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Review

Research questions to facilitate the future development of European long-term ecosystem research infrastructures: A horizon scanning exercise

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ABSTRACT

Distributed environmental research infrastructures are important to support assessments of the effects of global change on landscapes, ecosystems and society. These infrastructures need to provide continuity to address long-term change, yet be flexible enough to respond to rapid societal and technological developments that modify research priorities. We used a horizon scanning exercise to identify and prioritize emerging research questions for the future development of ecosystem and socio-ecological research infrastructures in Europe. Twenty research questions covered topics related to (i) ecosystem structures and processes, (ii) the impacts of anthropogenic drivers on ecosystems, (iii) ecosystem services and socio-ecological systems and (iv), methods and

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research infrastructures. Several key priorities for the development of research infrastructures emerged. Addressing complex environmental issues requires the adoption of a whole-system approach, achieved through integration of biotic, abiotic and socio-economic measurements. Interoperability among different research infrastructures needs to be improved by developing standard measurements, harmonizing methods, and establishing capacities and tools for data integration, processing, storage and analysis. Future research infrastructures should support a range of methodological approaches including observation, experiments and modelling. They should also have flexibility to respond to new requirements, for example by adjusting the spatio-temporal design of measurements. When new methods are introduced, compatibility with important long-term data series must be ensured. Finally, indicators, tools, and transdisciplinary approaches to identify, quantify and value ecosystem services across spatial scales and domains need to be advanced.

1. Introduction

A key issue for environmental research is to answer complex questions emerging from the grand environmental challenges facing humanity. Scientific research is required to objectively inform how society can mitigate and adapt to threats posed by climate change, biodiversity loss, deteriorating water quality, resource supply, migration and food security (United Nations, 2015). Understanding multiple aspects of global change requires long-term observations over large spatial scales, experiments, comparative studies and sophisticated facilities for computation (Schimel and Keller, 2015). These are most efficiently achieved through distributed research infrastructures, i.e. multi-national geographically separated place-based entities that perform, facilitate or sponsor research (OECD, 2014), usually with relevant stakeholders (Angelstam et al., 2019). Elements of these research infrastructures may vary in scope, size and instrumentation, but as part of coordinated networks they facilitate research on overarching research questions. Remote sensing techniques are an integral part of this concept as they offer multiple opportunities to extend the spatial and temporal scope. To steer planning and prioritization, it is necessary to identify key issues and questions that distributed research infrastructures should address.

Research infrastructures dedicated to long-term ecosystem research are typically fragmented, unevenly distributed in space and focused towards specific scientific questions (Haase et al., 2018). One initiative trying to overcome these limitations is the European Long-Term Ecological Research Network (LTER-Europe). Its main objective is to enhance the understanding of processes that shape ecosystems and socio-ecological systems under global change (Mirtl et al., 2018). The network currently comprises 25 national networks with a pool of around 400 LTER sites (DEIMS-SDR 2019) and about 45 active LTSER (Long-Term Socio-Ecological Research) platforms (Angelstam et al., 2019; Haberl et al., 2006). These cover the main European ecosystem types, climatic and land use gradients, and usually involve co-located measurements of physical, chemical, biological and socio-economic variables. LTER-Europe is part of the global network ILTER (International Long-Term Ecological Research). The Critical Zone Observatories (CZO) represent another interdisciplinary research network created to study the chemical, physical, and biological processes that shape Earth's surface (Lin et al., 2011; White et al., 2015). The CZO program was funded in 2007 by the U.S. National Science Foundation, and was extended to Europe in the SoilTrEC initiative (Banwart et al., 2011). Currently there are around 230 sites registered in the global Critical Zone Exploration Network (CZEN, 2019), many of them located in Europe. The wide range of expertise, topics and measurements across the ILTER and the CZO networks provides unique opportunities to foster cross-disciplinary research. Nevertheless, different histories of research sites have resulted in considerable heterogeneity in research approaches, measurements and methods which hamper cross-site and cross-network analyses. Therefore, LTER-Europe and the European CZO community are collaborating in the EU funded project eLTER H2020 (LTER-Europe, 2019) to improve the existing network of LTER sites and LTSER platforms and to implement an improved co-location approach with Critical Zone Observatories in Europe.

The establishment and operation of research infrastructures need to be based on a strategic research agenda (Haberl et al., 2006; NEON, 2011; TERN, 2013). Many aspects of global change are difficult to predict since rapid societal changes and technological developments

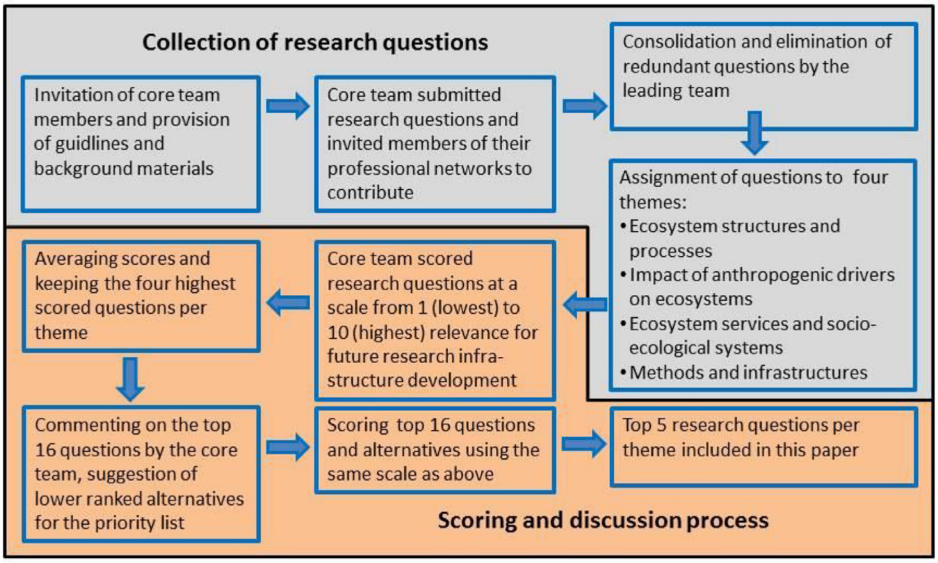

Fig. 1. Conceptual scheme illustrating the identification of the 20 priority questions for future ecosystem research infrastructure development. Grey areas indicate the initial collection of research questions while the prioritization process is highlighted in orange.

may have unknown, unforeseen and potentially interactive effects on ecosystems and social systems. Thus, long-term research strategies need to be regularly reviewed to allow the most appropriate adjustment of existing research infrastructures. Horizon scanning methods represent a common tool to detect emerging issues by consulting a large group of individuals (Sutherland et al., 2011). They have been applied in a range of scientific fields such as conservation (Dicks et al., 2013), agriculture (Pretty et al., 2010) and sustainability science (Shackleton et al., 2017). Here we report on an extensive horizon scanning exercise that was motivated by the current efforts to further enhance the LTER-Europe and CZO site networks. The aim was to capture, classify and prioritize research questions that need to be considered for the future development of long-term ecosystem and socio-ecological research infrastructures. The focus was on research questions that are currently emerging or which address important knowledge gaps.

2. Methods

The horizon scanning presented in this work (Fig. 1) followed a modified Delphi approach as described by Sutherland et al. (2015). The core team (authors of this article) comprised 28 experts from a range of disciplines (e.g. terrestrial and aquatic ecology, Earth science, soil science, forest science, landscape ecology, sustainability science) originating from the international LTER and CZO communities as well as scientists not linked to either community. People were selected from the personal networks of the leading team (four people; MM, GG, NN, SK), and hence do not represent a random sample of scientists. The core team included both research infrastructure managers and scientists using research infrastructures. Following Pretty et al. (2010) we did not conduct a workshop but implemented several online surveys (Fig. 1). The core team members collected emerging research questions in their personal networks by spreading a link to an online survey. Thus, research questions were obtained from both core team members and other people who were invited by them to participate in the survey. Survey participants were requested to identify emerging questions related to ecosystem and socio-ecological research that have not been sufficiently addressed to date, and that form important gaps in knowledge. They were also asked to provide requirements for future ecosystem research infrastructure development. The survey was restricted to terrestrial, freshwater and transitional water systems (coasts, estuaries but no open marine systems) and encompassed both the biotic and abiotic components of ecosystems as well as their relationships to humans. Participation during all stages was anonymous, so that responses could not be linked to the identity or origin of participants.

A total of 98 research questions from 55 individuals (core team members plus participants invited by them; see above) were collected (Fig. 1, Supplementary material 1). Questions were consolidated to eliminate duplicates and to edit language. This was done by the leading team. Research questions were then assigned to four overarching themes that reflect different levels of interaction between humans and ecosystems (i-iii), or focus on methods and infrastructural needs (iv):

(i) Ecosystem structures and processes: Fundamental questions in ecosystem research without explicitly linking them to human activity (23 questions).
(ii) Impact of anthropogenic drivers on ecosystems: How humans alter ecosystem structures and processes (33 questions).
(iii) Ecosystem services and socio-ecological systems: How humans depend on ecosystems, and in which ways human societies may respond to maintain essential ecosystem services (25 questions).
(iv) Methods and infrastructures: The methodological advancements that are required to address complex issues in ecosystem research (17 questions).

The categorization of questions also considered the additional explanations provided by the contributors. Core team members were asked to rank the consolidated research questions according to their relevance for future ecosystem research infrastructure development on 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 for discussion by the core team, in total 16 questions (Fig. 1). This stratification approach was chosen to reduce potential bias due to the composition of the core team and to widen the range of topics. Core team members were given the opportunity to comment on this selection and to express their agreement or disagreement. As a result of this discussion process questions were reformulated, merged or widened in scope. Further, core team members 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 justify their choice. The option to re-instate initially lower ranked issues as part of the discussion process is implemented in many Delphi-approaches (Sutherland et al., 2011). The highest ranked questions and possible alternatives were further consolidated and ranked again using the same scale as described above. The resulting five highest ranked questions within the four themes were included in the list of the 20 most important research questions. These questions were further refined by the horizon scanning core team. In the results section, we consider each of the these 20 questions in turn, specify current gaps in knowledge and set out the consequent needs for ecosystem research infrastructure development.

3. Results

3.1. Research questions focusing on ecosystem structures and processes

Q1. How do changes in species diversity, functional diversity and community composition affect ecosystem functioning?

It is generally accepted that biodiversity underpins the functioning of ecosystems and that species loss can reduce functions such as biomass production or decomposition (Tilman et al., 2014). To date, evidence for the latter hypothesis is largely based on experiments in simplified ecosystems, with few studies on real-world ecosystems with 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), and the response of communities to disturbances (Mouillot et al., 2013b). Nevertheless, many aspects of the relationship between biodiversity components and ecosystem functioning remain unexplored. It is still not fully understood to what extent functions of particular species can be compensated by others (functional redundancy, Mouillot et al. (2013a), whether shifts in functional trait space can be used to quantify ecosystem resilience (Mori et al., 2013) and how trait variation changes in relation to specific disturbances (Bjorkman et al., 2018; Kissling et al., 2018b).

A basic requirement to address these questions is to further develop biodiversity monitoring schemes that represent a wide range of taxonomic groups, trophic levels, species traits, functional types, habitats and ecosystems. To explore the relationships between species assemblages and ecosystem functioning, measurements of biodiversity and abiotic variables need to be coordinated in space and time. Research infrastructures will need to conform to established data standards to enhance interoperability. This will maximize the potential to infer the functionality of individual species and assemblages, and aid the development of functional diversity indices that work across temporal and spatial scales. As more trait information becomes available, the efforts to compile such information in trait databases should be advanced (e.g. Kattge et al., 2011). Such databases should explicitly consider intraspecific trait variability (Kissling et al., 2018b) to examine how this variability affects whole communities (Bjorkman et al., 2018; Carmona et al., 2015). In order to identify functions of individual species it is also necessary to establish facilities for experiments, for example enclosure experiments to measure interacting effects of keystone and invasive species on soil functions and productivity (Mahon and Crist, 2019).

Q2. How can we restore degraded soils in order to improve soil functions and services?

Approximately one third of the world's soils are considered degraded, i.e. their capacity to provide ecosystem services is significantly diminished (FAO and ITPS, 2015). Major threats include decrease in soil organic matter, erosion, landslides, contamination, sealing, compaction, decline in biodiversity, salinization, acidification, eutrophication, and desertification (Kibblewhite et al., 2008). Given the fundamental importance of soils in ensuring human wellbeing (Amundson et al., 2015), soil protection and restoration have become major issues in environmental science and policy. Key strategies to improve soil quality include measures to reduce erosion, increase soil organic matter, maintain appropriate micro- and macronutrient availability, promote soil biodiversity and enhance rhizosphere processes (Lal, 2015). There are several ways to implement these strategies. For example, soil organic matter content can be increased by establishing perennial grassland or forest, increasing organic matter inputs or reducing tillage. The success of such practices may largely depend on site-specific environmental conditions such as climate (Ogle et al., 2005) and land use (Giller et al., 2015). Research is needed to identify and develop the most appropriate soil restoration measures considering environmental and socio-economic aspects. It is important to develop tools that quantify and monitor soil functions and relate soil fertility and function to land use practices and organic matter management.

Since many soil processes are rather slow, long-term approaches are needed. Soil monitoring in existing site networks should be extended to areas where restoration measures have been or will be implemented. Controlled experiments are needed to explore mechanisms underlying the successful restoration of soils. These experiments would benefit from placement in existing long-term research sites to align with existing observations of environmental parameters and enable the implementation of a Before-After Control-Impact (BACI) design (Smokorowski and Randall, 2017; Stewart-Oaten et al., 1986). Many soil properties show considerable spatial variation that complicates the detection of trends, e.g. in soil organic carbon (Saby et al., 2008). Thus, for large-scale restoration approaches remote sensing may be appropriate for detecting change, e.g. visible, near-infrared (VNIR) and mid-infrared (MIR) diffuse reflectance spectroscopy (DRS) to measure soil organic carbon (McDowell et al., 2012).

Q3. Can we quantify the lags between external stressors, biotic responses and dependent ecosystem processes?

The response of species to natural or anthropogenic drivers is often delayed (Devictor et al., 2012; Gilbert and Levine, 2013). The extent of time lags may depend on species traits, the type of disturbance (Hylander and Ehrlen, 2013) and overall ecosystem complexity (Cadenasso et al., 2006). A recent theoretical framework proposes that specific lags occur at each link in cause-effect chains that occur across different organizational levels of biodiversity (Essl et al., 2015b). In this way time lags accumulate at more complex organizational levels. Changes in ecosystem processes may only become visible long after changes in the underpinning biodiversity components have occurred. Therefore, time lags have the potential to alter human perception of biodiversity change particularly when ecosystem service provision is not immediately affected (Essl et al., 2015a). A proper quantification of time lags and an understanding of mechanisms that drive them are indispensable to inform policy and biodiversity management.

The expansion of monitoring networks that measure biodiversity at different organizational levels and drivers of biodiversity change is essential for assessing time lags (Essl et al., 2015a). Efforts to compile historical data should be strengthened to explain the role of time lags in patterns of contemporary biodiversity and to identify baselines to which changes can be compared. To improve the understanding of mechanisms modulating lagged biodiversity response, long-term experimental approaches are needed. This is especially challenging for ecosystems dominated by long-lived species such as trees, where the consequences of changes occurring today may only be visible after decades or even centuries.

Q4. How do the multi-species interactions that underpin ecosystem services vary across space and time?

The structure and functioning of an ecosystem depends on its network of interactions. Network linkages deliver many ecosystem services, e.g. pollination of wild and cultivated plants, pest control, carbon and nutrient cycling (de Vries et al., 2013; Hagen et al., 2012). Global change can lead to considerable alteration of species interactions and service delivery (Angelstam et al., 2017; Burkle et al., 2013; Gray et al., 2016). Little is known about how complex interaction networks vary across space and time (Kissling and Schleuning, 2015). Moreover, biotic interactions are widely ignored in forecasting biodiversity changes in relation to climate and land use change (Kissling et al., 2012; Wisz et al., 2013). Currently there is no widely established monitoring system to track changes in species interactions over space and time (Navarro et al., 2017).

Long-term species observations within current site networks need to be extended by monitoring targeted species interactions in relation to key drivers of change. A focal set of relevant species interactions and associated measurements (e.g. via human observations, sensor networks, isotope and gut analyses etc.) need to be identified and recorded. Given the obvious monetary constraints innovative and cost-effective approaches that can be applied across environmental gradients are needed (Hegland et al., 2010). Suggestions for such measurements have been made by the Group on Earth Observation (Walters and Scholes, 2017). Monitoring should include a wide variety of biotic interactions with relevance to ecosystem services and explicitly include below-ground interactions which commonly receive little attention (van der Linde et al., 2018).

Q5. How is community structure related to landscape level processes?

The composition of local biological communities is determined by factors acting across spatial scales. The size of the regional species pool is key (Cornell and Harrison, 2014), reflecting historical and evolutionary processes as well as large-scale environmental gradients (Svenning et al., 2010). Small scale environmental heterogeneity and the biophysical properties of habitats have been identified as key factors influencing species communities at the local scale (Tonkin et al., 2016). In addition, local biodiversity patterns are determined by structures and processes beyond the local level (Leibold et al., 2004; Tscharntke et al., 2012b). For example, species traits and landscape structure influence dispersal and persistence of species (Hagen et al., 2012) and thus the composition of local communities. There are still many unanswered questions resulting from the complexity of associated processes, interactions and feedback mechanisms. In particular there are gaps in understanding of interactions of habitat loss and fragmentation as well as the role of the matrix and habitat edges (Spiesman et al., 2018; Tscharntke et al., 2012b). Research is needed on the relationships between landscape level processes, functional diversity and important services, for example pollination (Hass et al., 2018) and biological control (Grab et al., 2018).

To investigate the relevance of the landscape for local communities, comparative field studies replicated across different landscape settings are required. Observational studies should be complemented by experiments to assess the relative importance of different drivers and to identify the mechanisms behind community changes. Data on potential drivers such as climate, pollution, landscape composition and habitat connectivity need to be collected beyond the local scale in catchments, landscapes and regions. Remote sensing may be appropriate for collecting such data.

3.2. Research questions addressing the impact of anthropogenic drivers on ecosystems

Q6. How will climate change affect the carbon cycle and what are the consequences for the provision of ecosystem services?

Climate change influences the cycling of energy and matter in terrestrial and aquatic systems via linkages to biogeochemical cycles of carbon, water and nutrients (Ciais et al., 2013). Although rising CO_2 levels have the potential to stimulate plant productivity and hence carbon sequestration, the strength, sustainability and spatial variability of this carbon sink remains poorly understood (Donohue et al., 2013; Lindner et al., 2014; Zhu et al., 2016). Links between biogeochemical cycles can accelerate the effects of climate change on ecosystems. Changes in temperature and soil water availability have the potential to reduce the stability of soil organic matter (SOM) pools (Schmidt et al., 2011) and to increase carbon and nutrient losses by erosion (Frank et al., 2015). Such alterations may also increase decomposition rates, accelerate CO_2 efflux and the release of dissolved organic carbon (DOC) to drainage waters (Camino-Serrano et al., 2016). However, effects of changing temperature and soil moisture on SOM decomposition rates remain poorly quantified (Aerts, 2006). Alterations in soil nutrient availability and plant nitrogen use efficiency in a changing climate may have marked impacts on ecosystem responses, particularly in previously nutrient-poor ecosystems (Kanter et al., 2016; Karhu et al., 2014). Carbon cycle sensitivity to climate change is arguably greatest in the Arctic, which is also warming fastest (Kramshøj et al., 2016). Furthermore, wetland and permafrost ecosystems in particular have enormous climate-feedback potential due to their large organic carbon storage in soils and their methane production capacity (Davidson and Janssens, 2006). Climate change impacts on the terrestrial carbon store are likely to have profound consequences for the delivery of ecosystem services including carbon sequestration and the production of drinking water and food. Climate-induced effects on soil aggregation and disaggregation, soil carbon turnover rates (Banwart et al., 2012) and the fate of nutrients and toxins released from SOM decomposition (Karmakar et al., 2015) require further studies. The terrestrial carbon cycle and fundamental ecosystem services are tightly interlinked. There is potential for climate change-related tipping points, whereby relatively small changes may result in massive carbon releases and forest dieback (Lindroth et al., 2009; Seidl et al., 2014). While specific processes are being studied in isolation at single sites, a much more comprehensive, integrated system-scale approach will be required to understand the broader complexities of climate change impacts on ecosystem functions. This will require research infrastructures operated in a sustainable manner along ecological and land use gradients at continental or global scale (Djukic et al., 2018). Experiments addressing e.g. feedbacks or the efficiency of ecosystem management options should be integrated with long-term observatories.

Q7. 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?

Models of climate change project an increase in frequency and intensity of extreme weather events (Kirtman et al., 2013). Extreme events such as storms, floods, forest fires, droughts or heatwaves can have strong ecological impacts at various levels of organization, from individuals (Pipoly et al., 2013), to populations (Roland and Matter, 2013), communities (Mouthon and Daufresne, 2015) and ecosystems (Allen et al., 2010). Extreme variation in environmental variables can be more important in shaping biological processes than gradual long-term changes (Gutschick and BassiriRad, 2003; Thompson et al., 2013). However both factors do not act independently of each other (Collins et al., 2011). It remains difficult to disentangle effects of short-term events from dynamic natural and anthropogenic background processes. This is particularly true for naturally dynamic ecosystems such as streams and rivers (Ledger and Milner, 2015). There are considerable gaps in knowledge regarding the long-term impacts of extreme events on species interactions, food webs and ecosystem functioning (Woodward et al., 2016), and ecosystem recovery capacities. Understanding the effects of extreme events is necessary to inform management targeted at increasing the resilience of ecosystems and sustaining the provision of ecosystem services. This issue also applies to extremes not related to climate such as sudden releases of nutrients and pollutants.

Observational research infrastructures are not always sufficiently equipped to capture extreme events and their impacts. Baseline measurement frequencies may need to be increased and in many cases adaptive sampling techniques will be needed to quantify episodic behavior once “extreme” thresholds have first been defined (Smith, 2011). Understanding 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.

Q8. How do nutrient cycles change in the long term?

Nutrient cycles are characterized by complex abiotic and biotic processes that take place in terrestrial, aquatic, and marine systems and in the atmosphere. Of particular importance are the element cycles of carbon (C) nitrogen (N) and phosphorus (P), but also potassium (K), magnesium (Mg), calcium (Ca), sulphur (S) and micronutrients. Many of these cycles are heavily impacted by anthropogenic activity and C, N and P cycles in particular are likely to have transgressed planetary boundaries, risking destabilization of the Earth system (Steffen et al., 2015). Current quantification of global N budgets and fluxes is subject to large uncertainties (Fowler et al., 2013; Shibata et al., 2015). Knowledge gaps exist regarding the spatial heterogeneity of anthropogenic N inputs and the response of different ecosystems (Shibata et al., 2015). Nitrogen leaching from terrestrial systems needs to be better quantified as it affects water quality and the trophic structure of aquatic ecosystems (Fleck et al., 2017). Research needs for aquatic ecosystems concern the storage and denitrification of reactive N in aquifers, the level of nitrate retention by riparian wetlands, and the character and origin of dissolved organic N (Durand et al., 2011). There is also the need to better quantify the biogeochemical cycles of other nutrients. This includes the contributions of artificial inputs, e.g. through fertilizer use and atmospheric deposition, and natural inputs through mineral weathering (Meesenburg et al., 2016). It is also clear that a deeper understanding of the socio-ecological dimensions of nutrient cycles is required to improve future predictions (Winiwarter et al., 2011).

Research infrastructures need to be configured to allow for the best estimates of major nutrient fluxes across system boundaries as well as their uncertainties in order to deduce nutrient budgets for the respective ecosystems. Measurements at site, landscape and regional levels should also include internal fluxes such as nutrient uptake and release by plants as well as conversion by microorganisms. Monitoring of N-species in aquatic systems is particularly insufficient in southern and eastern Europe (Durand et al., 2011). Agricultural and urban ecosystems are currently underrepresented in research networks such as LTER and CZO despite their importance as sources of nutrients (Shibata et al., 2015). Measurements of nutrients and their impacts should link closely to related initiatives such as the Nutrient Network (NutNet, 2019).

Q9. What will be the consequences of climate change for hydrology and catchment water balances?

Climate change is projected to cause significant shifts in the global hydrological cycle (Jiménez Cisneros et al. 2014). For example, river flow regimes are predicted to change considerably by 2050, the direction and magnitude of change depending on the region (Arnell and

Gosling, 2013). Flood frequency may change in some regions of the world, with consequences for human populations, energy production, forest and agricultural production (Arnell and Gosling, 2016). Groundwater recharge will be affected by climate, as well as land use and vegetation cover change in many regions (Taylor et al., 2013). The predicted changes in hydrology are expected to significantly affect the availability of water resources also for human use (Schewe et al., 2014). Water availability is often a dominant driver of inter-annual variability in ecosystem productivity, and thus changes in hydrology provide an important feedback to climate (Jung et al., 2017). Hydrological models represent a key requisite to quantify components of the 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 include insufficient quantification of human water extraction, limited knowledge on the response of vegetation and land cover to future climate and levels of carbon dioxide, and uncertainties in climate projections. The latter problem has been identified as a major limitation for projections of river flow regimes (Arnell and Gosling, 2013), flood risks (Arnell and Gosling, 2016), and groundwater recharge (Taylor et al., 2013). Further challenges refer to the exploration of differences among models, the consideration of seasonality in water availability and use, and the inclusion of groundwater flows (Döll et al., 2016). An increasing number of studies deal with the linkages between climate change, hydrological patterns, biodiversity and ecosystem functioning (Domisch et al., 2013; Kakouei et al., 2018). While the effects of changes in hydrology on biodiversity become more and more clear there is still an insufficient understanding of climate change effects (i.e. hydrological alterations) on ecosystem functioning.

Research infrastructures are needed to provide data on the relationships between climate, hydrology and ecosystem functioning across spatial scales. Limited data constrains the analysis of ongoing hydrological changes as well as predictions on the development of the hydrological cycle under future climate scenarios. A lack of global groundwater data limits the understanding of climate change impacts on global groundwater stocks and constrains the development of adaptation strategies (Taylor et al., 2013). Additional measurements are needed to make better use of remote sensing data, for example by mapping habitat change or soil moisture content. Detection and attribution of changes in freshwater systems are hampered by limited measurements of river discharge and direct measurements of evapotranspiration in many regions (Döll et al., 2016).

Q10. What are the major impacts of invasion by alien species on ecosystems and on society, and what is their magnitude compared to other drivers of global change?

Biological invasions represent a major component of global change (Ricciardi et al., 2017; Simberloff et al., 2013). Yet, the magnitude of their impacts is heavily debated (Davis et al., 2011; Simberloff et al., 2011). This lack of consensus hampers the ability of decision makers to react to increasing numbers of alien species (Dawson et al., 2017; Seebens et al., 2017). There has been progress in developing an internationally accepted risk assessment of alien species according to their environmental impacts (Blackburn et al., 2014; Hawkins et al., 2015; McGeoch et al., 2015). Recently, a comparable method for socio-economic impacts has been proposed (Bacher et al., 2018; Nentwig et al., 2016). However, many aspects of biological invasions are not known, as data on the occurrence of invasive alien species, their status and impacts are not routinely collected over large spatial scales (Latombe et al., 2017), even though for some taxonomic groups respective data have become available recently (Dyer et al., 2017; Pyšek et al., 2017).

Existing long-term research networks such as LTER sites provide a promising platform to study the establishment, spread and impacts of alien species, and their interactions with other drivers of global change. Information on alien species need a greater consideration in standard measurements across site networks. These should include species that pose serious risk for human well-being such as pest species and disease vectors. Species listed under the European Commission's Regulation on Invasive Alien Species (European Commission, 2016) may be a starting point. Efforts to establish and further develop a biodiversity monitoring system that comprises entire taxonomic groups and extends spatial coverage for known hotspots of invasion (e.g. urban areas, coastal regions) 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 alien species should fit into global initiatives to establish a monitoring of biological invasions (Latombe et al., 2017) and to standardize assessments of their impacts (Bacher et al., 2018; Hawkins et al., 2015).

3.3. Research questions on ecosystem services and socio-ecological systems

Q11. How does biodiversity affect the provision of regulating ecosystem services?

Biodiversity strongly determines ecosystem functioning and ecosystem service delivery (Harrison et al., 2014; Soliveres et al., 2016). This link is particularly tight for provisioning services underpinned by 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, but the role of biodiversity remains less clear for other services, e.g. freshwater purification or long-term carbon storage (Cardinale et al., 2012). Limited knowledge exists on the role of different biodiversity components for service delivery, the importance of the environmental context and the mismatch between functions measured and the final service provided to society (Balvanera et al., 2014). Research is also required to understand the role of structural aspects of biodiversity for service provision, e.g. the relationship between processes mediated by forest canopy structure and carbon storage (Hardiman et al., 2013).

Monitoring is needed to assess links among biodiversity, ecosystem functions and resilience (Oliver et al., 2015), and the actual delivery of ecosystem services. Research needs to include observational, comparative and experimental approaches and should be co-designed in researcher-stakeholder partnerships. Observational studies need to be conducted under representative management conditions (Balvanera et al., 2014) that should be performed at management- and policy-relevant scales. Site networks need to cover relevant environmental, landscape history and socio-economic gradients. Biodiversity measurements should include a broad range of taxonomic groups and life history traits. Primary producers, above-ground herbivores and soil decomposers are particularly relevant for the provision of multiple ecosystem services (Soliveres et al., 2016), whereas specific groups may be relevant for particular services, e.g. pollinators.

Q12. How can an increasing human population be fed in an environmentally sustainable way?

Global agricultural production must grow to meet the demands of an increasing human population, while at the same time reducing negative environmental impacts (Foley et al., 2011). Several approaches to alternative agricultural systems that ensure both aspects have been proposed such as diversified farming, sustainable intensification, ecological intensification, agro-ecological farming and organic farming (Bender et al., 2016; Garibaldi et al., 2017). Some concepts put a strong focus on technological advancements aiming at enhancing resource use efficiency, e.g. precision agriculture (see McConnell et al., 2017 for an overview). However, such technology-oriented concepts have been criticized for neglecting broader societal needs (Loos et al., 2014). Conversely, it has been argued that introducing practices like organic farming at large scales may lead to a global reduction rather than an increase of agricultural production (Leifeld, 2016; Seufert et al., 2012). Large scale and long-term assessments of the overall performance of alternative farming practices are limited. Many studies focus on direct economic effects, e.g. yield measurements, without taking into account a wider range of potential benefits to society (Garibaldi et al., 2017). There are a number of unanswered questions that constrain a realistic assessment of costs and benefits across scales and stakeholders. 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 (Bender et al., 2016; Garibaldi et al., 2017). Whether food security and biodiversity conservation can be best achieved by pursuing a strategy that integrates both goals in the production process (land sharing) or that favors a spatial segregation (land sparing) is up for debate (Tscharntke et al., 2012a).

Research infrastructure development must account for the ecosystem and socio-economic dimensions of this question. Examining the effects of alternative agricultural approaches on ecosystems, and on soil restoration (Q2, above), requires long-term experiments and observations under realistic management conditions. An evaluation of how existing long-term agricultural experiments (Berti et al., 2016; Rasmussen et al., 1998) can be included should be made. Essential measurements include crop and livestock productivity, 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 include soil organisms as they play a key role in sustainable intensification practices (Bender et al., 2016), but also species that provide supporting and cultural services. Variable and indicator selection should not only focus on the quantification of provisioning services but also include the whole suite of ecosystem services that may benefit the wider community (Garrido et al. 2017a, 2017b). Such a holistic approach is necessary to assess the overall socio-economic dimensions of alternative agricultural approaches. The success of alternative approaches is highly context-dependent (Seufert et al., 2012). Therefore, assessments need to be conducted at relevant large scales, consider different environmental and socio-economic contexts, and account for biodiversity opportunity costs i.e. the value of alternative ecosystems. Cost/benefit analysis from multiple stakeholders' perspectives represents an essential component of such assessments. LTSER platforms will be suitable research infrastructures for that purpose, provided that they cover spatial extents large enough to include rural-urban gradients (Angelstam et al., 2019).

Q13. What are the most promising management options to foster adaptation of ecosystems to climate change?

Climate change will strongly affect ecosystems and their capacity to deliver essential ecosystem services (Settele et al., 2014), but large regional variation in effects and changes in demands is expected. Losses in overall ecosystem service supply due to climate change and associated processes are predicted to exceed gains under low mitigation scenarios (Scholes, 2016). Adaptation strategies will therefore be needed to increase the resilience of the most threatened services. These strategies will require maximizing the adaptive capacity of ecosystems, i.e. their ability to adjust to climate change in ways that sustain ecological functions or that enable desired ecosystem transitions (Chornesky et al., 2015). Numerous adaptive options are currently proposed that are likely to differ in their potential effectiveness and contribution to secondary (unintended) effects (Felton et al., 2016; Fleck et al., 2017). Research into a wide range of potential solutions will be necessary to identify those most appropriate to address multiple conservation goals. Adaptation measures that have already been implemented need to be accompanied by robust monitoring procedures to assess their efficacy and enable changes where they are perceived to be ineffective. 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).

For some ecosystems and ecosystem services, long-term adaptive management experiments will be required to elicit the best adaptive strategies. To assess the success of management measures long-term monitoring of relevant ecosystem components is necessary. Both experimental and observational infrastructures should cover large spatial scales and be distributed among socio-economic regions and biomes. 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. Such work requires close collaboration with a variety of stakeholders responsible for implementation of adaptation strategies, e.g. agriculture, forestry and water regulation. Measurements 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.

Q14. Are ecosystem services provided by alien species comparable to those provided by native species and what is the proper currency for valuing positive and negative impacts?

Alien species can strongly affect ecosystem services (Vilà and Hulme, 2017), but their impacts may vary (Katsanevakis et al., 2014). Many species, or genetically improved variants, have been deliberately introduced to enhance ecosystem service supply, such as the provision of timber (Woziwoda et al., 2014) or the regulation of pests by biocontrol (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 can have detrimental impacts, e.g. by modifying disturbance regimes, water quality or hydrological services (Vilà and Hulme, 2017). Further research is required into the role of alien species in ecosystems degraded by other drivers of global change that no longer support the original native communities ("novel ecosystems", Hobbs et al. (2009)).

Basic infrastructural needs are consistent with those formulated for research Q10 reviewed above, i.e. to establish comparative studies among LTSER platforms with different ratios of alien vs native species, and a targeted monitoring system at multiple spatial scales. Apart from large-scale observations, experiments built on invaded vs. non-invaded plots can help to improve the understanding of mechanisms of service supply and suppression, respectively (Bacher et al., 2018; Kumschick et al., 2015). To address this research question, relevant ecosystem processes used as proxies for estimating potential ecosystem services need to be included in both observational and experimental studies. Socio-economic approaches are needed to value service supply by alien vs. native species from different stakeholder's perspectives (Kumschick et al., 2012).

Q15. What is the most effective approach to valuing ecosystem services to ensure that ecosystem management protects and enhances ecological status?

Many policies aimed at regulating anthropogenic pressures on ecosystems have adopted the concept of ecosystem services as a metaphor and means of advocacy, although the legislative framework remains important. The concept has launched a large and expanding field of research, which seeks to measure and value human and societal dependence on ecosystems (Norgaard, 2010). While biodiversity captures the potential supply of ecosystem services in terms of what can be derived from species, structures and processes (Brumelis et al., 2011), the ecosystem services 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 disservices, and there are trade-offs among services, stakeholders at different governance levels and spatial scales. In addition, abiotic resources need to be considered (Field et al., 2015), and human investment is often required to realize the potential of biodiversity to deliver human benefits (Lele et al., 2013). Merlo and Croitoru (2005) provide a good overview of economic valuation techniques of tangible goods and intangible services and values. It is still under discussion whether economic arguments help improve ecosystem management and resilience. So far valuation of ecosystem services has been dominated by biophysical assessments and economic valuation approaches (Nieto-Romero et al., 2014). In contrast, relatively little attention has been devoted to valuation based on stakeholders' perceptions, notwithstanding that a stakeholder perspective is critical to successfully tackle land management issues linked to human well-being (Garrido et al. 2017a, 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. The potential supply and demand of ecosystem services need to be mapped as input to landscape planning, management and stewardship (Raudsepp-Hearne et al., 2010). Research is also needed to understand how values based on different stakeholders' perspectives influence decision making in environmental issues.

Distributed research infrastructures can be used to design social experiments to illuminate value formation and decision making. One approach to knowledge production and learning is to compare multiple landscapes as socio-ecological systems across various dimensions. Angelstam et al. (2013) reviewed the landscape concepts' biophysical, anthropogenic, and intangible dimensions and exemplified how different landscape concepts can be used to derive measurable variables for different sustainability indicators. Hypotheses could be tested by choosing samples of socio-ecological systems located along gradients of the three above-mentioned dimensions across continental scales. This approach can improve collaborative learning about development towards sustainability in socio–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 (Angelstam et al., 2019), 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., 2018; Elbakidze et al., 2018).

3.4. Research questions dealing with methods and research infrastructures

Q16. How can we detect critical thresholds/ tipping points in ecosystem response?

Tipping points are defined as critical points where a system abruptly and potentially irreversibly shifts into another state. Abrupt changes in response to certain drivers have been demonstrated at local and regional levels or for specific ecosystems (Kosten et al., 2012) and socio-ecological systems (Reyers et al., 2018) whereas the existence of global tipping points is subject to ongoing debate (Montoya et al., 2018; Rockström et al., 2018). A detection of critical thresholds in advance may provide management opportunities to prevent non-resilient changes (Pace et al., 2017). A series of early warning signals have been proposed to serve as indicators for the detection of imminent regime shifts (Dakos et al., 2012). However, analyses of long-term data have shown that these indicators are often inconsistent in their inferences (Gsell et al., 2016). False positives, i.e. the indication of early warning signals without significant nonlinear changes, have been highlighted as a particular problem (Burthe et al., 2015). Therefore, alternative resilience measurements have been suggested that take into account simultaneous data sets from multiple sources, e.g. spatial data and trait information (Clements and Ozgul, 2018). The combination of high-frequency measurements and remote sensing may provide extended opportunities to detect early warning signals (Dakos et al., 2012). Ecosystem research infrastructures such as LTER need to provide and integrate such data, and they must enable manipulative experiments to investigate the relationships between drivers and regime shifts (Carpenter et al., 2011; Dakos et al., 2012).

Q17. Given differences in monitoring methods, how can changes in biodiversity be compared among different sites and species groups?

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 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 (Mollenhauer et al., 2018). 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 provide a more promising approach (Henry et al., 2008; Pagel et al., 2014). Thorough efforts are needed to enable the joint analysis of large data sets arising from citizen science (Isaac et al., 2014) and the emergence of new methods for biodiversity assessment such as remote sensing, camera trapping or soundscaping (Schmeller et al., 2015). Given the rapid development of such techniques the challenges associated with methodological heterogeneity will remain an important issue in the future.

Q18. How can we reduce uncertainties in climate change projections provided by Earth system models?

Projections of climate change by global and regional climate models are subject to uncertainties derived from various sources (Flato et al., 2013; Foley, 2010) 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 biogeochemical cycles such as the carbon (Bradford et al., 2016; Friedlingstein, 2015), water (Clark et al., 2015) and nutrient cycles (Thomas et al., 2015) cycle. Improving the parameterizations of such processes that are important for climate simulations is necessary to reduce overall uncertainty. Well-instrumented research sites can be used for model testing and development through an optimization in the parameterization and process representations in the land surface schemes of global and regional climate models. More emphasis should be put on the harmonization of field methods to enable the use of data from different national observation networks for modelling purposes. For example, weather stations should ideally be operated according to World Meteorological Organization standards. Sites encompassing harmonised measurements across all domains; i.e., biosphere, hydrosphere, cryosphere, lithosphere and atmosphere are particularly valuable for the analyses of feedback processes and interactions between systems (Hari et al., 2016), as needed for improving Earth system models.

Q19. What emerging technological developments have the greatest potential to benefit ecosystem research?

Ecosystem research deals with complex challenges from dynamic systems shaped by the interactions of multiple drivers and ecosystem components across a range of spatial and temporal scales. New technologies that allow for extended measurements in space, at higher frequencies and likely at lower costs now offer powerful opportunities to better understand ecosystem functioning and response to multiple stressors. Wireless sensor networks (WSN) that deliver real-time data at high spatial resolution are one example of such technology (Othman and Shazali, 2012). WSNs are increasingly applied for monitoring and research purposes, e.g. monitoring of water quality (Blaen et al., 2016; Marcé et al., 2016), forest soil water variability (Rosenbaum et al. 2012), forest fire detection (Molina-Pico et al., 2016), or tracking of animal movements (Dressler et al., 2016). Recent work on urban air pollution demonstrates that good data quality can be achieved if networks are calibrated using standard measurements (Moltchanov et al., 2015). Many questions remain regarding their overall costs, stability, sensitivity, duration and required effort to manage data (Kumar et al., 2015). Similarly, opportunities to apply remote sensing technologies for environmental research are evolving rapidly (Lausch et al., 2016). In this context, it is important to consider scaling issues when transferring information collected at local level to various scales where ecosystem management and decision making takes place (Abelleira Martínez et al., 2016; Wu and Li, 2009). A growing number of open software products facilitate sampling, management (e.g. GeoNetwork, 2019) and analysis of data derived from such technologies. Given the magnitude of opportunities there needs to be a focused discussion on how a standard configuration of comprehensive environmental monitoring sites should be accomplished. 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 requires new user-specific and easy-to-use assistance tools for data provision and processing. For example, online toolboxes have recently been developed to enable the analysis of high frequency data from lakes (Obrador et al., 2016). Given the diversity of existing data sources, data acquisition tools and scales, strategies and methods need to be developed to bring research activities and products from science to a more service-oriented level.

Q20. How can new molecular high-throughput technologies be used to analyze the links between genetic diversity, functional diversity and ecosystem processes?

Although there has been much progress in using genetic methods in ecology, there are major knowledge gaps concerning the importance of genetic diversity for patterns and processes at the ecosystem level (Crutsinger, 2016; van der Linde et al., 2018). The increasing availability of high-throughput sequencing platforms (Reuter et al., 2015) and rapidly advancing genomic methodologies could revolutionize this area of research, if data can be matched to long-term measurements of ecosystem processes. However, there remain unsolved problems associated with a broad-scale application in ecosystem research. Sequencing error rates are still high for some techniques, and data processing and analysis are computationally intensive (Bruford et al., 2017). To maximize benefits for ecosystem research considerable investment in infrastructure is needed, including appropriate sampling and lab facilities and sophisticated infrastructures for data management and analysis. Data infrastructures are particularly important to integrate genomic and 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 (GSC, 2019). 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

4.1. Research questions

This horizon scanning identified emerging research questions that can guide the future development of long-term ecosystem research infrastructures. Twenty priority questions were identified (Supplementary material 2), forming four overarching themes (Fig. 1). These themes were arranged along a gradient that reflects increasing complexity and policy relevance (Fig. 2). In this context, theme 4 (methods and research infrastructures) represents a cross-cutting issue. Research approaches corresponding to themes 1–3 and the required infrastructures can also be classified along this gradient. Subject-specific research in a single locality may be sufficient to address basic questions. However, most of the research questions identified require inter- and transdisciplinary, cross-site research in a coordinated network. Such network-based approach is also necessary to investigate topics of high policy relevance that concern the interactions between ecosystems and society.

Clearly, the selection of research questions was influenced by the personal interests of the participants, and is not representative of the views of the entire European environmental and socio-ecological research community. For example, the numerous submissions of questions related to methods and infrastructures reflect that many researchers work with the operation and management of field sites and monitoring networks. In contrast, social systems and economic aspects were arguably under-represented even though some of them were partly addressed by questions related to ecosystem services. By applying a stratified approach to the scoring process we tried to mitigate potential bias towards certain topics. Many other important research questions may arise from the linkages between the topics identified in this exercise, e.g. interactions between species (Q4), carbon cycle (Q6) and maintenance of ecosystem service provision under climate change (Q13). Horizon scanning as applied in the present study aims to provide first insights into emerging or insufficiently addressed topics. Subsequent work may apply more rigorous social science methods to get a

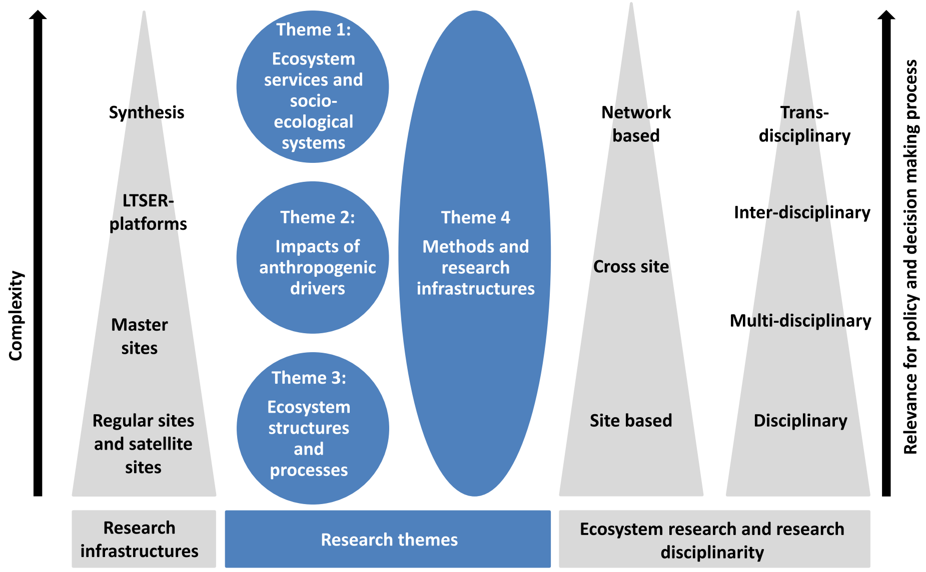

Fig. 2. Results of the horizon scanning: The relationship between thematic complexity and policy relevance of research infrastructures, research themes and ecosystem research. Triangles are symbolizing quantity (e.g., there are many more "regular sites" than "LTSER platforms"). Site categories refer to Mirtl et al. (2018).

deeper understanding of the identified issues.

Despite encouragement to focus on specific emerging topics, participants tended to ask more generic questions and they also gave these the highest scores. This may partly be due to the choice of the method. The possibilities to guide the discussion and selection process online were limited compared to workshops with higher intensity of personal exchange. Nevertheless, the knowledge gaps identified emphasized a number of important but currently under-researched areas. Obviously, the participants found it more important to address the complexity behind these questions and to develop methods and infrastructures to explore it, rather than select subject-specific questions with a narrow focus. This is particularly true for research questions concerning interacting systems (multi-species interactions – Q4, human-ecosystem interactions – Q6 to Q14), relating to different spatial scales (landscape level processes and local biodiversity – Q5) or dealing with processes that involve multiple feedback mechanisms (biogeochemical cycles – Q6, Q8, Q9). Infrastructure-related limitations are among the reasons why this complexity has only been addressed to a limited extent so far. For example, there are variables that are hardly considered in current monitoring programs, such as interactions between organisms (Q4). Consequently, ecosystem services based on such interactions cannot be quantified properly, e.g. pollination. Other variables are not sufficiently measured across space and time, and methods are not harmonised. This complicates large-scale analyses which require comparable and scalable data such as those needed to answer Q5, Q13 and Q14. Many variables are collected spatially and temporally independently, so that they cannot be related to each other. The problem concerns biotic, abiotic and socio-economic measurements and it inhibits research on cause-effect relationships, e.g. between anthropogenic drivers and ecosystem responses (Q6-10). These infrastructural constraints apply to several research questions discussed above. In the following the main cross-cutting issues are summarized and possible solutions are suggested.

4.2. *Cross cutting issues for research infrastructure development*

4.2.1. *Whole-system approach*

The horizon scanning approach used in this study also revealed some cross-cutting issues and challenges that are important for the future development of long-term ecosystem research infrastructures. Specialized research infrastructures have often been developed to address specific research domains. Their future development would benefit from adopting a whole-system approach (Mirtl et al., 2018). This requires simultaneous measurements of a broad range of abiotic, biotic and socio-economic variables over a range of spatial scales. One way to implement such a strategy is to set up a network of master sites for intensive measurements such as the Australian SuperSite Network within TERN (Karan et al., 2016). However, the costs of such a network will often limit its spatial extent. The combination of existing research sites with different thematic priorities offers an alternative way to cover a wide range of variables (Haase et al., 2018). Such networks of co-located sites offer the possibility to use existing infrastructures and data more effectively. The adoption of a whole system approach also implies a stronger consideration of socio-economic measurements, as intended by the concept of LTSER platforms (Angelstam et al., 2019; Gingrich et al., 2016; Haberl et al., 2006).

4.2.2. *Developing standard observations and measurements*

Standardized long-term data sets that cover large spatial extents are necessary to address environmental problems of global relevance (Haase et al., 2018; Kissling et al., 2018a; Latombe et al., 2017; Skidmore et al., 2015). However, many research infrastructure networks such as LTER are locally organized, which leads to a high degree of methodological heterogeneity. Ideally, a set of standard variables should be defined to fit into various conceptual frameworks and to be used to inform a wide range of indicators (Haase et al., 2018). It must be accepted that it will not always be possible to achieve the desired level of methodological harmonization, e.g. if new scientific questions make it necessary to introduce novel methods. Apart from harmonization of measurements there are further possibilities to increase interoperability among research sites and networks. In particular the development of standardized workflows for data management, processing and exchange is necessary to integrate and analyze data from different sources and to make them accessible to the research community (Kissling et al., 2015).

4.2.3. *Multiple use of research infrastructures*

Participants highlighted the importance of experimental manipulations to address fundamental questions in ecosystem research. Experiments facilitate the understanding of single processes by controlling others, but do not always reflect “real world” conditions and findings are not always applicable to whole ecosystems. In contrast, observations can inform on state and condition over a wide range of spatial and temporal scales but often do not explain causal relationships. Experiments embedded within long-term observatory plots may enable the most mutually beneficial exploitation of the two approaches (Djukic et al., 2018). Long-term observational networks such as LTER are particularly well suited for the establishment of coordinated distributed experiments (Fraser et al., 2013).

4.2.4. *Increase flexibility in monitoring schemes*

Many long-term research site networks are based on a fixed spatiotemporal observation design. However, the highly dynamic and in many cases unpredictable nature of environmental change, as well as human responses, may only be addressed using flexible monitoring approaches. For example, to evaluate the success of adaptation measures for ecosystem management under climate change (Q13), the adjustment of the spatial design of site networks will be necessary to coincide with management scales. Investigating the impacts of extreme climatic events (Q7) may require temporal adjustments, i.e. temporarily increasing the frequency of measurements during and after episodes. The increasing availability of low-cost data loggers that enable high-frequency data acquisition (Q19) partially meets this requirement. In view of limited resources, strategies need to be developed to adapt established LTER sites and LTSER platforms to newly emerging questions while sustaining the integrity of long-term time series.

4.2.5. *Balancing technological advancements and long-term time series continuation*

There will be methodological advancements in many fields of ecosystem research with new technologies providing 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, new methods can threaten the continuity of long time series produced by more traditional methods when the former are not fully compatible with the latter. Furthermore, there are also risks that new methods are rapidly superseded by next generation technologies, preventing the further development of robust time series. Research infrastructures need to be flexible with regard to new methods but we need strategies to ensure consistency and comparability of measurements across time (Ellingsen et al., 2017).

4.2.6. *Ecosystem services and stakeholder engagement*

Quantifying the potential supply of ecosystem services as well as stakeholders’ demands represents a key requirement to address several research questions. While some ecosystem services can be measured directly, the majority must be quantified using proxies (Eviner et al., 2012; Kandziora et al., 2013). The provision of many ecosystem services, especially cultural ones, involves ecosystem management. This requires new methods to integrate biophysical data with quantification of human perception (Vaz et al., 2018). LTSER-platforms need to provide opportunities to value differences in ecosystem service demand among stakeholders and levels of governance (Garrido et al. 2017a, 2017b). To assess a broad range of ecosystem services, efforts to prioritize and harmonize the corresponding measurements across sites and platforms need to be intensified (Angelstam et al., 2019). Finally, different bundles of ecosystem services contributing to human well-being (Balvanera et al., 2017) need to be captured by developing methods for valuation, including monetary and non-monetary methods (Merlo and Croitoru, 2005).

5. Conclusions

To address complex scientific issues sophisticated research infrastructures are required that operate in the long-term, and cover large spatial scales as well as multiple dimensions of ecosystems and socio-ecological systems. The combined network of LTER sites, LTSER platforms and Critical Zones Observatories offers great potential as a distributed infrastructure. A crucial task is the harmonization of variables and methods, as well as the integration and access of data. Closer co-operation with other monitoring networks and initiatives is essential to achieve this goal. Addressing complex questions also requires the combination of experiments, observations, modelling and comparative studies. The ability to respond flexibly to emerging issues in space and time represents a key requirement of future research infrastructures. Lastly, research infrastructures need to enable transdisciplinary research that goes beyond natural sciences. LTSER platforms should be developed into pilot areas that will allow researchers, managers and decision makers to make evidence-based choices which centre on finding the balance between sustaining landscapes and the demands placed upon them by different stakeholders.

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Appendix A. Supplementary data

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