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Long-Term Perspectives and Infrastructure in Terrestrial Research in Germany – A Systemic Approach

Strategy Paper

Working Group “Infrastructures in Terrestrial Research“
Senate Commission on Agroecosystem Research
Senate Commission on Water Research
Senate Commission on Future Directions in Geoscience
National Committee on Global Change Research

DFG

Deutsche Forschungsgemeinschaft
German Research Foundation
Kennedyallee 40 • 53175 Bonn, Germany
Postal adress: 53170 Bonn, Germany
Phone: + 49 228 885-1
Fax: + 49 228 885-2777
postmaster@dfg.de
www.dfg.de

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Authors

Alliance Working Group “Infrastructures in Terrestrial Research“

Senate Commission on Agroecosystem Research[1] (principal author)

Chairperson: Prof. Dr. Ingrid Kögel-Knabner

Scientific Secretariat: Dr. Margit v. Lützow

Senate Commission on Future Directions in Geoscience[2]

Represented by: Prof. Dr. Erika Kothe

Senate Commission on Water Research

Represented by: Prof. Dr. Harry Vereecken

National Committee on Global Change Research

Represented by: Prof. Dr. Georg Teutsch

DFG Head Office: Dr. Patricia Schmitz-Möller

DFG Head Office: Dr. Ute Weber

Experts from Various Research Areas and Institutions

Prof. Dr. Susanne Crewell, University of Cologne (Geophysics and Meteorology)

Prof. Dr. Heinz Flessa, Thünen Institute (Climate-Smart Agriculture)

Prof. Dr. Bernd Freier, Julius Kühn Institute

Dr. Klaus Friedrich, Hessian Agency for the Environment and Geology

Prof. Dr. Peter Grathwohl, University of Tübingen (Geosciences)

Prof. Dr. Peter Haase, Senckenberg Research Institute and Natural History Museum, Deputy Chair of LTER-D

Prof. Dr. Bernd Hansjürgens, Helmholtz Centre for Environmental Research - UFZ Leipzig (Socioeconomics)

Prof. Dr. Daniela Jacob, Max Planck Institute for Meteorology (Regional Climate Modelling)

Prof. Dr. Florian Jeltsch, University of Potsdam (Vegetation Ecology and Conservation)

Dr. Wolfgang Leuchs, North-Rhine Westphalia Agency for Nature, Environment and Consumer Protection, Recklinghausen

Prof. Dr. Wolfram Mauser, LMU Munich, Chair of Geography and Geographical Remote Sensing

Dr. Uwe Rammert, Schleswig-Holstein Agency for Agriculture, Environment and Rural Areas, Flintbek

Prof. Dr. Erko Stackebrandt, Member of the Senate Commission on Biodiversity Research, Paris (Molecular Biology)

Prof. Dr. Thilo Streck, University of Hohenheim (Biogeophysics)

Prof. Dr. Hartmut Stützel, University of Hannover (Agricultural Production Systems – Crop Plants)

Professor Dr. Günther Turian, Baden-Württemberg Ministry of the Environment, Climate Protection and the Energy Sector, Stuttgart

Wolfgang Vogel (Director), Schleswig-Holstein Agency for Agriculture, Environment and Rural Areas, Flintbek

Prof. Dr.-Ing. Erwin Zehe, Karlsruhe Institute of Technology (Hydrology)

[1] Successor to the DFG Senate Commission Substances and Resources in Agriculture

[2] Successor to the DFG Senate Commission on Joint Research in Geosciences

Contents

1. Background and Aims of the Strategy Paper

In this strategy paper the Senate Commissions present concepts and recommendations which are intended to ensure access for Germany to adequate research infrastructures for terrestrial environmental research at national and international level. These infrastructures are needed in order to recognise negative developments in our ecosystems and initiate timely countermeasures or at least mitigate the negative impacts on society through long-term observations.

Terrestrial ecosystems are landscapes or parts thereof in which habitats with characteristic structures and functions have formed. They typically include the compartments of atmosphere, biosphere, anthroposphere, pedosphere, geosphere and the hydrosphere with its aquatic systems. Within terrestrial ecosystems, functional relationships and exchange processes (heat, water and material flow, chemical reactions etc.) take place as part of complex landscapes, for example between agricultural production areas and other habitats (DFG, 2005). These also include organisms and their interactions with their abiotic environment.

The main current trends affecting life on earth are a rapid increase in the world population and the spread of Western patterns of consumption with rising food and energy demand (Godfrey et al., 2011); associated with this is a change in social value patterns. As a result of human interventions in terrestrial ecosystems, we are seeing a shortage of resources, such as energy sources and raw materials, and the loss or degradation of soils and water supplies. At the same time, the composition of the atmosphere is undergoing long-term change and biodiversity is diminishing (inter alia WBGU, 2011; EIA, 2010; FAO & OECD, 2009; Rockström et al., 2009; RS, 2009; UN, 2009; von Braun, 2007). The impacts of these global changes affect all ecosystem compartments.

Terrestrial ecosystems exhibit enormous spatial and temporal variability, parameter and process complexity, and marked scale dynamics, which makes it difficult to predict regional changes. The reactions of individual ecosystem compartments to changes in climate and land use are therefore largely unknown at the present time (IPCC, 2007). For example, it is still unclear to what extent terrestrial systems will become sinks or sources for climate-relevant gases as a result of climate change and changes in land use patterns.

In order to understand and assess natural and anthropogenic fluctuations in ecosystems, qualitative and quantitative changes must be recorded and evaluated over long periods and attempts must be made to identify the causes of land use change. This applies not only to slow processes such as climate and land use change and extreme events such as floods and storms, but also to processes with high variability in terms of a valid trend prognosis (material input and output, e.g. for nutrients or anthropogenic pollutants, and microbially controlled processes). Generally, the assessment of complex processes and interdependency networks in ecosystems calls for long-term investigations over a period of at least a decade. The investigation and quantification of these interrelationships depends on permanent, multi-scale research and monitoring infrastructures that allow these coupled processes to be analysed in a coordinated approach. The detailed long-term recording of material and energy flows and biodiversity, with due consideration of the socioeconomic developments within an ecosystem, is an essential prerequisite if we are to address current issues of high social relevance, for example:

- maintaining the ability of terrestrial ecosystems to adapt to changing environmental conditions and their resilience to anthropogenic interventions and extreme events,
- protecting the functional capability of terrestrial ecosystems in order to maintain ecosystem services such as food production or climate regulation and protecting soil and water resources,
- analysing the causes of current disruptive factors affecting the state of the natural environment and identifying suitable remedial measures (e.g. in the implementation of the objectives of the European Water Framework Directive),
- identifying scientifically justified solutions to land use conflicts, e.g. between food and energy production, agriculture and water management, or higher-intensity production and conservation interests,
- identifying social value structures and specific investigation of causes to establish the reasons for specific trends and optimise decision-making processes.

1.1 Adressees

The paper is primarily aimed at three target groups. Firstly, it is intended to outline for researchers and research organisations in Germany the possibilities offered by the infrastructure systems and cooperations proposed here in terms of addressing current issues. Secondly, it is aimed at agencies and institutions responsible for nature, environment and resource use at national and federal state level in that it pinpoints potential synergy effects arising from the consolidation of existing data and the generation of new data. Thirdly, the paper is intended to provide research funding bodies with information about the necessity and advantages of a new generation of infrastructure systems.

1.2 Scientific and Social Challenges in Terrestrial Ecosystem Research

The central scientific challenge is the quantification of coupled processes and the prognosis of the dynamics, resilience and adaptation of terrestrial ecosystems in a changing environment. To this is added the analysis of anthropogenic drivers and the changes they cause in ecosystems. Investigations in the natural sciences must be designed to be of use in socio-economic projects and thus permit system-oriented research of the necessary disciplinary breadth.

Existing research and monitoring infrastructure systems, with their extensive data, measuring, testing and modelling systems, are largely focused on specific scientific questions, selecting partial aspects and analysing them in detail. However, society expects complete solutions that involve all actors, with consideration and disclosure of costs and benefits. To address complex problems in nature and the environment, the various scientific disciplines must contribute their different competencies so that individual contributions can be synthesised and integrated to form an overall perspective. These challenges have not as yet been successfully addressed (ICSU, 2010; Plieninger et al., 2008; UBA, 2003). This is illustrated by the following **current fields of research:**

- As dynamic systems, **ecosystems** have the capacity for self-regulation and self-renewal, within certain limits. If these limits are exceeded through the influence of external factors, the system may drift into a new state and thus lose its structural and functional identity: the original ecosystem ceases to exist. The duration of the destabilisation process and the extent of change depend on the resistance, resilience and fragility of the ecosystem. These characteristics are the subject of intensive research, but owing to the highly complex interaction of many individual processes, sometimes over a period of several decades, it is not yet possible to make a prognosis as to the resistance or collapse of ecosystems (Doré et al., 2011).
- **Material flows** in and between compartments are not generally caused by linear processes and are therefore coupled in complex ways. As yet we have an inadequate understanding of the relevance of influencing factors and trends, for example in relation to soil pollution and productivity or water quality. Consequently, it is not currently possible to record material flows up to the level of mass balances across all compartments and their prognosis on a large spatial scale.
- Within individual compartments there is a marked spatial and to some extent temporal **heterogeneity,** the mapping of which depends in different ways on the scale of observation used. There is still a lack of concepts for adequately taking this heterogeneity into account in models of larger regions and overcoming scale transitions.
- Changes in the terrestrial environment, particularly land use changes, are also due to a multitude of superposed **development trends,** ranging from demographic change to evolving consumption patterns and economic globalisation processes. In most cases there are no standard data sources that consistently cover all these trends and map their impacts on environmental compartments. So it is necessary to find new ways of generating and consolidating socioeconomic data and reconciling it with scientific data (Ohl & Hansjürgens, 2011).

An integrative and system-oriented approach to research topics such as these will make an essential contribution to the development of long-term prognoses of ecosystem changes and the assessment of their consequences, including the costs of changes to ecosystem services. Special attention should be given to the meaningfulness of highly complex and coupled prognosis models in order to derive workable adaptation strategies and courses of action and describe uncertainties adequately in quantitative terms.

Prognoses of these change processes and their consequences demand the development of comprehensive environmental system theories to consistently describe these interlinked dynamics. Such theories would not only represent clear progress in terrestrial environmental research, but also lay an important foundation for a new generation of numerical model systems, for example to explicitly model abiotic-biotic interactions and quantify interrelationships of biotic and abiotic adaptation processes. Simulations with this new generation of interlinked model systems would make a significant contribution to the formulation of workable and verifiable hypotheses on the impacts of global change in complex terrestrial ecosystems.

Such infrastructure platforms would also serve as an “accelerator” for individual research projects because there would be no need for preliminary investigative work, for example producing a functional soil map or obtaining hydrometeorological data. Ultimately, terrestrial infrastructure platforms are the key to a number of methodological problems, particularly problems of scale, because only through joint efforts can the necessary multi-scale observation networks of adequate density and quality be constructed and operated.

Government research institutions and agencies at national and federal state level would benefit from the fact that for action-oriented issues, “scientific” research data and findings could be used in addition to their own basic data. Existing, well established and valid data providers should also be retained and integrated in the overall approach. In this context, data and monitoring systems designed for long-term use are operated which in collaboration with research disciplines can generate data standards and quality-assured data pools for future projects. In addition to technical measuring networks this includes networks that study direct organismic reactions to changing environmental conditions (e.g. phenological gardens or species inventories).

Diagram: Holger Vanselow

Air, soil, water and organisms directly interact with one another. As a result, the various processes that occur within them are coupled in multiple ways (heat, water and material flow, biogeochemical reactions, and so on). Changes in one compartment affect the neighbouring compartments too. The challenge is to detect future, potentially very gradual, changes in these heterogeneous compartments early on, because large-scale changes in the conditions are often irreversible once they start. Examples include the impacts of climate and land use change on vegetation and soils, which have consequences for groundwater and surface water quality, and the effects of falling/rising water levels on ecosystems and their capabilities. To respond to needs such as these and to develop management strategies, it is necessary to determine state variables for the various compartments from the microscopic to the landscape scale over a long time series (a period of decades). It will then be possible to produce mass and energy balances for an entire area, study the integration of processes at different scales and scale levels and analyse functional relationships and interrelationships by integrating various monitoring methods from different research disciplines. Monitoring activities range from soil-based, airborne and satellite-based remote sensing systems to sensor networks and direct sampling of air, soil, water and organisms.

2. Current Developments in Terrestrial Ecosystem Research

Over the last 30 years there have been three main developments which indicate that the establishment of cross-system infrastructures would be a promising approach:

1. The establishment of national and international observatories and "Exploratoriums" has created an excellent scientific basis for systematic approaches that go beyond current limitations.
2. The development of non-invasive research methods and rapid advances in soil-based, airborne and satellite-based remote sensing have brought scientists in participating disciplines closer to the scales they are studying. These are traditionally very different, with the result that in many areas, cooperation has appeared all but impossible.
3. Developments in scientific computing have made it possible to carry out coupled simulations with the necessary complexity and high spatial and temporal resolution. However, the availability of high-performance computers is essential in order to manage and analyse large amounts of data, as generated by satellite and remote sensing, for example.

Investigating processes and interrelationships on the scale of catchment basins or landscapes is made difficult by their heterogeneity and the multitude of interactions that occur. In addition, the relevant processes take place over very different, sometimes very long time scales. Hence, a research infrastructure with shared research platforms and simulation models must be designed for long-term use. Under these conditions, research would benefit from close collaboration between the various disciplines. Additional social value-added could then be achieved through networking with the remits of the responsible agencies.

2.1 International Investigation Areas and Research Infrastructures

In global terms, the multitude of ecosystems can only be covered through international cooperation. In the area of ecological and atmospheric research, global, long-term terrestrial research platforms have existed for several years, for example *FLUXNET* and *LTER* (for explanation of abbreviations, see appendix). In the USA, the *National Ecological Observatory Network (NEON)* was established in 2011. The aim of this platform is to record and predict ecological changes in 20 selected ecoclimatic zones on the North American continent over a period of several decades. At around the same time the USA began to set up *Critical Zone Observatories (CZO),* funded by the National Science Foundation.

In Europe, the *Integrated Carbon Observation System (ICOS),* the first research platform to integrate all compartments, is in the implementation phase.

The objective of *ICOS* is the long-term observation of trace gases with an impact on climate in the atmosphere, the ocean and terrestrial ecosystems. It is funded by the EU member states through *ESFRI*. Another *ESFRI* initiative is the research and experimentation platform *ANAEE.* The focus of this initiative is the development of a network of experimentation platforms to investigate, analyse and predict ecosystem changes in the context of climate and land use change in Europe. Other platforms in the field of biodiversity research and hydrological research are either in preparation or at the proposal stage (e.g. *LifeWatch*).

To reinforce German participation in European terrestrial research platforms and secure a leading and coordinating role, a joint, coordinated approach is required from the German research community, across disciplines and research organisations. In this way, existing research platforms and those currently being established, which tend to be geared towards specific disciplines or the specific remits of individual research organisations, could be better integrated in these international networks. This would further increase their international visibility and competitiveness. At present Germany is actively involved in various platforms but does not play a leading role at European level in any of the current activities.

A good example of the challenges and development opportunities offered by close co-operation between different disciplines is the coupling of physical processes at the land-atmosphere boundary, the interface between the soil compartment (including vegetation) and the atmosphere. This interface traditionally also forms the boundary between disciplines such as hydrology, hydrogeology, soil science and plant science on the one hand and meteorology on the other. Due to a lack of data and interdisciplinary knowledge, flows and state variables at such boundaries tend to be treated by the individual disciplines as marginal conditions. Soil scientists, hydrologists etc. use data from weather stations, or from climate simulations in the case of projections based on climate scenarios. For the purposes of model calibration, boundary flows are often optimised (as in the case of groundwater recharge in hydrogeology) or simply negated (in the case of surface runoff in meteorology).

Simplifications such as these may be justified for the purposes of specific disciplinary questions, but are not acceptable when it comes to depicting the entire hydrological cycle. Meteorologists are now aware of the importance of the land surface, particularly soil water storage, in the formation of weather processes, and take the soil-plant system into account. (Hydro)geologists have begun to give due consideration to microbial transformation processes. However, the basic processes are so simplified that simulated variables are virtually unusable for potential users, for example in soil or plant science or indeed agricultural economics. For example, the state of growth of plants, which is important to the partitioning of incoming radiation into latent and sensible heat flow, is only recorded indirectly through remotely sensed surface temperature and reflectance. In addition, in typical plant growth models the actual evaporation is calculated from the potential evaporation via reduction functions of soil moisture, without taking into account how this alters energy distribution at the land-atmosphere boundary. However, energy distribution is related to processes in the atmospheric boundary layer and the formation of clouds and precipitation. In addition to the inadequate depiction of such interactions, the failure to take these relationships into account produces inconsistencies in boundary flows and thus the violation of physical principles such as the conservation of energy and mass.

A close collaboration with adjacent disciplines will make it possible to better measure and simulate the formation and heterogeneity of the sensible and latent heat flow through a landscape of complex orography. It is also to be hoped that specific measurement problems, such as the closure of the energy balance in eddy flux measurements, can be resolved. The study of long-term interrelationships, for example between climate change, land use and geomorphology, will also benefit from close collaboration between different disciplines. An additional benefit will arise from the fact that disciplinary hypotheses and models can be rigorously tested when boundary conditions of adjacent disciplines are considered more accurately and interpolated, for example through process models.

3. Starting Point and New Research Methods

The existing observation platforms for terrestrial ecosystem research in Germany, including monitoring systems at national and federal state level, offer an excellent starting point from which to address the outlined challenges and play a leading role in the formation of European research platforms. The individual disciplines involved in systematic ecosystem research operate within a very good framework (Adams, 1998) and in some areas enjoy a leading international status. The academic competence is wide-ranging and is shared among universities, the institutes of the Helmholtz Association of German Research Centers, the Leibniz Association, the Max Planck Society and government departments. However, in spite of the high standard and disciplinary breadth of German ecosystem research, it is currently unable to fulfil its potential due to geographical and disciplinary fragmentation (Plieninger et al., 2008; Albarran et al., 2010). The national and state governments have created large, quality-assured databases (covering soil, geology and hydrology) and operate dense (by international standards) measuring networks and measuring stations, some of which deliver data with high temporal resolution. Again, only insufficient use has been made of this data due to a lack of resources. In addition, little effort has been expended on linking this scientific data with socioeconomic data. Initial attempts have been made in the form of “ecosystem services” (TEEB, 2010).

3.1 Existing Research Centres

The first integrated ecosystem research centres in Germany were established in the 1980s. Their objective was to develop efficient precautionary environmental protection measures within the framework of long-term research projects. These centres were established at universities and large research institutions and included, for example, the *Munich Agroecosystems Research Group (FAM),* the *Bayreuth Institute for Terrestrial Ecosystem Research (BITÖK),* the *Forest Ecosystems Research Centre (FZW)* in Göttingen and the *Ecosystem Research Project Centre (PZÖ)* in Kiel. Dedicated to finding responses to topical and nationally relevant issues, they concentrated on areas such as forest damage research and questions relating to soil and water protection. They had a considerable influence on political and administrative decisions and on legislation, and also led to a greater general awareness of the need for systematic approaches in environmental conservation.

There is also a large number of measuring stations and research sites which were primarily set up for official monitoring programmes or specific research concerns. As part of their remits, the national and state governments operate representative long-term research sites, measuring station networks and monitoring programmes for water, soil, nature, agriculture, forestry, meteorology and air, collecting measurement and analysis data on a continuous or discontinuous basis (with a resolution of minutes to years). The field of quantitative and qualitative hydrology comprises, for example, gauging stations, precipitation measurement stations, lysimeter stations, water quality measurement stations and groundwater measurement stations. In some cases, discharge and water level data goes back over 100 years.

Long-term soil observation, long-term agricultural experiments, the Agrometeorological Network, biotope and species conservation monitoring and the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests *(ICP-Forests)* have all been up and running for almost 30 years, supplying important information and time series data. Air monitoring programmes are concerned with both qualitative air pollution (immission measurements) and impacts of dry and wet deposition.

LTER-D, the German network for long-term ecological and ecosystem research, was set up in 2004 as a platform for communication, documentation and collaboration between researchers in long-term, system-oriented and interdisciplinary environmental observation in Germany. It consists of 20 *LTER* areas covering the whole of Germany and encompassing ecosystems ranging from mountains to mudflats. *LTER-D* is a member of the international network *ILTER* and the European network *LTER-Europe* (Müller et al., 2010).

Recently established networks include the DFG-funded *Biodiversity Exploratoriums* and *iDIV,* which take an integrated approach incorporating different disciplines in biodiversity research. The Biodiversity Exploratoriums are internationally linked via *LTER-D.*

In 2008 the Helmholtz Association began to set up *TERENO* sites, which concentrate on the observation and forecasting of coupled material flows in terrestrial systems in an integrated approach. The aim is to provide long-term data series for the validation of mathematical models, develop new technologies to record important system states, and establish a basis for the development of adaptation strategies in the context of climate and land use change. At some locations *TERENO, ICOS-D* and *LTER-D* are merged and measurements are coordinated.

Because there are so many investigation areas and stations in operation, a complete list will not be given in this paper. Instead, a few current national and international initiatives are listed in Table 1 (see appendix) by way of example. These sites provide an important basis for long-term terrestrial environmental research and the formulation of sociopolitical strategies, for example strategies for adaptation to climate change and the management of land use changes. They serve as points of reference for the global observation of terrestrial ecosystems.

However, the list of examples also shows that the overwhelming majority of sites are primarily focused on subject-specific, small-scale investigations and are operated by different institutions. Additionally, very little has been done to link socioeconomic data with scientific data relating to the state of and trends in environmental compartments. Research sites that integrate the various compartments and disciplines on a larger investigative scale are still in the setup phase *(ICOS, TERENO)* or the planning phase *(NOHA).* In Germany there is no coordinating, cross-institutional procedure for harnessing the potential of existing sites and the experience acquired through them for integrated ecosystem research at national and international level and rendering it usable for the responsible agencies.

3.2 New Measurement Methods and Linking Scales

The rapid advancement of non-invasive measurement systems (soil-based, water-based, airborne and satellite-based) and sensor networks, combined with modern communication systems and geoinformation systems (GIS), opens up new possibilities that will enhance our understanding and prediction of terrestrial processes in ways that were inconceivable just a few years ago.

The transition from primarily process-oriented, small-scale “point” measurement programmes to the entire land-atmosphere boundary continues to present one of the biggest challenges in terrestrial ecosystem research, particularly in view of the considerable spatial and temporal variability of the system. Interactions between processes have been individually studied in detail but we still know astonishingly little about the spaces between measurements that make up by far the largest area of the earth's surface.

As one of the few large-scale measurement techniques, satellite-based remote sensing of the land-atmosphere boundary has the potential to close the gap between the process-oriented/ point measurements of traditional ecosystem research and the answers needed to scientists' larger-scale questions. Various satellites are already surveying the land-atmosphere boundary on different scales, with the number set to increase. Thanks to both qualitative improvements and quantitative expansion in recent years, the pictures of the past have been replaced by a calibrated, reproducible, continuous flow of information about the reflection and emission characteristics of the earth's surface. This continuous flow of remote sensing data can be used to decode the interactions that take place between the biosphere (as the driver of terrestrial material cycles) and geological, meteorological and land management parameters. For example, microbially controlled substance conversions in soils are heavily impacted on by cultivation, temperature, precipitation and soil texture and are sources of atmospheric trace gases, which in turn influence the productivity and evaporation activity of plants. Altered evaporation activity, in its turn, has a local and regional effect on insolation conditions and precipitation.

Precision agriculture uses sensors, automation technologies and information processing systems for process-oriented *in-situ* data gathering to maximise production in a given area while minimising resource consumption. In the process it generates a great deal of information on the variability of the agroecosystem.

But data obtained in this way is only of use if it can be used in conjunction with an understanding of processes acquired from observatories and exploratoriums in land-atmosphere boundary models. A global, universal application in the "spaces in between" calls for new approaches in remote information acquisition. Unlike the locally valid statistical regression approaches which are currently the norm, these new approaches must examine physical interrelationships between land-atmosphere boundary processes and heterogeneity patterns and their role in radiative transfer and make these a basis for universally valid algorithms to ascertain the structure and dynamics of the earth's surface. It is evident that only cross-disciplinary and cross-departmental research can guarantee success in an endeavour of such scope and complexity.

3.3 Numerical Modelling and Computing Capacities

The rapid pace of development in scientific computing and the use of high-performance computers and supercomputers have made it possible to simulate systems of this complexity with the necessary spatial and temporal resolution. Models that depict water and energy flows in the atmosphere- soil/plant-subsoil systems must calculate complex, at least two-dimensional flow fields in the atmosphere and in saturated and partly saturated subsoils. These flow fields are coupled with one another by complicated mechanisms of energy and material exchange at the land surface (the soil-plant system). Another important area with complex interactions exists between groundwater and surface water (the hyporheic zone).

To calculate the conversion and transport of material, models of differing complexity are coupled to the flow fields, ranging from simple transfer functions to fully coupled thermodynamic equations with phase transitions (dissolution, precipitation) including the consideration of reaction kinetics. Spatially explicit economic models to simulate land use changes (multi-agent systems) are nearly as computationally intensive, and must be linked to biophysical models, at least for long-term calculations such as climate projections.

Inverse simulations and data assimilation require many times this computing capacity, which is already approaching the limits of what is currently possible. Inverse simulations are used to estimate the spatial distribution of parameters that are very difficult to measure directly, mainly underground (groundwater). Data assimilation is an essential process in high-resolution weather and climate simulations for the estimation of starting fields and boundary values and also in reanalysis.

The general view today is that simulations should be assigned confidence intervals, as is normal in statistics, particularly if they are to be used as a basis for policy and economic decisions, usually with different scenarios. In large numerical models, confidence intervals are typically generated using Monte Carlo or similar techniques, which require numerous simulations with the fully coupled model and thus very high computing capacity.

4. Aims and Purpose of an Integrated Infrastructure

Future integrated research infrastructures in terrestrial ecosystem research must:

- support systematic, long-term cross-compartment and cross-scale research,
- promote better networking between the different research institutions in Germany than exists at present,
- serve as a basis on which to intensify collaboration with government ministries and agencies at national and federal state level,
- develop methods and services for data availability which deliver in an exemplary way measurement data and research results in a standardised, quality-assured form,
- permit standardisation and harmonisation of research methods and techniques,
- have the potential to be integrated in international research networks.

In the following sections, suggestions are developed for the establishment of a German network of “Infrastructure for Terrestrial Ecosystem Research”. They cover research locations, data management, international networking, and education and knowledge transfer.

4.1 Observation and Experimental Platforms

Observation and experimental platforms constitute the core of an integrated national research infrastructure. These comprise regionally localised landscape sectors with well equipped facilities which record the temporal and spatial variability of system states and cross-compartment material flows. Research locations should ideally be situated in a catchment basin because this simplifies the process of calculating mass and energy balances for the area as a whole.

As part of the establishment of integrated terrestrial infrastructures, closer coordination between research locations belonging to institutions with existing basic data surveys (e.g. soil mapping or digital terrain models), measuring stations and the observation areas of public institutions would be desirable in order to exploit synergies in relation to the data basis and evaluation. System maintenance and backup, in particular, could be improved through reciprocal support.

Observation and experimental platforms should provide ground space and facilities to carry out specific field experiments with controlled factor variations (e.g. water and nutrient availability or CO_2 concentration), in which the effect factors of human interventions that are essential to land use modelling, such as tilling or fertilisation, can be calculated.

Because there is a broad base of research sites in Germany, it should be used as effectively as possible – in other words networked – in order to achieve coverage with representative locations. In this context, representative means taking into account the essential landscape forms and land use types, including urban space and the different soil and climate regions found in Germany.

In the first stage, suitable existing locations would have to be identified and interlinked to form an infrastructure network. In the second stage, the objective would be to establish whether additional locations were required with regard to national and international research questions and the adequate representation of regions.

Starting from the current level of instrumentation, the investigation areas of an infrastructure network must be equipped with state-of-the-art measuring technologies tailored to the relevant research question in order to meet the following requirements:

- Spatial and temporal high-resolution observation of selected system states and material flows Material flows of water, carbon, nitrogen, phosphate and selected anthropogenic substances should be continuously measured. In this context the use of environmental tracers such as isotope measurements should be increased.
- As great as possible a reduction in manual sampling to gather core data resulting from the use of soil-based observation methods such as moisture sensors, *in-situ* data loggers, surface geophysics; multitemporal and multiscale observation through the combination of soil-based observation methods and remote sensing methods.
- A reduction in manual sampling can also be achieved in biodiversity surveying, e.g. through *barcoding,* metagenomic analysis (Jansson, 2011) or *environmental* DNA analysis.

To complete the stationary measurement facilities, a pool of mobile measuring equipment should be established which can be used at different sites. This might include radiometers, GPR, EMI, 3D lidar, DTS, DirectPush, isotope analysers and soil sensor systems. This would support time-limited measurement campaigns with a specific goal as part of a standardised procedure and standardised data management.

4.2 Central Data Platforms and Data Management

The current infrastructures in terrestrial ecosystem research operate with relatively little coordination between them. Consequently there is little exchange of data, research methods, evaluation results and numerical models between the various sites.

One important prerequisite for the management of terrestrial systems is the construction of a shared knowledge basis consisting largely of collected data and measurements. The successful, close collaboration between agencies and scientific institutions as part of the *German Strategy for Adaptation to Climate Change (DAS)* and between the BMBF, BMVBS and federal state projects within the *KLIMZUG, KLIWAS* and *KLIFF* funding programmes have shown that fast, uncomplicated and non-bureaucratic access to existing databases is possible. Within these joint projects – which were not however based on shared infrastructures – a significant knowledge gain was achieved for all participants.

The DFG's Biodiversity Exploratoriums operate a central data management system in which collected research data can be fed in and then interlinked. The data infrastructure is currently being further professionalised in a DFG-funded project to create an information infrastructure which is available to other joint projects. The project is part of efforts by the University of Jena / MPI to establish a centre of competence for research data management.

Within the framework of *TERENO* a central data portal, *TEODOOR,* was set up. This is the shared access point to the local databases of centres and institutions involved in *TERENO.* Data from *TERENO* is made available to all interested researchers and institutions on the basis of a data management agreement. This agreement, which defines data transmission standards, guarantees the compatibility of data access, efficient data backup and processing, the use of agreed data and metadata standards, and copyright protection. Data is exchanged via web services in line with the specifications of the *Open Geospatial Consortium (OGC).* Metadata is stored in a separate database and published on the Internet using the OGC-compatible catalogue service WCAS.

The rapid development of *Next Generation Sequencing (NGS)* of metagenomes and pure cultures of species in medicine and ecology is producing a flood of data that is very difficult to evaluate efficiently and quickly with today's computer systems. High-performance computers (HPCs) are required, which will open up new dimensions in rapid, reliable data analysis through the adaptation of algorithms for assembling and mapping NGS data to the HPC hardware architecture. The potential of HPCs is pushed to its limits when it is necessary to assemble the metagenome of a site sample containing over 10 000 species, detect genes and predict functions.

These examples should be seen as a motivation to agree on a continuous opening-up of existing state and scientific data archives in the area of terrestrial research infrastructure, even for users not involved in joint projects – the usual current requirement for access.

To secure access to comprehensive distributed databases, it is necessary to operate a metainformation system as a central communication and data management platform for efficient information exchange. It is important to provide information about what data exists, where it is stored, detailed content, scale range, formats, data protection, access, terms of use and contact persons. Setting up and operating a metainformation system of this nature is a major undertaking, particularly with regard to the long-term maintenance of the highly dynamic data. So the first step must be to integrate existing national and international metainformation systems and data platforms (PortalU, GDI-DE, infoGEO, D-GEO, WasserBLIcK, INSPIRE etc.) with due regard for the data requirements of terrestrial research. The objectives that cannot be achieved through this integration process should be implemented with appropriate measures in a second stage. Appropriate incentives should also be created to encourage data owners to document data promptly and make it available on a central communication and data management platform. In return, research results based on terrestrial data should also be made freely available and become part of the metainformation for terrestrial research.

4.3 International Networking

To better integrate German research sites in international initiatives, their visibility must be enhanced. A German infrastructure network with concepts for integrated observation could make a key contribution in this respect, as well as functioning as a national point of contact. Central access to information and data also plays an important role in this regard.

A partnership with existing or planned *ESFRI* projects such as *ICOS, ANAEE, NOHA* or *LifeWatch* and other European activities (e.g. *LTER-Europe*) could be supported by a German infrastructure network offering a broader representation of our research landscape. With regard to the USA, closer networking with *NEON* and *CZO* would be promising in view of the good existing scientific contacts.

4.4 Education and Knowledge Transfer

Integrated research infrastructures provide an ideal platform for giving students and doctoral researchers access to well-equipped research sites. The cross-disciplinary approach makes it easier for early career researchers to come into contact with researchers in other disciplines and their ways of working. Furthermore, this kind of site enables ongoing training for established researchers and agencies relating to current developments in the various disciplines. This could significantly accelerate and improve the mutual exchange between research and practice.

5. Recommendations for Implementation

To build a representative and internationally competitive network of research sites in Germany, we propose a two-stage process. Firstly, suitable existing sites should be linked to form a network, and secondly, the need to add new sites to the network should be evaluated. Such a networking process can only succeed through the joint effort and support of all relevant actors. This includes the different scientific disciplines, universities, non-university research institutions, research funding organisations, government research bodies and the relevant agencies at national and federal state level.

5.1 Organisation

The authors of this statement recommend that the Alliance of Science Organisations in Germany address the issue of infrastructure for terrestrial ecosystem research at its research funding forum. To initiate a German infrastructure network, we propose setting up an operational working group with representatives of Alliance member organisations, relevant national and state institutions, and government research bodies. The BMBF and the BMU would play a central role because long-term research funding comes within the remit of the BMBF and the long-term protection of our environment is the core task of the BMU.

5.2 Instruments

The task of the working group is to construct the infrastructure network described. The first step must be to bring together the basic requirements, such as existing infrastructures, data basis and data availability. Building on this, an initial network could be established through a competitive process in which existing platforms apply to be included in the network. The criteria for inclusion would include not only a suitable existing infrastructure but also the will and competence of the individual platform to integrate its research more deeply in cross-compartment, systematic research and participate in the ongoing development of joint research and data management and – where possible – international platforms. A network of this type could be gradually expanded through further rounds of competition. Within this process and in terms of the selection of applicant institutions, the working group would also be responsible for maintaining a balance with regard to the different starting situations of non-university, university and government groups. If it became apparent that certain research locations or equipment were lacking in terms of national and international research questions or regional representation, these would have to be created.

The development of central data platforms and management structures for terrestrial ecosystem research requires, as a first step, the examination of existing databases and management approaches. This would include considering which data storage structures are already being used by agencies and academic institutions and how a link can be established with existing databases. It would therefore be appropriate for an **expert group** within the working group mentioned above to be responsible for **data management.**

The establishment of integrated research platforms is key to the development of comprehensive environmental system theories. The high complexity of interacting abiotic and biotic interrelationships of terrestrial ecological systems demands long-term, cross-compartment and cross-scale data recording and processing. A systematic knowledge base of this kind allows the model-based development and ongoing review of environmental system theories and more reliable prognoses of the dynamics, resilience and adaptation of terrestrial ecosystems in a changing environment. To promote this objective from the beginning, we suggest setting up an **expert group on environmental system theories** within the Alliance working group described above.

Also under the umbrella of this working group, an **expert group on international networking** should be formed with the task of developing a concept as to how existing sites or sites within a German network could be integrated early on in international initiatives. Such a concept should continue to provide recommendations for enhancing the influence of German research in the development of international initiatives.

Appendix

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List of Abbreviations and Glossary

Alliance of Science Organisations in Germany	The member organisations are the Alexander von Humboldt Foundation (AvH), the German National Academy of Sciences Leopoldina, the German Academic Exchange Service (DAAD), the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation), the Fraunhofer Society (FhG), the Helmholtz Association of German Research Centers (HGF), the German Rectors' Conference (HRK), the Leibniz Association, the Max Planck Society (MPG) and the German Council of Science and Humanities (WR).
ANAEE	Analysis and Experimentation on Ecosystems
BITÖK	Bayreuth Institute for Terrestrial Ecosystem Research (1989–2004)
BMBF	Federal Ministry of Education and Research
BMUB	Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety
BMVBS	Federal Ministry of Transport, Building and Urban Development
CZO	Critical Zone Observatory
DAS	German Strategy for Adaptation to Climate Change
DirectPush	A geophysical research technology involving the use of small machines to drive small-diameter measuring and sampling probes quickly and cost-effectively into the subsoil.
D-GEO	German contribution to the Group on Earth Observations and the establishment of the Global Earth Observation System of Systems
DTS	Distributed Temperature Sensing. DTS uses fibre-optic cables to measure soil moisture and temperature.
EMI	Electromagnetic induction, non-invasive geophysical technique for measuring the electrical conductivity of soils and sediments
ESFRI	European Strategy Forum on Research Infrastructures. ESFRI is a multidisciplinary platform for the EU member states, operating on a "meta-level" of European research activities.
FAM	Munich Agroecosystems Research Group (1990–2003)
FAO	Food and Agriculture Organisation of the United Nations
FLUXNET	Global network of micrometeorological tower sites which use eddy covariance systems to measure the exchange of energy, water and trace gases between the earth's surface and ground-level atmosphere. Its aim is to provide information to validate remote sensing products for net primary production, evaporation and energy absorption.
FZW	Forest Ecosystems Research Centre at the University of Göttingen (1989–2003)
GCEF	Global Change Exploratory Facility
GPR	Ground Penetrating Radar, also known as Radio Echo Sounding (RES), is used to characterise the subsurface and is used in particular to measure electric permittivity by detecting reflected electromagnetic waves.
GDI-DE	Geodata Infrastructure Germany is a national, state and local initiative. The partners network geodata from all over the country. This data is freely accessible to organisations and private individuals and provides a reliable basis for efficient decision-making.
HPC	High Performance Computer
ICOS	Integrated Carbon Observation System
ICP-Forests	International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests

iDIV	German Research Foundation (DFG) Research Centre on “Integrative Biodiversity Research“ (since 1.10.2012). http://www.idiv-biodiversity.de/
infoGEO	Website of the State Geological Surveys of Germany. http://www.geokommission.de/
INSPIRE	Infrastructure for Spatial Information in Europe. Guidelines for the establishment of a European geodata infrastructure
IPCC	Intergovernmental Panel on Climate Change
KLIFF	Climate impact and adaptation research in Lower Saxony. Strategies for adaptation to climate change
KLIMZUG	BMBF network project: Managing climate change in the regions. The aim of KLIMZUG is to develop innovative strategies for adaptation to climate change and associated weather extremes for the regions on the basis of concrete local requirements.
KLIWAS	BMVBS research programme: Impacts of climate change on waterways and navigation – Searching for options of adaptation
LAI	Leaf Area Index
3-D-Lidar	Light detection and ranging, a radar-like technology that measures atmospheric variables with distance resolution.
LifeWatch	Research Infrastructure: E-Science and Technology Infrastructure for Biodiversity Data and Observatories
LTER	LTER stands for Long-Term Ecosystem Research: research concerned with whole ecosystems and the development of processes and structures over the course of decades.
LTER-D	Long-Term Ecosystem Research Germany. The German network for long-term ecological and ecosystem research is a platform for communication, documentation and collaboration between researchers in long-term, system-oriented and interdisciplinary environmental observation in Germany. LTER-D is a member of the international network ILTER and the regional network LTER-Europe. ILTER and LTER-Europe are open networks which define themselves solely through a commitment to shared goals. LTER-Europe focusses on a joint research strategy and the definition of criteria and standards for national networks in Europe.
NEON	National Ecological Observatory Network der U.S. National Science Foundation
NGS	Next Generation Sequencing
NOHA	Network of Hydrological Observatories, an EU project that measures the hydrological balance in many regions of Europe.
OGC	The Open Geospatial Consortium is a not-for-profit organisation set up in 1994 to define the development of spatial information processing (particularly geodata) on the basis of universal standards that support interoperability. The OGC is a consortium of government agencies, companies and universities.
PortalU	German Environmental Information Portal Web service offered by Germany’s national and state environmental agencies. http://www.portalu.de/
PZÖ	Ecosystem Research Project Centre in Kiel
Radiometer	Detector that measures the brightness temperature of surfaces.
Reanalyse	Reconstruction of the conditions in the atmosphere and on the earth’s surface through a combination of historical observations and a forecast model. The European reanalysis ERA-40, which describes the climate for the period 1957–2001, is particularly well known.
TDR-Sonden	Probes that measure soil water content.
TanDEM-X	The TanDEM-X mission (TerraSAR-X add-on for Digital Elevation Measurement) is based on two almost identical earth observation satellites, TerraSAR-X and TanDEM-X. Both are equipped with a powerful modern radar system known as Synthetic Aperture Radar (SAR), which can survey the earth not only in daylight but also at night and with cloud coverage.
TEODOOR	Online Data Portal of the TERENO Observatories
TERENO	TERrestrial ENviromental Observatories. Initiative of the Helmholtz Association with the aim of creating an observation platform that links terrestrial observatories in different regions. Three observatories were set up in 2008.

TERENO-MED	The TERENO-MED network of observatories for the Mediterranean region was established in 2012 on the basis of concepts and insights of the TERENO project in Germany, the focus of its activities being on the study of the hydrological cycle.
UN	United Nations
WasserBLIcK	A German information portal about the EU Water Framework Directive
WCAS	Web Catalogue Service (WCAS), also known as Catalogue Service for the Web (CSW). Web-based publication of information relating to geoapplications, geoservices and geodata (metadata) in a geodata infrastructure. The service does not contain geodata, only descriptive metadata. This geoservice was specified by the Open Geospatial Consortium (OGC).

Table 1: Examples of National and International Platforms for the Long-Term Observation of Terrestrial Systems

Platform	Compartment	Land Use	Scale	Status	Exp.	Obs.	Hyp.	RS	Timescale*	Organisation
National Platforms –Germany										
ICOS-D	PE/BIO/AT	FO/FI/G	P/F	P	-	+	+	-	2008–2031	BMBF
Long-Term Soil Observation (BDF)	PE/BIO/HY	FO/FI/G	P/F	IP	-	+	-	-	Start 1982	Federal states
Forest Soil Condition Survey (BZE)	PE/BIO/HY	W	P/F	IP	+	+	-	-	Start 1987	Federal states
Agriculture Soil Condition Survey (BZE-LW)	PE/BIO/HY	FI/G	P/F	IP	+	+	-	-	Start 2011	Thünen Institute
Long-Term Agricultural	PE/BIO	FI/G	P/F	IP	+	+	+/-	-	Various	Federal states
ICP-Forest Level	PE/BIO/AT	W	P/F	IP	-	+	-	-		Federal states
TERENO	PE/BIO/AT/HY/GE	FO/FI/G	P/F/CB/R	IP	+	+	+	+	Start 2008	HGF
GCEF	PE/BIO	FI/G	P/F	P	+	-	+	-	Start 2012	HGF
COSYNA	BIO/AT/HY	Sea	R	IP	-	+	-	+	Start 2009	HGF
DFG Biodiv. Exploratoriums	PE/BIO	FO/FI/G	P/F	IP	+	+	+	-	Start 2006	DFG
Agrometeorological Network	PE/BIO	FO/FI/G	P/F	IP	-	+	-	-	Various	DWD
LTER-D	PE/BIO	FO/FI/G	P/F	IP	-	+	+	+	Start 2004	LTER
WasserBLIcK, WISE	HY	FO/FI/G	P/F/CB/R	IP	-	+	-	-	Start 2004	Federal government
National platforms – other countries										
MISTRALS	PE/BIO/AT/HY	FO/FI/G	P/F/R	IP	+	+	+	+	2007–2020	CNRS, France
NATIONAL CRITICAL ZONE OBSERVATORY PROGRAME	PE/BIO/AT/HY	FO/FI/G	P/F/CB/R	IP	+	+	+	-	Start 2007	USA
NEON	PE/BIO/AT/HY	FO/FI/G	P/F/CB/R/G	IP	-	+	-/+	+	2012: start of construction phase	USA
International Platforms										
ANAEE	PE/BIO	FO/FI/G	P/F/R	P	+	+	+	+	2010: start of preparation phase	ESFRI
ICOS	PE/BIO/AT/HY	FO/FI/G	P/F/R/G	IP	-	+	+	-	Start 2014	ESFRI
IAGOS	AT/BIO	-	R	IP	-	+	+	-	Start 2012	ESFRI
NOHA	PE/BIO/AT/HY	FO/FI/G	P/F/CB/R	P	+	+	+	+	In planning	ESFRI
SOILTREC	PE/HY	FO/FI/G	P	IP	+	+	+	-	2009	EU
LTER-Europe	PE/BIO/HY	FO/FI/G	P/F/CB/R	IP	-	+	-	-	2003	LTER
TERENO-MED	PE/BIO/AT/HY	FO/FI/G	P/F/CB	P	+	+	+	+	Start 2012	HGF

Key

Compartment:	AT = atmosphere, BIO = biosphere, HY = hydrosphere, PE = pedosphere, GE = geosphere
Land Use:	FI= field, FO = forest, G = grassland
Scale:	P = plot (10^2 m²), F = field (10^4 m²), CB = catchment basin (10^9 m²), R = region (10^{10} m²), G = global/continental
Status:	P = planned, IP = in progress
Methodology:	Exp. = experimental, Obs. = observations, Hyp. = hypothesis-based, RS = remote sensing

**According to available information*

Platforms

ANAEE	Analysis and Experimentation on Ecosystems
CNRS	Centre national de la recherche scientifique, France
COSYNA	Coastal Biodiversity Exploratories
DFG-Expl.	DFG Biodiversity Exploratories
GCEF	Global Change Exploratory Facility
IAGOS	In Service Aircraft for a Global Observing System
ICP Forests	International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests
ICOS	Integrated Carbon Observation System
LTER-D	Long-Term Ecosystem Research-Deutschland
LTER-Europe	Long-Term Ecosystem Research Europe
MISTRALS	Mediterranean Integrated Studies at Regional and Local Scales
NEON	National Ecological Observatory Network
NOHA	Network of Hydrological Observatories for Water Resources Research in Europe
SOILTREC	Soil Transformations in European Catchments
TERENO	TERrestrial ENvironmental Observatories
TERENO-MED	TERrestrial ENvironmental Observatories-Mediterranean

Deutsche Forschungsgemeinschaft
German Research Foundation
Kennedyallee 40 · 53175 Bonn, Germany
Postal address: 53170 Bonn, Germany
Phone: +49 228 885-1
Fax: +49 228 885-2777
postmaster@dfg.de
www.dfg.de