrastructures to meet user needs. There are numerous rapid and often unforeseen societal and technological developments that cause potential threats to the environment (e.g. Sutherland *et al.* (2016)). There is a clear need for research infrastructure managers to permanently investigate emerging issues to provide the infrastructural basis for successful science. Horizon scanning may be one possible way to identify emerging issues. However, there are also alternatives such as collaborative reviews or expert workshops on specific topics.

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