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Using long-term ecosystem service and biodiversity data to study the impacts and adaptation options in response to climate change: insights from the global ILTER sites network

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The International Long Term Ecological Research (ILTER) network can coordinate ecological research to provide observations of the ecosystem changes, and their socio-economic impacts on human societies at different scales. In this paper we demonstrate the importance of the ILTER network in the study and monitoring of environmental changes at a global level. We give examples of how biodiversity and ecosystem service data can be used to study impacts and adaptation options in response to climate change. Analysis of the 107 recent publications from LTER networks representing 21 countries show that LTER studies are often local and heterogeneous. There are some ecosystem types, such as agricultural or coastal ecosystems that are not covered with current ILTER network. Standardized monitoring schemes and techniques should be considered for future steering of ILTER collaboration. Integrating and synthesizing the collected data should be prioritized for future cooperation, and integrated in decision-making.

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Introduction

Climate change poses a serious threat to biodiversity, ecosystem services, and the future of coupled human–environment systems. Biodiversity loss and changes in ecosystem functioning are often local or regional while climate change has a global influence. This makes it difficult to understand the global impact of biodiversity loss and changes in ecosystem function, and to determine their potential negative effects on society. Fundamentally, human-wellbeing and societies are dependent on the health of ecosystems. Ecosystem research is dependent upon time series, and long-term monitoring is the only way to detect and understand changes in the environment. The complex nature of the global environmental challenges such as climate change and biodiversity loss has revealed the need for new forms of producing and sharing knowledge, international research collaboration, and long-term research and monitoring of social–ecological systems [1••,2,3]. Traditionally, long-term ecological research has been linked with academic research questions such as phenological variation, ecosystem functioning, and flows of material and energy. More recently, increasing understanding of the impacts of human beings on ecosystems, and the dependence of societies' well-being on planetary boundaries have raised further questions for science. For example, what is the impact of climate change and other human-induced pressures on ecosystem services? How can social–ecological systems adapt to predicted environmental changes? How should societies be steered to decrease the pressures on the environment and biodiversity? Long-term monitoring of ecological processes forms the basis for observing changes along the predicted trends resulting from climate change and land use pressure. Integrated management of the coupled human–environment systems has also emphasized the importance of dialogue at the science-policy interface, that is, among scientists from different disciplines and stakeholders at multiple levels, to find solutions for global environmental problems [1••].

Long Term Ecological Research (LTER) activities started in USA in 1980, in China in 1988, and followed later in many other countries [4•,5•]. The International Long Term Ecological Research (ILTER) was founded in 1993 as a 'network of networks' in terms of a global network of research sites. The ILTER network is the global umbrella for regional and national LTER networks, which coordinate the research and monitoring carried out at individual LTER sites and within countries. ILTER also incorporates Long Term Socio-Ecological Research (LTSER) platforms (http://www.lter-europe.net/sites-platforms) that investigate socio-economic variables that can reveal important linkages between ecological and social systems. Located in a wide array of ecosystems worldwide, this network can help us understand environmental change across the globe. ILTER was formed to meet the growing need for global communication and collaboration among long-term ecological researchers. Since ILTER's establishment, global long-term ecological research programs have expanded rapidly, reflecting the increased appreciation of the importance of long-term research in assessing and resolving complex environmental issues. The ILTER network can contribute to solving international ecological and socio-economic problems through question and problem-driven research, with collaborative, site-based projects in which a comparison of data from a global network of sites forms the basis for detecting global trends. One of the goals of ILTER is to improve comparability of long-term data from both local sites, and entire social–ecological systems such as landscapes, around the world, and to facilitate the exchange and preservation of these data. ILTER also aims to deliver knowledge to scientists, policymakers, and the public (www.ilternet.edu).

Most ILTER members are national or regional networks of scientists engaged in long-term, site-based ecological and socio-economic research. They have expertise in the collection, management and analysis of long-term environmental data. Together they are responsible for creating and maintaining a large number of unique long-term datasets. Currently forty member-networks have established formal LTER programs and joined the ILTER network.

The founding member of the ILTER network in the USA was designated to study five core areas covering: first, pattern and control of primary production, second, spatial and temporal distribution of populations selected to represent trophic structure, third, pattern and control of organic matter accumulation in surface layers and sediments, fourth, patterns of inorganic inputs and movements of nutrients through soils, groundwater and surface waters, and fifth, patterns and frequency of site disturbances [4•]. Many of the ILTER sites have their roots in the study of the natural sciences, but over the latter part of the 20th century the focus has evolved to consider interdisciplinary and transdisciplinary research to address linked social and environmental issues. For instance, several urban LTER sites were added to national LTER networks, for example, Helsinki in Finland, Beijing in China, and Baltimore (Maryland) and Phoenix (Arizona) in the USA. These developments advanced the creation of the LTSER concept [6].

In this paper we give examples on how the ILTER networks have contributed to the understanding of the linkages between climate change, biodiversity, and ecosystem services. Our aim was to assess the recent ILTER output from the ILTER network, to highlight potential gaps in the information being collected, missing elements in current national and regional approaches, and to make suggestions for targeted global-scale long-term integrative research. We hope to provide useful information for scientists, policymakers and the public, and also to contribute to improved coherency, comparability and use of long-term data about ecological and social systems around the world.

Analysis of the ILTER publications

Materials and methods

Our exploration of recent ILTER publications took into consideration 107 ILTER articles provided by country representatives and authors working within the ILTER network all over the world (Table 1). National ILTER counterparts were asked to send what they believed were the most important recent publications from their LTER site or network that concerned biodiversity and ecosystem services, and the impact of climate change and adaptation to it. These publications were not gathered using any systematic criteria or on random basis. Instead, they reflect the belief of the national representatives knowledge of the recent studies conducted in the LTER sites and their views of its importance. The collected ILTER publications were then grouped according to several categories, including the country and year of publication, research focus, type and output from the article (partly based on Fu *et al.* [5•]), ecosystem type [7], ecosystem service [8], ecosystem service cascade

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Table 1

Analysed ILTER publications.

Country	Number of analysed articles	National informant
Brazil	5	Francisco Barbosa
China	1	Bojie Fu
Czech Republic	2	Petr Petřík
Finland	4	Martin Forsius, Jussi Vuorenmaa
Germany	12	Cornelia Baessler, Stefan Klotz
Hungary	1	Kertesz Miklos
Israel	4	Marcelo Sternberg
Japan	21	Hideaki Shibata
Korea	1	Eun-Shik Kim
Latvia	5	Viesturs Melecis
Malawi	1	James Chimphamba
Mexico	1	Patricia Balvanera, Manuel Maass
Mongolia	3	Bazartseren Boldgiv
Romania	10	Geta Risnoveanu
Slovakia	3	Robert Kanka
Slovenia	4	Tanja Pipan
South Africa	1	Johan Pauw
Sweden	13	Hjalmar Laudon, Per Angelstam
Thailand	2	Yongyut Trisurat
United Kingdom	3	Jan Dick, Jill Thompson
USA	8	Scott Collins, Jianwu Tang, Jill Thompson
Multinational	2	–

model [9,10], in relation to climate change, spatial scale, disciplinary approach, data type, and presence/absence of biodiversity data and data time-frame. Each of these categories is expressed as a percentage of occurrences in the 107 ILTER articles received from ILTER contributors for assessing the publications given (Table 2).

Analysis of topics studied

Our results show that ILTER sites have covered a wide variety of themes. Almost 70% of the ILTER articles analysed here were published over 4 years (2009–2012). We believe that this set of ILTER studies can reveal some key foci of current research as well as gaps and future research needs. Given the small number of papers contributed by each specific country, drawing national trends was neither possible nor reasonable.

The ILTER articles were mostly focused on components and processes involving biotic communities. Only a smaller number of articles were focused on material/energy cycles and on ecosystem services. Only a few of the articles were focused on more than one topic (Figure 1). Regarding the type of ILTER articles, the majority (58%) were case studies, dealing with the analysis of a unit/phenomenon. A total of 21% of the articles were dedicated to the analysis of methods and principles for a particular to a branch of knowledge. Finally, 14% of the articles did not fall into any of these categories.

In terms of output, the majority of the ILTER articles contributed for this article (42%) served monitoring purposes. A total of 16% of the articles were based on environmentally controlled experiments, with some parameters artificially changed and monitored. Other types of output were homogenously distributed among the articles: Modelling and management both

Table 2

Data analysed from the ILTER publications.

Country and year
The analysis of the ILTER publications took into consideration 105 ILTER articles from 21 countries and 2 joint publications from several countries, published between 1999 and 2012.

Focus, type, and output
The ILTER articles are grouped based on their focus or main topic (i.e. biotic communities, ecosystem services, material/energy cycles), on the type of research/approach (i.e. methodologically oriented, real case study) and on the output of the research (i.e. monitoring, scientific research, management, LTER, modelling).

Ecosystem type, service and cascade model stage
Each ILTER article generally deals with only one ecosystem type (i.e. marine, coastal, inland waters, forest, dryland, mountain, polar, cultivated, urban, subterranean). The articles might deal with one or more ecosystem service(s) (i.e. provisioning, regulating, cultural or supporting/maintenance). Articles are also grouped based on the stage of the cascade model they focus on (i.e. ecosystems and biodiversity: structure, process, function, service, human wellbeing: benefits and human wellbeing: economic value).

Relation to climate change
For those publications directly related to climate change, a distinction was made between the articles focused on impact of climate change on ecosystems and biodiversity, and on adaptation of ecosystems and biodiversity to climate change.

Spatial scale and disciplinary approach
Articles can be focused on a national scale or multinational scale, or might deal with non-physical place. Articles are also grouped based on their disciplinary approach, as in how many disciplines (e.g. natural science, social science, economics) are involved in the research.

Data type and time-frame
Each ILTER article usually bears more than one data type (i.e. spatial, numerical, statistical and qualitative). The analysis also shows those articles gathering, using or presenting biodiversity data. Each article generally uses data collected during a continuous period of time (i.e. 1 year, 2–5 years, 6–10 years, 11–15 years or >15 years). Articles based on a non-continuous data collection are categorized as discontinuous.

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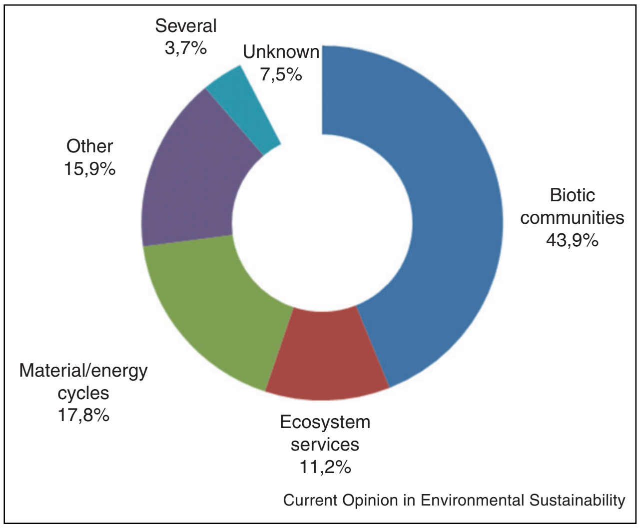
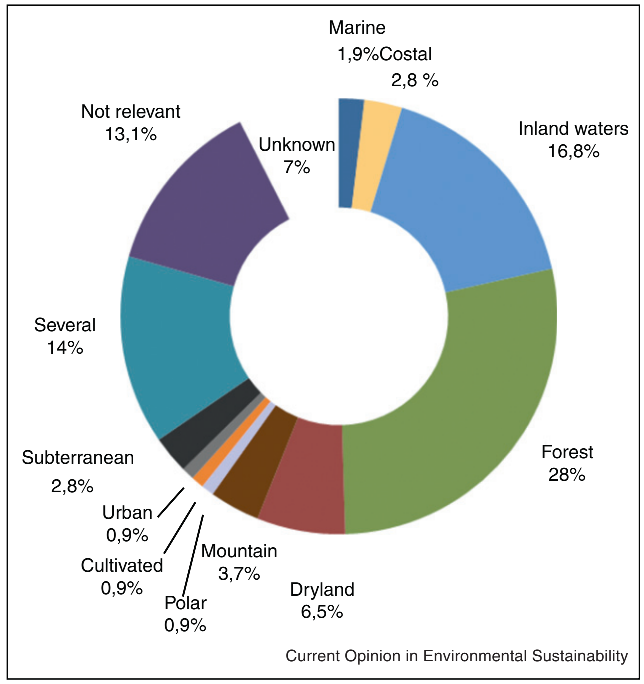
Figure 1



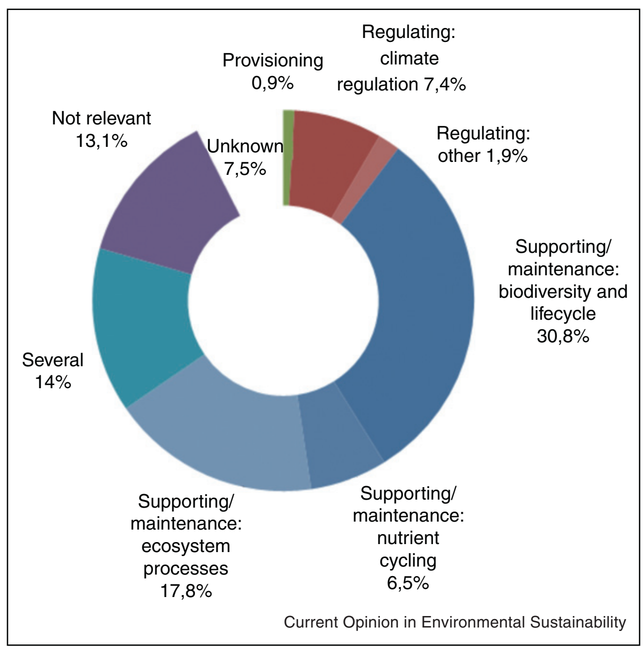
The share of ILTER articles for each focal topic.

Figure 2



The share of ILTER articles per ecosystem types.

Figure 3



The share of ILTER articles for each ecosystem service, with details for regulating and supporting services.

represented 7% of the ILTER articles; 8% of the articles dealt with the description, status, trends or comparisons of long-term research at LTER sites. Brazil, China, Korea, Latvia, UK and USA contributed at least one article related to the national LTER network. Five percent of the articles had several outputs, while 8% of them did not deal with any of the previously mentioned outputs.

The most frequent ecosystem types recurring in the ILTER articles were forests and inland waters, followed by ILTER articles that focused on several ecosystem types. For 13% of the articles the ecosystem type was not relevant. Subterranean, coastal, marine, polar, urban and cultivated ecosystems represented a minor share of the ILTER articles (Figure 2). The majority of the ILTER articles analysed dealt with biodiversity and the supporting/maintenance services of ecosystem processes and nutrient cycling. Many of the articles also dealt with regulating services, mostly related to climate regulation. A proportion of the articles dealt with more than one ecosystem service, while for almost the same proportion ecosystem services were not relevant (Figure 3).

Categorization of the ecosystem service research follows the ecosystem service cascade model [10], and this was used to analyse the publications (Figure 4). Ecological research was more common than socio-economic research in the contributed ILTER articles. The majority of the ILTER articles analysed were focused on the first stages of the cascade model, thus involving structure, process and function of ecosystems and biodiversity. Other stages of the cascade model, such as services and human well-being constituted a minor share of the ILTER articles. Some of the articles could not be linked with any cascade stages. This same trend was confirmed by the fact that the majority of the ILTER articles (71%) involved only one discipline (which was almost always natural science),

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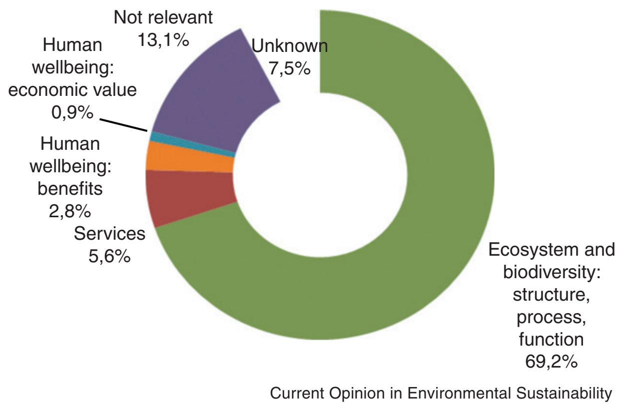
Figure 4



The research focus of the ILTER articles according to the ecosystem service cascade model (see Refs. [9,10]).

while 22% involved more than one (e.g. social science, economics).

The issue of climate change was directly addressed by 22% of the ILTER articles. Most of the articles related to climate change are focused on its impact on ecosystems and biodiversity (20%) rather than adaptation of ecosystems and biodiversity to climate change (2%), while the majority of the articles (70%) do not deal with climate change. Altogether 28% of the ILTER articles were based on data collected during 1–5 years, while 22% of the ILTER articles were based on data collected from 6 to 15 years. For 37% of the articles, data time-frame was not specified/relevant. Most of the data had been collected from the 1980s to the 2000s.

The majority (60%) of the ILTER articles was set in only one country, and just 20% of the articles covering more than one. Finally, articles that did not focus on any specific geographical location made up 13%. Each article generally presented more than one data type. Statistical data were the most frequent (47%) among ILTER articles, followed by spatial data (22%), qualitative data (15%) and numerical data (11%). A total of 41% of the articles presented biodiversity data, which is not surprising since the most frequent focus of ILTER articles is on 'biotic community'.

Results from the ILTER articles in this paper show that the information produced by the ILTER network was heterogeneous. Existing gaps in the information result from the fact that most studies were developed independently in each country and with dissimilar agendas. There were cases where the LTER research was predominantly oriented towards one or few specific direction(s). However, monitoring data and research varied considerably among countries. Opportunities for enhanced coordination and more effective ILTER cooperation are suggested in the discussion. In the next chapter we provide examples of some significant results of the ILTER research that represent the great variety of topics studied.

Selected findings and cooperation highlights of the ILTER network

Soil biodiversity response to climate change

Decomposers have overwhelming species diversity and provide invaluable services to humans by cleaning the environment of various biological remains and returning nutrients to soil for plant uptake [11]. It is important to find out if climate warming will affect these active components of the soil ecosystem, and to determine what the consequences climate change will be on the soil ecosystem supporting services, such as soil formation and cycling of biomass and nutrients. In this respect soil fauna could be used as a bio-indicator of soil ecosystem conditions. However, there are few data available on long-term studies of soil fauna and the effects of climate change on soil animal communities [12].

The effects of climate warming on soil fauna have been studied by Latvia LTER since 1992 in Scots pine forest sites. Some results on long-term changes in Collembola communities have demonstrated negative effects of a temperature rise on species richness and density of these animals over a decade [13,14]. This suggests that significant changes in forest soil formation may occur, as it has been calculated that a Collembola population with density of 10,000 individuals/m^2 adds 0.2 mm to the forest humus layer annually [15]. Long-term ecological research can also reveal the response of other components of soil biodiversity to climate change that may affect regulating and supporting ecosystem services but few studies have been reported. Current results cannot be extrapolated to larger scales since changes in soil fauna in response to global warming have only been studied at small scales in a few sites, but this should be an important topic for future coordinated research among ILTER sites.

Recent advances in microbial genomic techniques have been used to study microbial biodiversity in soil and aquatic systems. For example, the Microbial Inventory Research Across Diverse Aquatic Long Term Ecological Research Sites in the U.S. aims to extensively sample both common and rare members of microbial populations across aquatic US LTER sites (http://amarallab.mbl.edu/mirada/mirada.html). The methodology could be extended to upland soils and to other ILTER sites, to facilitate cross-site comparisons and provide valuable baseline data for understanding the climate change impact on microbial biodiversity and microbe-driven biogeochemical cycles.

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Phenological variation

Changes in phenology, that is, the seasonal timing of biological events, have been recorded across the globe, providing conclusive evidence for responses to climate change [16,17]. Shifts in flowering phenology could be wide-ranging, as they may cause temporal mismatch with pollinator activity and modify gene flow among plant populations. Warming can also modify flower quantity, thereby affecting the resources available to pollinators and, potentially, seed production. The flowering responses to climate change have the potential to profoundly affect plant community composition, ecosystem services, and livelihood of many people all over the world. For instance, the semi-arid, northern Mongolian steppe, a part of Hövsgöl LTER site still supports pastoral nomads and has experienced an average 1.7 °C temperature increase over the last 40 years. The region is also expected to experience rapid climate change in the future. In an experimental approach using open-top passive warming chambers (OTCs) that are similar to those used in other systems, researchers [18] examined how flowering phenology responded to the climate warming manipulation, which increased daytime air temperature by about 1.5 °C and decreased soil moisture by $\sim$30%. Results of the experiment showed that warming reduced flower production and delayed peak flowering in graminoids on the whole, but only affected forbs on the upper part of the landscape, where peak flowering was also delayed.

The results from phonological studies demonstrate the importance of taking landscape scale variation into account in climate change studies and also contrast with those of several studies set in cold, but wetter systems, where warming often causes greater or accelerated flower production [19–22]. In cold, water-limited systems such as the Mongolian steppe, the timing of flowering is vulnerable to climate change and warming, which may reduce flower numbers or the length of the flowering season by adding to water stress more than it relieves cold stress. The dramatic decrease in flower production, particularly in the graminoids, and the contraction and shift in flowering phenology not only has important implications for plant community structure, but also has ramifications for the steppe's ability to support livestock herding and livelihoods [18].

Carbon flux and nutrient cycles

Observations of CO_2 flux at ILTER sites have provided evidence of the ecosystem services that regulate the regional and global climate with different temporal patterns and driving factors [23,24]. On the basis of long-term monitoring of CO_2 flux in Takayama, a core-site of the Japanese LTER network, Ohtsuka *et al.* [25] and Saigusa *et al.* [23] found that inter-annual variability of the forest productivity and their ecosystem services in Japan and East Asian countries were driven not only by the local environmental factors but also by regional climate forces such as El Niño Oscillation. In addition, Saigusa *et al.* [26] suggested that alteration in the activity of the East Asian seasonal rain front that may result from future global climate changes might cause different spatial patterns of forest productivity in the Asian monsoon region, based upon their integrated analysis using intensive field-based monitoring data on carbon cycling and satellite remote sensing.

Future climate changes including the gradual warming and episodic extreme events [27,28] also have the potential to alter nutrient cycles in various natural ecosystems. Soil microbial nutrient transformation is a key process in the nutrient cycling in forest ecosystem. The decrease of snowpack due to climate change could alter the heat and water regimes in soil, possibly causing significant disturbances to natural nutrient retention and leaching which are strongly regulated by soil microbial activities in winter and early spring [28,29]. Park *et al.* [27] reviewed the possible impacts of future climate changes and variability (including the extreme events) in Asia on the biogeochemical processes and water quality that are important indicators of the water purification services in watershed ecosystems. Those findings indicated that the field-based long-term monitoring and experiments on ecosystem processes [30–34] are strong tools that will provide deeper scientific insights and early warning signals of the impact of future climate changes to various ecosystem functions and services at multiple temporal and spatial scales [35–41].

Among several complementary approaches, including long-term observations, regional gradient studies, chronosequence studies, synthesis analysis, and modelling, long-term experiments have been an effective way to study the controls and mechanism of the carbon and nutrient cycles in ILTER sites. All 26 sites of the U.S. LTER conduct manipulative experiments [42•] to investigate changes in temperature, nitrogen, rainfall, snow, and carbon dioxide [CO_2]. Single-factor manipulation has evolved into multifactorial experiments, while single site experiments have evolved into multi-site or network-level experiments. These include the Nutrient Network, the International Tundra Experiment (ITEX), and the Long-Term Intersite Decomposition Team (LIDET) [42•]. The long-term biodiversity experiment in a grassland, Tilman *et al.* [43,44] found that biodiversity increases ecosystem productivity and carbon sequestration; Reich *et al.* [45] found that plant diversity increased the positive response of biomass productivity and carbon sequestration to nitrogen deposition and elevated atmospheric CO_2 concentration. Using a long-term soil warming experiment in a temperate forest, Melillo *et al.* [46] reported that soil respiration was increased by about 25% during the first five years if heated by 5 °C relative to the ambient, but this warming effect diminished over time.

Disturbance, resistance, and resilience

US LTER sites consider the study of disturbances as a core activity (http://www.lternet.edu/overview/) and this focus lends itself to studies of resistance and resilience [47]. A quick search for resistance and resilience in the USA LTER publications list show studies for a range of organisms and ecosystems, such as macro-invertebrates [48], coral reef fish [49], floating vegetation [50], bacteria [51], plant diversity [52], soil in ecosystems [53], forest communities [54–56], fungi [57], and riparian ecosystems [58]. The recent book from the Luquillo LTER site in Puerto Rico [59] synthesizes studies that consider the multi-dimensional nature of disturbance and response, including disturbance caused by humans, hurricanes, floods and landslides, and the resistance and resilience of forests, streams and biogeochemical cycles in response to these disturbances in the forested ecosystem of the Luquillo Mountains. These LTER resistance and resilience studies cover different organisms and ecosystems in different locations, but few if any studies cover the same ecosystem type and disturbance in many locations. Conducting studies across ILTER sites would significantly improve our understanding of these phenomena and the potential impact of climate change.

LTER sites are model settings for studying resistance and resilience in the face of climate change and the consequent adjustments in the delivery of ecosystem services. Ecosystem service data from ILTER sites are especially useful when investigating resistance and resilience as both pulse and press disturbances can be investigated at the same site because of the multi-decadal datasets of biophysical and social data. The UK Environmental Change network have started to develop a standard protocol for the assessment of ecosystem services that are relevant to upland, lowland, mountain, forest and agricultural sites [60a]. The assessment of 73 ecosystem services or proxies at regular intervals will facilitate the study of resilience at the sites and allow comparison between sites by a standardized methodology. The list has also been adapted for the arctic LTER sites [60b] as it is recognised that these LTER sites are currently experiencing a significant influence of climate change with an associated impact on the resilience of these systems [61•].

The impacts of climate change on ecosystem services and related adaptation options have been studied at Finnish LTER-sites [62]. Climate change was predicted to have both positive and negative effects on key ecosystem services, the results being sector and scenario specific. Provisioning services such as food and timber production would largely benefit from increasing temperatures and prolongation of the growing season in the cold Finnish conditions. On the other hand, climate change was predicted to pose a major threat to several endangered species, water and air quality, and tourism services dependent on present climate conditions. Goal conflicts between maximising service production and meeting environmental quality objectives were also identified [62].

Adaptive capacity of social–ecological systems

Adaptive capacity, the ability of a social–ecological system to adjust their responses to changing internal demands and external drivers is a frequent topic of study in the resilience literature. LTER sites have been used as sources of data as they have detailed knowledge of ecophysiology, population ecology, community ecology, ecosystem ecology, and landscape ecology combined with social system data about demography and the economy, and processes of societal governance. LTER sites have also contributed to resilience thinking as they are well-studied sites that can exhibit nonlinear dynamics with thresholds, reciprocal feedback loops, time lags, vulnerabilities and heterogeneity. The study of panarchy, that is, ecological and social–ecological systems forming nested sets of adaptive cycles arose in part through the LTER community [63]. ILTER sites, therefore, provide a unique opportunity for comparative research to study global social–ecological challenges, develop and test tools and theories and consequently engender knowledge leading to a more resilient future for the world.

Social–ecological research was also addressed in the recent ecosystem services initiative of the ILTER network in which ecosystem services, human outcomes and behaviour, and how they influence each other were studied in a range of biomes. The efforts of 17 ILTER member networks at 19 sites implement, as well as test, components of the conceptual iterative framework for social–ecological research. Twenty-five services in four categories (provisioning, regulating, cultural, and supporting) were identified. Only four of them were all identified at more than 50% of the sites. An overwhelming majority of the services were declining at all sites regardless of the geographic, climatic, and socio-cultural settings. Results indicate that the trends in ecosystem services depend more upon the management regime of the area than any other factor. Finally, crossing a single threshold between alternative regimes often leads to a ‘cascading effect’ in which multiple thresholds may be breached across multiple scales. The impact of such changes on ecosystem structure and function — including the creation of new stable states — extends to ecosystem services, their interactions, and trade-offs. Trade-offs in ecosystem services have changed across space and time due to changes in socio-economic conditions. Moreover, they often result in multiple ecosystem services being compromised for the benefit of a solitary ecosystem enhancement. Although trade-offs vary among sites and biomes, patterns emerge in trends, scale/domain interactions, and degree of reversibility. Diversity of critical ecosystem services was found to be a function of societal use, not necessarily ecosystem type.

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Knowledge generation and capacity building on adaptation to climate change through long-term research in tropical forests

The ILTER network can make a valuable contribution to developing management practices and linking society to the ecological systems. As shown from Mexico, long-term research on biodiversity, ecosystem functions and ecosystem services has been building up for the last 30 years in the tropical dry forest at Chamela in coastal western Mexico. Today the Chamela LTER provides an excellent platform for socio-ecological research, including assessing adaptation options to cope with climate change.

In Mexico (Chamela) monitoring of hydrological and biogeochemical cycle components started in 1984 in a system of small (15–30 ha) watersheds [64–66]. Such long-term data sets provide a unique source of information on how, for example, the strong intra-annual and inter-annual variability in precipitation patterns influences the primary productivity of the system [67]. Primary productivity oscillations in turn drive the dynamics of the rest of the food chain; long-term data in Chamela on parrot populations and insect diversity are being used to explore such inter-linkages. The research focus has to be extended to understand how the ecosystem is managed [68] and how management practices affect biodiversity and the ability of ecosystems to provide key services to local stakeholders — as is the case of the regulation of soil fertility — and to global ones, such as for carbon stocks and uptake [69]. The environmental history, social perceptions, land tenure, and institutional arrangements that underpin management decisions are increasingly being assessed with interdisciplinary research projects [70].

The knowledge generation and capacity building that have been growing over the long term from the Chamela group provide the founding blocks to assess the impacts of climate change on tropical social–ecological systems and for exploring adaptation options. Projects on the vulnerability of the social–ecological system to climate change in the Chamela region, its resilience to the impacts of Hurricane Jova, and the role of biodiversity in climate change mitigation in selected neotropical countries are underway [71,72].

GLORIA — Global Observation Research Initiative in Alpine Environments

Large-scale international cooperation is a great opportunity provided through the ILTER network that was demonstrated in the recent Alpine collaboration project with the Global Observation Research Initiative in Alpine Environments (GLORIA, http://www.gloria.ac.at/). This network aims to collect detailed vegetation and temperature data on established and maintained alpine summits within the world-wide long-term observation network including 115 active target regions all over the world, from tropical to polar latitudes; evaluate them, assess and predict losses of biodiversity of vascular plants, bryophytes and lichens under the pressure of climatic change. Alpine ecosystems represent isolated pockets of plant and animal diversity, hosting a high number of endemic, threatened and rare species, despite being exposed to harsh environmental conditions. The long-term observation network was established for the comparative studies of climate change impacts on mountain biota [73]. A crucial precondition to keep such a large-scale network effective in terms of comparability is a standardized sampling design such as Gloria's Multi-Summit approach. Methodology is based on detailed sampling of vascular plants, bryophytes and lichens within permanent vegetation plots. Measurement of the soil temperature is realized by using temperature loggers buried 10 cm below soil surface.

Pauli *et al.* [74••] showed that accelerating climate change exerts a strong pressure on Europe's mountain flora. Increasing numbers of species were only found on the mountain summits of northern and central Europe. By contrast, numbers of species were stagnating or declining at nearly all sites in the Mediterranean region. On summits further north in Europe, more plant species are prospering. This could be interpreted to indicate that these are much safer sites for alpine flowers. Gottfried *et al.* [75••] showed that ongoing climate change gradually transforms mountain plant communities. These authors provided evidence that more cold-adapted species decline and more warm-adapted species increase, a process described as thermophilization. This thermophilization process mirrors the observed degree of recent warming that is more pronounced in areas where the temperature increase has been greatest. In view of the projected climate change in Europe the observed transformation suggests a progressive decline in biodiversity of cold mountain habitats and their biota [75••].

The number of active target regions involved in GLORIA increased from 18 in Europe at the beginning (2001) to 115 on all continents by November 2012. Manifold additional activities as part of GLORIA in the wider sense, or in its close relation have now been initiated on most continents. Standardized protocols for ecosystem monitoring and research are also available from other networks such as the National Ecological Observatory Network (NEON) (www.neoninc.org/) and International Cooperative Programme (ICP) on Integrated Monitoring of Air Pollution Effects on Ecosystems (ICP IM) (www.environment.fi/syke/im).

Discussion and conclusions

ILTER research is mainly focused on components and processes involving biotic communities with a minor share of the papers contributed for this article dedicated to material/energy cycles and ecosystem services. The

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importance of ecosystem services, however, has grown rapidly in recent years [76,3] and this should continue to have a significant role in ILTER research.

Recently, the ILTER network launched the ILTER Ecosystem Services Assessment project (ILTER 2012). This project is the first network-level attempt by the ILTER to address the linkages among ecosystem services, human outcomes and behaviour, and how they influence each other in different biomes. A new European Union funded project on the Role of Biodiversity in Climate Change Mitigation (ROBIN http://robinproject.info/home/) across Meso and Latin America, has a significant focus on human outcomes and behaviour and involves several ILTER partners. Results from this project should help develop cross ILTER network activities and further identify research gaps and opportunities.

Most of the LTER research is directed towards monitoring the natural environment and their biota or assessing environmentally controlled experiments, while modelling and management studies are less common outputs. Modelling is critical to our understanding of the spatial and temporal dimensions of ecosystems in order to extrapolate and predict how global changes are likely to impact ecosystem processes and functioning, and ultimately the delivery of ecosystem services to human society. The development of methods to address ecosystem restoration and management in relation to global changes and threats, and forecasting ecosystems' response in space and time, is also important. Given the possibility of comparing global scale, long-term, site-based research, the ILTER network has the potential to address these aspects and provide solutions to current and future environmental problems, which is ultimately, the ILTER mission. Some knowledge related to the conceptual framework, description of status and trends of national LTER research has been produced at national level. Korea has realized a comparison among its LTER network activities, and the framework activities of the LTER networks of the United States and China [77•]. In general, very few systematic reports and comparison of LTER research within, and across nations, have been produced. This kind of synthesis activity would be a precious tool to create a coherent and coordinated ILTER network and to improve comparability of long-term ecological data from sites around the world. Individual studies do not have the same impact as a comprehensive synthesis when the aim is to influence policy making and management decisions.

Biodiversity observation data of the ILTER sites could be better utilized than have been done so far in international collaborative projects, for example, related to early warning signals of ecosystem shifts. The advantage of long-term research and monitoring data resides in the ability to accurately describe the distribution of species. This is limited with fuzzy distribution data (e.g. herbarium specimens) with which true negatives cannot be defined. Floristic data, however, if obtained over the course of a century or longer [78], can be used to test hypotheses. Resampled standardized data (e.g. grid mapping) can be seen as primary sources from which certain early warning signals at a larger scale could be deduced [79]. However, the limitations that result from sampling bias have to be taken into consideration [80]. The data acquisition depends also on the spatio-temporal scales of the studied phenomenon. For instance, the databases of the multi-scale approach are scale and regionalization concepts developed and extensively used in hydrology (e.g. catchment and representative elementary area) and terrestrial sciences (e.g. science, geology, ecology, and hydrogeology). The multi-temporal approach refers to a hierarchy of time scales ranging from event based, continuous, and periodic measurements requiring precisely dated geoarchives (annually layered lake sediments and tree rings) and technological platforms such as ground-based geophysical, meteorological, and remote sensing techniques, low-cost and dedicated flying platforms (small and large airplanes, zeppelins, or helicopters), up to satellite-based remote sensing [81,82]; Terrestrial Environmental Observatories (TERENO www.teodoor.icg.kfa-juelich.de/overview-de).

As a world-wide network, ILTER sites cover a diversity of ecosystems. Among the papers analysed in this article, forests and inland waters are favoured ecosystem types. Until now little has been done in many important ecosystem types, including marine, coastal, cultivated and urban areas, all of which are critical to human well-being. Clearly this is due to the location of LTER sites, which are often chosen according to ecological and cultural relevance or based on the already existing reserves, parks, among others. Embracing a more heterogeneous range of ecosystem types might be one of the long-term goals of the ILTER network. For example, Alpine climate has changed during the last few decades and the future changes are predicted to be even larger. The development of observational and experimental networks represents a powerful tool for alpine ecosystems monitoring and for obtaining knowledge about their response to environmental pressures.

There is a relatively strong emphasis of ILTER research on highlighting regulating and supporting ecosystem services. This is not surprising, given the nature of the individual LTER sites, which were established with different and somehow complementary purposes rather than for comprehensive ecosystem service assessments (e.g. such as TEEB [8]). Ecosystem service assessments have been focused on compiling already existing information on the ecological and socio-economical value of ecosystem services, while the ILTER network is engaged in long-term, site-based ecological and socio-economical research.

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Within the ILTER research, ecological research is thus preferred to socio-economic research. The first stages of the cascade model — involving structure, process and function of ecosystems and biodiversity — are more frequently addressed by the ILTER rather than issues related to human benefits and wellbeing. Long-term ecological research is important in understanding the structure and functioning of natural ecosystems; however, it is important to explore the socio-economic value of ecosystem service in the ILTER sites, based on such knowledge of natural ecosystems.

The contribution of the ILTER network to the study of climate change is fundamental for several reasons. Firstly, knowledge production: many of the ILTER articles directly address climate change by researching status and trends of processes based on empirical data or by modelling. The ILTER articles directly dealing with climate change mainly focus on the impact of climate change on ecosystems and biodiversity rather than adaptation of ecosystems and biodiversity to climate change. This is possibly due to difficulties in discriminating whether a change in a system should be categorized by the positive meaning of 'adaptation' or the passive meaning of 'impact'.

A second factor contributing to develop solid climate change studies is that the ILTER network produces a great amount of information, which we might discover are important for future studies. ILTER articles include an assorted set of data, that is, spatial, numerical, statistical and qualitative, and also store a great quantity of biodiversity data, including species, habitats and processes. Phenological studies are a good example of data that were collected without the prior understanding of their importance, and the unique evidence they provide for climate change. Finally, both climate change-related and unrelated data are collected mostly on a national scale, while a smaller, but still relevant share of the articles are set on a multi-national scale. The vast amount of data and continuity in space and time are factors which make the ILTER network a unique resource of information for climate change studies. InfoBase, a metadatabase used in LTER EUROPE (http://www.lter-europe.net/info_manage/lter-infobase), is one example how data storage and management could be improved within the ILTER network.

In this context, the implementation of a systematically chosen selection of monitoring sites would greatly enhance the contribution of the ILTER network to global change research. Open data policy among ILTER collaborators could also significantly enhance the relevance of the research. Achieving efficient data sharing facilities requires the development of a cooperative data repository. Common accord and guidelines for data gathering, storing, documentation and use are prerequisites for success.

It is foreseeable that multidisciplinary and interdisciplinary papers, as well as problem-solving transdisciplinary studies [83] will play a wider role in the future of the ILTER research. It is thus important to maintain and reinforce the continuity in space and time of ILTER research, which is the stronghold of the ILTER network. It is also essential to develop studies into global-scale, long-term changes in social–ecological systems. In this regard, it is desirable to promote multi-national collaborations and synthesis of results with a global perspective. Integrating and synthesizing the data already collected should be at the top of the agenda of the ILTER, and might be most successfully performed with the adoption of an inductive approach. When dealing with data synthesis and integration, the need for standardized protocols and robust and detailed methodological approaches is an important issue to address the problem of future comparability and integration of information among sites, fundamental to achieve comprehensive monitoring and research and to provide necessary information at the world-wide level.

A joint ILTER study could significantly add to country-wide LTER/LTSER network studies, for instance on resistance and resilience, through increasing the number of ecosystems, species, communities, biogeochemical processes and disturbance regimes studied at ILTER sites around the globe. The ILTER network could also be significantly improved by devising a series of standard methods to be used across sites. This would contribute to a better understanding of the mechanisms that underlie ecosystem resistance and resilience and thus a more realistic way to predict, manage and mitigate the impact of climate change on the environment and the ecosystem services that it provides. As the number of ILTSER sites increases the understanding of how different socio-economic and governance contexts affect ecosystems will improve, as new meta-analyses of social systems [84•] and entire social–ecological systems [85] are completed.

It is evident that critically designed and carefully analysed long-term monitoring is irreplaceable due to their information value and practical use such as in the development of invasive species management plans [86]. Thanks to these observations, we now know more about changes in biodiversity induced by acidification and eutrophication, and the recent recovery of water bodies and forests [87]. From long-term monitoring and experimental studies, for instance of permafrost in Mongolia, we understand more about interactions of vegetation and livestock grazing on the thaw-and-freeze dynamics of permafrost that in turn can lead to significant changes in ecosystems, especially in the soil thermal state and moisture content [88]. We also know a lot about long-term cycles including climate-induced changes in European biodiversity, even if the monitoring did not last a very long time (see GLORIA [74••]). Manipulative

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experiments (e.g. ITEX experiments in the tundra [89]) and space-for-time substitutions [90] can partly serve as a surrogate of long-term monitoring data.

These analyses also show deficits in indicator development, observation schemes and unifying concepts for global change monitoring and analysis. Presently, global change monitoring is scattered, disorganized and not well combined. Biodiversity monitoring is often separated from abiotic monitoring schemes. A coherent strategy for the measurement of ecosystem services is still lacking. There is a large potential to use the intensive, long-term site data for validation and development of global remote sensing products such as those produced by GEO BON (www.earthobservations.org/geobon.shtml).

Views of the future

This paper has identified several aspects that should be taken into account to overcome the deficits in the integration of ILTER research and the greater benefits that could be realized through improved collaboration across the network. We would like to highlight six core themes based on the findings of this article that could form the agenda for improved ILTER collaboration in future:

(1) More local, regional and global synthesis of specified topics (e.g. climate change, biogeochemical cycles, biodiversity, ecosystem services);
(2) Harmonized and standardized methods for ILTER research, data gathering, and monitoring — better guidelines;
(3) Better data documentation (including metadata), storage, and open sharing for collaborative projects;
(4) Finding and understanding the linkages between social and ecological systems; including communication as the research-policy interface;
(5) Supporting the best techniques for biodiversity and ecosystem service assessments, including also automated data gathering;
(6) Filling the gaps of knowledge — both thematic and geographical balance.

To fulfil these needs, the first step forward could be to select global priorities of ILTER research, as has been done nationally in USA and China. In addition to the coordination of ILTER research, ILTER should also develop improved strategies for linking data from long-term monitoring and research to policy processes. The role of research–policy interface is increasing, for example, via IPBES, and global-scale ecosystem research networks are of great importance in supporting the way towards the solutions of future environmental challenges. Further development of modern infrastructure for monitoring, Earth observation and ecosystem assessments, open access databases, and virtual institutes for data exchange and analyses are some examples in which the ILTER network can have a leading role.

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