Special Section:
Critical Zone Observatories

A Network of Terrestrial Environmental Observatories in Germany

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Multicompartment and multiscale long-term observation and research are important prerequisites to tackling the scientific challenges resulting from climate and global change. Long-term monitoring programs are cost intensive and require high analytical standards, however, and the gain of knowledge often requires longer observation times. Nevertheless, several environmental research networks have been established in recent years, focusing on the impact of climate and land use change on terrestrial ecosystems. From 2008 onward, a network of Terrestrial Environmental Observatories (TERENO) has been established in Germany as an interdisciplinary research program that aims to observe and explore the long-term ecological, social, and economic impacts of global change at the regional level. State-of-the-art methods from the field of environmental monitoring, geophysics, and remote sensing will be used to record and analyze states and fluxes for different environmental compartments from groundwater through the vadose zone, surface water, and biosphere, up to the lower atmosphere.

Abbreviations: EDK, external drift kriging; TERENO, Terrestrial Environmental Observatories.

From 2008 onward, Terrestrial Environmental Observatories (TERENO), a network of observatories for integrated environmental research focusing on the impact of climate change and land use change on the terrestrial ecosystems, has been established in Germany. The TERENO research concept in general and conceptual approaches for different environmental compartments and terrestrial fluxes in particular are described and explained.

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Climate change and land use change are key factors in global environmental change that have to be managed by society in the coming decades. The changes take place on different spatial and temporal scales and the challenges for environmental research are immense. Many important ecosystem functions are expected to change, jeopardizing the life-sustaining resources and the future developmental options of mankind. Steady long-term trends in temperature, precipitation, and other climatic gradients affect most environmental niches, exhibiting very complex feedback mechanisms. Terrestrial environmental research has to tackle this challenge, using new research approaches based on integrated and long-term environmental data (National Research Council, 2008; Reid et al., 2009; Richter and Mobley, 2009; International Council for Science, 2010).

One of the key problems in recent environmental monitoring is the gap in temporal and spatial scales between measurement and management. The present understanding of water, energy, or matter fluxes, as well as their biological and physical drivers and the interactions with and within the terrestrial system, are often based on investigations performed at scales not capable of explaining the system behavior. On the one hand, local system parameters strongly affect the overall system, and on the other hand, effective parameters at a large scale determine the processes and functioning of highly complex natural systems at a very local scale. A comprehensive consideration of multicompartment interactions and scale dependencies remains a major scientific challenge in current terrestrial environmental research to predict the behavior of the terrestrial system in response to changing environmental conditions. As a consequence, the development and implementation of large-scale, long-term, and integrated research infrastructure for environmental monitoring and research has been the subject of intense discussion during the past few years across all scientific disciplines (Quetin and Ross, 1992; National Research Council, 2000, 2003, 2006; Zoback, 2001; Lin, 2003, 2010; Parr et al., 2003; Reckhow et al., 2004; McDonnell et al., 2007; Montgomery et al., 2007; Nisbet, 2007; Willis et al., 2007; Burt et al., 2008; Keller et al., 2008).

Coupled with a growing awareness that holistic, synergistic approaches incorporating regional heterogeneities that fulfill the need for redundancy are urgently required, several initiatives toward environmental observatory networks have been initiated around the globe.

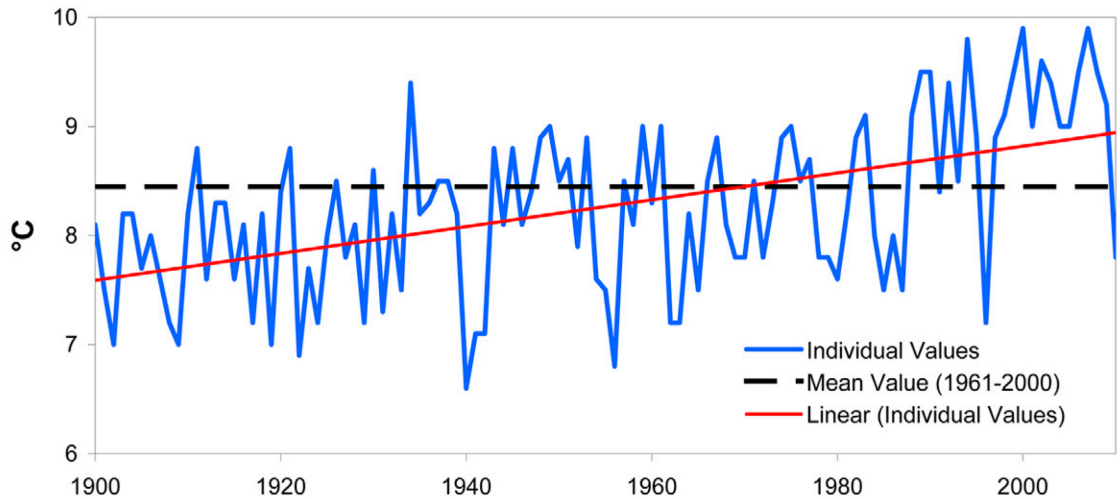

Fig. 1. Annual average mean daily temperature in Germany, 1900 to 2010 (data source: German Weather Service).

Accordingly, an integrated approach toward a better understanding of natural systems has to be able to capture (Lin, 2010)

- the external and internal forcing as well as their interconnection,
- the coupling of the different environmental cycles,
- the most relevant interfaces of the system, and
- all relevant spatial and temporal scales adapted to the scale of system management.

An integrated framework combining monitoring, modeling, and regionalization is necessary to address the complex interactions and geographic aspects of natural systems (Parr et al., 2003; Paola et al., 2006; Ohl et al., 2007; Lin, 2010). The design of appropriate monitoring and research concepts and networks is challenging and expensive and requires input from different scientific disciplines, both fundamental and applied. It is obvious that to implement a network of environmental observatories on a continental or even on the global scale, a community effort bringing together different teams, organizations, and also funding is needed (Parr et al., 2002; Keeling, 2008; Lin, 2010).

To address these challenges, the German Helmholtz Association started the infrastructure activity Terrestrial Environmental Observatories (TERENO) in 2008 (Bogena et al., 2006). The TERENO observatories started to investigate the consequences of climate and land use change in Germany and will provide long-term observation data related to the so-called "critical zone," including multiple spatial and temporal scales of the hydrosphere, biosphere, pedosphere, lower atmosphere, and anthroposphere. We describe here the methodological aspects and the interdisciplinary framework of observatory implementation and present the TERENO network as a community platform for research in terrestrial science in general and critical-zone processes in particular. Important elements of the TERENO monitoring concept, with specific focus on processes within the hydrosphere, lower atmosphere, pedosphere, and biosphere, are presented, and potential applications of the TERENO data are highlighted.

The TERENO Observatories

It is a given fact that climate change is affecting Germany. The mean annual temperature has risen about 1°C during the past 100 yr (Fig. 1). At the same time, the precipitation slightly increased, which is mainly due to an increase in winter precipitation. These changes in precipitation are characterized by strong seasonal and also regional variations. While the increase in winter precipitation is particularly pronounced in western Germany, in eastern Germany a decline in summer precipitation is already notable (German Federal Environmental Agency, 2008). Recent climate projections for Germany predict a further intensification of these trends (Fig. 2).

The general aim of TERENO is the long-term integrated observation of climate change and global change impacts on the terrestrial system for Germany, for which a terrestrial system in the context of TERENO is defined as a system consisting of the subsurface environment, the land surface including the biosphere (organized in ecosystems), the lower atmosphere, and the anthroposphere. These systems are organized along a hierarchy of evolving spatial scales of structures ranging from the local scale to the regional scale. Furthermore, temporal scales ranging from directly observable periods (up to several years) to long time scales (centennial to multimillennial) derived from geoarchives are considered. With regard to the latter, TERENO focuses on precisely dated and annually to subseasonally resolved synchronized long-term data from lake sediments and tree rings. From monitoring and process studies on climate and environmental signal transfer into these archives,

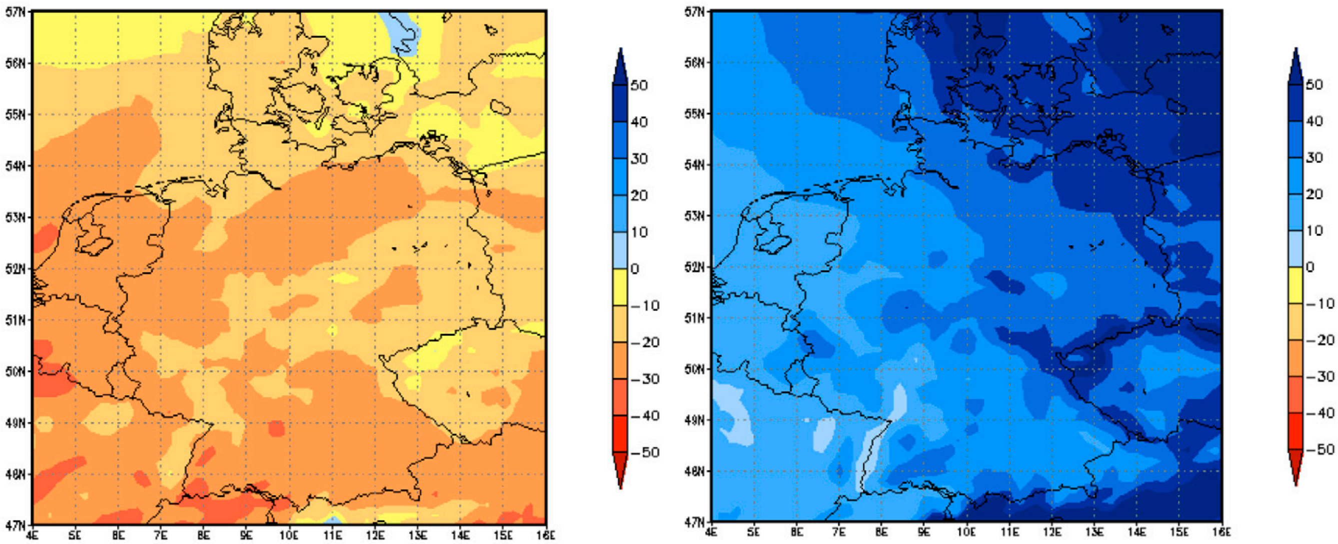

Fig. 2. Predicted mean relative change (%) in seasonal precipitation in Germany for summer (left) and winter (right) for the period 2071 to 2100 compared with 1961 to 1990 (ensemble mean from 12 regional climate simulations; www.regionaler-klimaatlas.de, verified 2 July 2011, Meinke et al., 2010).

novel transfer functions will be developed. Data sets from these archives can then be generated for a direct calibration and verification against present-day instrumental data. The result will be a database of greatest precision on the natural background variability of climate and landscape evolution for multimillennial time scales.

The TERENO observatories aim at combining observation with dedicated larger scale experiments and integrated modeling to increase our understanding of the functioning of terrestrial systems and the complex interactions and feedback mechanisms among their different compartments. A geographically distributed framework combining monitoring with regionalization is mandatory for covering this range of spatial and temporal scales. To capture the given climatic gradients, terrestrial and atmospheric feedback, socioeconomic disparities, and demographic gradients, the spatial scale of a terrestrial observatory covers the landscape scale (>10^4 km^2). By combining observatories within Germany, larger scale atmospheric feedbacks and impacts can be investigated, and thus a more pronounced general link to the atmospheric research community can be established.

Within TERENO, four terrestrial observatories were selected as being representative for Germany and other central European regions with the highest vulnerability with respect to climate change effects (Fig. 3). Furthermore, these regions can be expected to represent dominant terrestrial processes and the different roles of groundwater, surface water, soils, and their links to the atmospheric boundary layer. All of the selected regions are either already affected by climate change or will probably react sensitively in the foreseeable future. The establishment of three of the observatories started in 2007 and will be finished in 2011. The implementation of the Northeastern German Lowland observatory commenced in 2011.

The observed regions have different vulnerabilities (German Federal Environmental Agency, 2005):

- Eastern Germany (northeastern German lowland, central German lowland): low water availability, strong coupling between a shallow groundwater table and water availability in the root zone, risk of summer droughts, further decrease in summer precipitation expected, flooding in the river basins of the Elbe and Oder rivers;
- Rhine Valley: critically high temperatures (upper Rhine valley) and expected strongest increase in temperatures, higher risk of flooding due to an expected increase in extreme precipitation events and precipitation shift from summer to winter;
- Prealpine Region: high sensitivity of the ecosystem, higher risk of flooding in the Alps, risks for winter tourism due to temperature increase.

In general, the TERENO observatories

- provide real-time measurement platforms that will allow observation of terrestrial systems directly influenced by human activities,
- carry out and monitor controlled scientific experiments across a nested hierarchy of scales ranging from the local scale (small test sites) to large catchments, and
- provide long-term environmental data in a multiscale and multitemporal mode to study the long-term influence of land use change, climate change, socioeconomic development, and human interventions in terrestrial systems.

The multiscale approach is based on scale and regionalization concepts developed and extensively used in hydrology (e.g., catchment and representative elementary area) and terrestrial sciences, such as soil science, geology, hydrogeology (regionalized variables, representative elementary volume, local scale, and field scale). The multitemporal approach refers to a hierarchy of time scales ranging from event based, continuous, and periodic measurements requiring

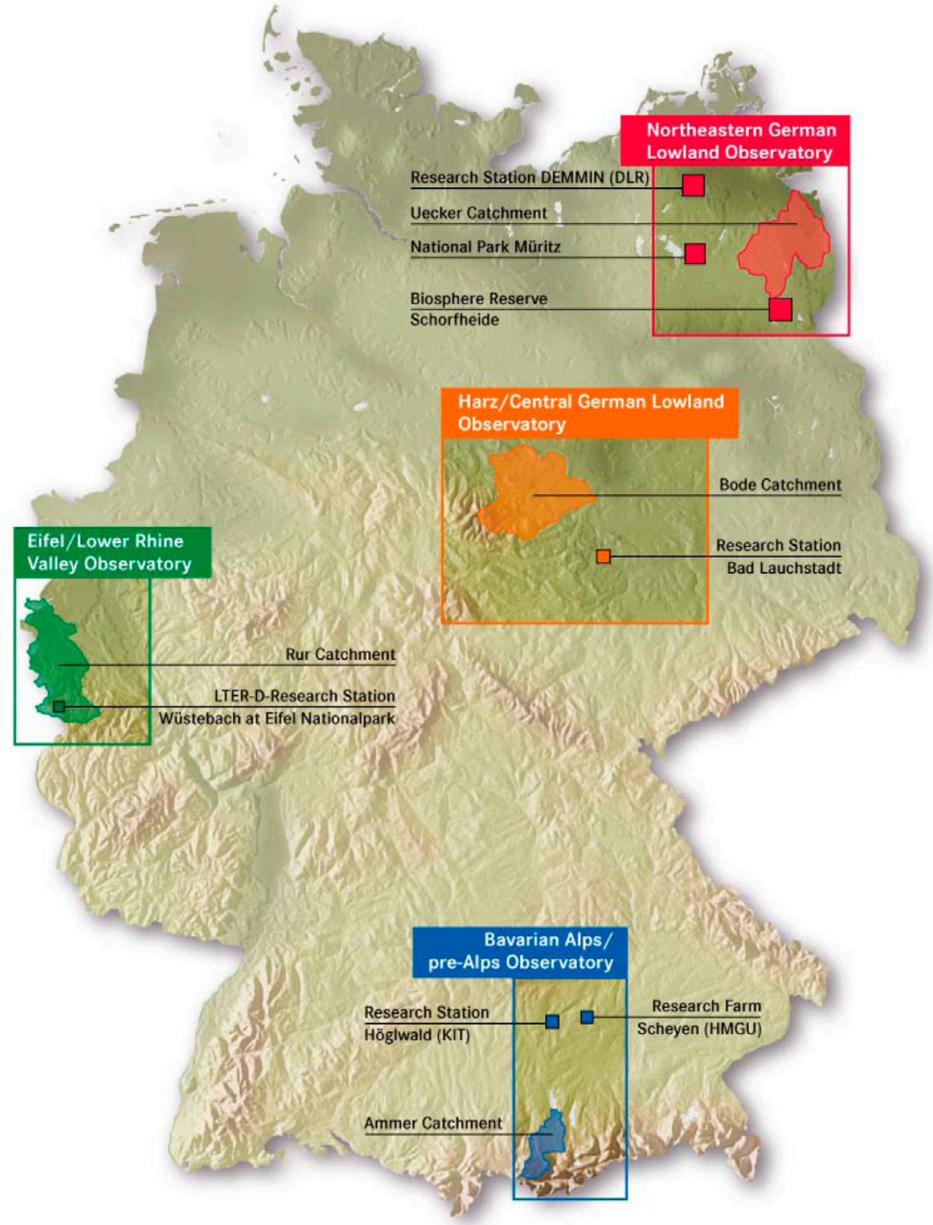

Fig. 3. Map of Germany, indicating the locations of the four selected TERENO observatories, including the experimental catchments and research stations.

precisely dated geoarchives (annually layered lake sediments and tree rings) and technological platforms such as ground-based geophysical, meteorologic, and remote sensing techniques, low-cost and dedicated flying platforms (small and large airplanes, zeppelins, or helicopters), up to satellite-based remote sensing. A detailed description of the implementation framework, the implementation plan and a description of the single observatories can be found at the project website (teodoor.icg.kfa-juelich.de/overview-de; verified 2 July 2011; in German and English). The implementation plan also contains detailed descriptions of data management and communication strategy as well as a description of the integration of modeling activities and data assimilation approaches used in TERENO.

In this sense, TERENO is a initiative complementary to the existing measurement networks in Germany and all over the world, such as the Critical Zone Observatory Program, FLUXNET, Long-Term Ecological Research (LTER) Network, or the Integrated Carbon Observation System (ICOS), and can be perfectly linked to the existing initiatives to

- study the impact of land use changes, climate change, socioeconomic development, and human intervention in the evolution of terrestrial systems and to analyze the interactions and feedback between the soil–vegetation and atmosphere compartments in these systems across scales;
- develop methods for upscaling of parameters, fluxes and state variables (PFS) that describe processes controlling matter and energy fluxes across the soil–plant–atmosphere systems

at the selected scales based on theoretical and modeling concepts, especially the spatial variation of PFS at different scales, which has up to now not been taken into account in most of the operational networks;

- provide high-quality data to validate existing and newly developed model concepts (e.g., inverse modeling and stochastic data fusion approaches) and upscaling theories to estimate effective parameters, fluxes, and state variables at various scales;
- bridge the gap between scales, measurement, and modeling currently present in hydrologic and terrestrial sciences and to develop and improve decision support systems for environmental management in the view of sustainable development;
- determine the balances and spatial and temporal patterns in energy and matter fluxes of the soil–vegetation–atmosphere system;
- improve continuously integrated models that predict the evolution of anthropogenic terrestrial systems;
- promote and support the development and use of early warning systems (flooding, freshwater quality, etc.); and
- integrate different disciplines to advance the analysis of the interactions between natural patterns and processes of landscapes with anthropogenic patterns and processes at different scales.

As mentioned above, the Northeast German Lowland Observatory has been integrated into the TERENO network to complete the representation of landscape and climatic conditions across Germany. The TERENO implementation plan for a spatiotemporal exploration of the critical-zone state variables has been adopted for this latest observatory and the necessary infrastructure will be completed by 2013. The research concept driving its setup includes remote sensing, hydrology, geopedology, meteorology, and geoarchive analyses using tree rings and lake sediments as high-precision natural dataloggers (Fig. 4). The scientific concept pursued at the Northeast German Lowland Observatory provides an important enhancement to the overall TERENO concept in terms of temporal scaling. The integrated information and process understanding gathered in very high to low frequency domains will help to assess environmental change and verify models based on geoarchive data that are directly calibrated with on-site instrumental data (Czymzik et al., 2010). The incorporation of the Durable Environmental Multidisciplinary Monitoring Information Network (DEMMIN), which is one of the test areas within the new Northeast German Lowland Observatory, is bringing considerable added value to TERENO by addressing specific spatial scaling issues. The DEMMIN belongs to the Neustrelitz site of the Deutsches Zentrum für Luft- und Raumfahrt, and covers an intense agricultural area of approximately 30,000 ha cultivated by a consortium of local farmers (the IG DEMMIN) with whom it has been contracted for the use of certain parts of their properties. The DEMMIN network of meteorological stations, as well as its soil moisture and soil temperature sites, offers ideal conditions for linking remote sensing data with ground-truth information, which is necessary to estimate the effective values of state variables at large spatial scales as measured by space-borne sensors.

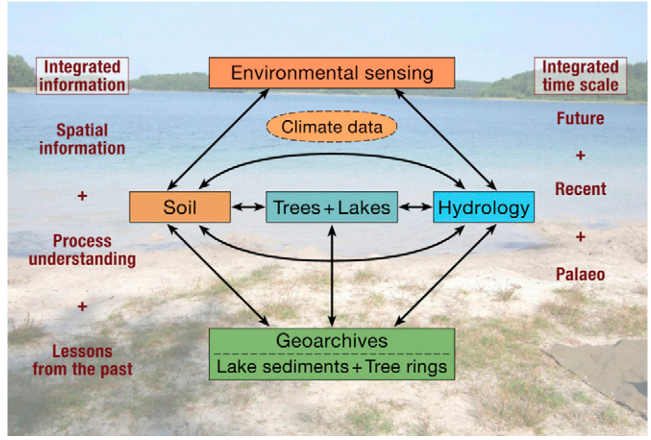

Fig. 4. Using geoarchives to integrate time scales and information.

The Hydrologic Observatory Concept

In the framework of TERENO, hydrologic observatories have been implemented within each of the TERENO observatories to observe hydrologic phenomena at several scales, from small, highly instrumented headwater catchments to mesoscale catchments covering several 1000 km^2. Hydrology is a science founded on observation. Only at the very smallest scale (e.g., at the headwater catchment scale), however, are hydrologists able to conduct experiments in which the effects of controlled manipulation are monitored to provide empirical data describing hydrologic process and responses. At larger scales, hydrologic data usually integrate a wide range of drivers (e.g., climatic, economic, and social) and a diversity of characteristics (e.g., vegetation, geology, soils, and topography). These drivers and characteristics may vary not only in space but also with time. It is by observing changes with time, and comparing observations from different sites, that hydrologists develop an understanding of hydrologic processes and responses. In addition to the impacts of climate change, social and industrial development continues to accelerate, requiring increased water resources for domestic, industrial, and agricultural activities. Land use dynamics not only have an effect on water quantity but can also lead to changes in water quality, erosion, and the timing and size of floods.

Conceptual Approach to Designing a Network for Precipitation Monitoring

An adequate rainfall measuring network is crucial for system understanding and water resources management. Key design factors such as density, sampling frequency, and topology (i.e., geographic location of the gauges), however, depend on the resolution requirements (i.e., spatiotemporal coverage), which, in turn, are closely related to the ultimate purpose of the network, for example: (i) national water resource assessment, (ii) operations and flood control, (iii) real-time warning systems, or (iv) research (Rodríguez-Iturbe and Mejia, 1974; Kassim and Kottegoda, 1991). The TERENO observatories are focused on the former because their main goal is to study the

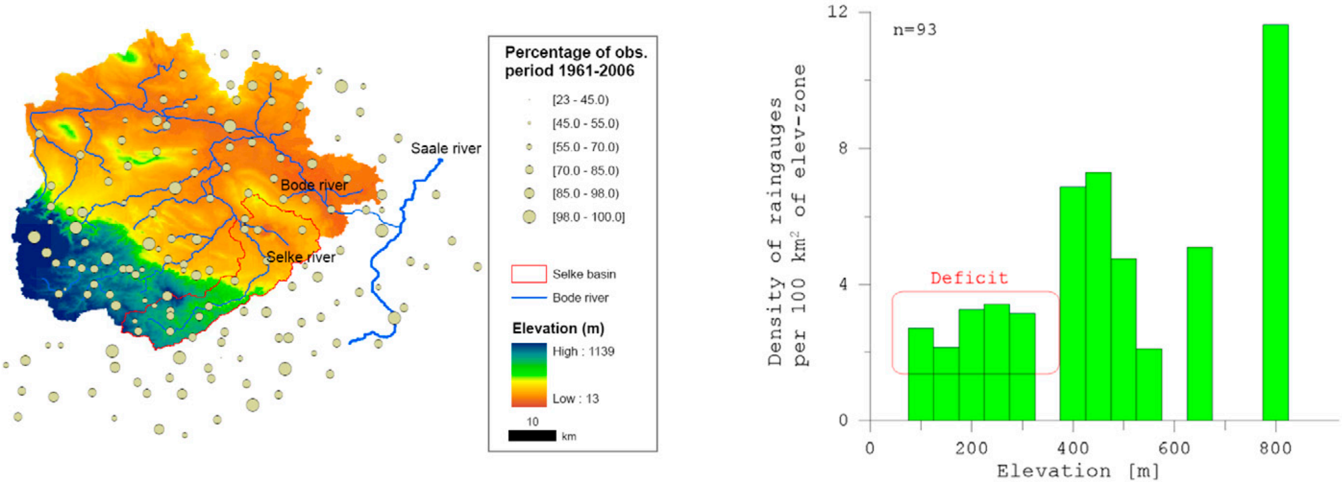

Fig. 5. Degree of completeness of precipitation time series for the Bode River basin and surroundings from 1961 to 2006 (left), and histogram of the density of rain gauges per 100 km^2 of elevation zone within the Bode basin (right).

long-term influence of anthropogenic activities on terrestrial systems and, in particular, to attempt to close as accurately as possible the water balance across a mesoscale catchment. These ambitious goals require a robust precipitation network that should cope simultaneously with a number of conflicting objectives. The conceptual design proposed in this study aims to determine the optimal precipitation network for the Bode River catchment and the Selke River subcatchment (Harz/Central German Lowland Observatory).

Experiences with rain-radar technology have shown that while the weather radar provides superior information about the spatial and temporal resolution of a rainfall event, estimates of rainfall accumulation may have phenomenal biases. The best results for streamflow prediction and forecast have been achieved with a combination of radar and rain gauges (James et al., 1993). For these reasons, the precipitation monitoring network in TERENO will be a combination of various instruments, some already existing and some to be placed within the observatories. For the Bode catchment, in the first category there are about 245 existing rain gauges operated by the German Meteorologic Service (DWD) having somewhat continuous daily readings since 1961 (Fig. 5), 25 hourly rain gauges (DWD), and one weather radar operated by the DWD. In the second category are included a rain scanner and a fixed number of high sampling (15-min resolution) rain gauges (including weather observations).

The existing precipitation network (DWD) within the Bode River basin and surroundings (~25-km buffer) covers approximately 39 and 27 km^2 per station within the Bode and Selke basins, respectively. These coverages, although fully satisfy the World Meteorological Organization requirements (at most 100 km^2 per station), are not sufficient for solving fundamental scientific challenges in surface water and groundwater hydrology or studying the spatiotemporal variability of rain due to the following reasons:

1. The spatial distribution of precipitation stations in elevation bands is particularly heterogeneous; consequently, the orographic effects cannot be assessed satisfactorily. In the elevation band between 300 and 400 m above sea level, there is a remarkable shortage of stations (Fig. 5, right). Moreover, the degree of completeness (percentage of days with valid information) of the observation time series during the period 1961 to 2006 indicated that the information content of the existing records is particularly weak in the Selke River basin (Fig. 5, left).
2. The spatio-temporal variability of precipitation in the Bode basin and its vicinity shows a marked directional anisotropy (e.g., the variogram in the north–south direction differs from that in the east–west direction) and a distinct yearly dynamics mainly due to its morphological settings (Fig. 6), as can be seen by the third and fourth eigenvectors of the correlation matrix of daily precipitation.
3. The actual rain gauge density and its sampling frequency do not allow identification of convective precipitation events that occur mainly during the summer or adjusting the reflectivity–rainfall rate relationships required to calibrate the rain scanner.

As a consequence of this deficit analysis, it was evident that new instruments need to be located within the Bode basin to achieve the highly demanding TERENO goals. In this particular case, the overall utility should include measurement accuracy and, to a minor extent, maintenance costs (e.g., personnel). The accuracy of rainfall measurement is mainly affected by wind, the height of the gauge, and the exposure. It should be noted that an "optimum" design is not attainable for many reasons: (i) the uncertainty of existing observations, (ii) the stochasticity of the rain, and (iii) logistics (planning regulations, lack of access roads, and private property rights, among others). Instead, a set of "good" and hence robust alternatives should be pursued. The term *robust* is to be understood in the sense that although the selected locations do not constitute an "optimum" from a numerical point of view, they still offer the best compromise under current conditions. Consequently, to carry out this concept, the following objectives were selected: (i) minimize the total estimation variance of the rain fields, (ii) minimize the observation effort (i.e., the number of additional rain gauges), (iii) maximize the predictive efficiency of the distributed mesoscale hydrologic model (Samaniego

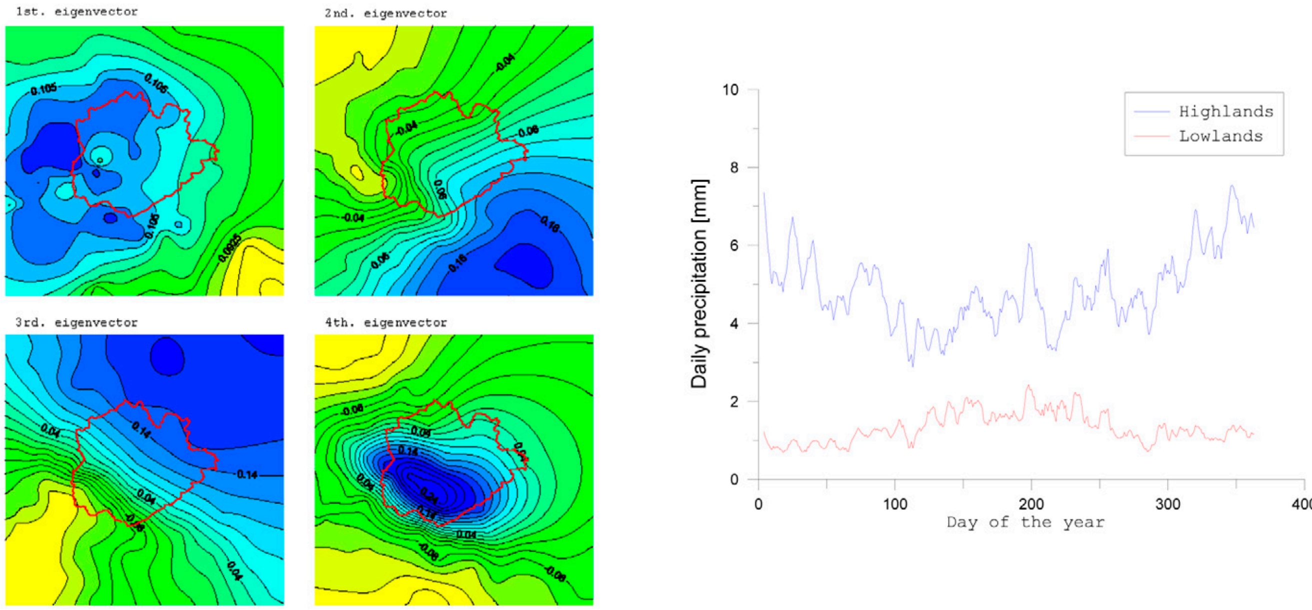

Fig. 6. Eigenvectors of the daily precipitation correlation matrix, indicating the main precipitation mechanisms that explain approximately 83% of the total variance (left), and annual cycle of daily average precipitation for two stations in the Bode River basin, one located in the Harz Mountains (mostly orographic) and the other on the lowlands near the Saale River (mostly convective) (right).

et al., 2010), and finally, (iv) maximize the observed spatio-temporal variability with a given number of additional rain gauges.

To find suitable locations for the rain scanner, the following utility functions were used:

1. The rain scanner should cover as much as possible of the Bode basin but should be as far as possible from the Harz Mountains to avoid reflections of the signal emitted by its antenna. Additionally, it should be located below 350 m above sea level, i.e., it should be in the lowlands.
2. The rain scanner should have a common coverage area with the DWD weather radar to minimize prediction errors (it is expected that DWD data would become available in the future). In any case, however, it should be 50 km farther from this existing weather radar at Ummendorf (Fig. 7).
3. The rain scanner should not be located in those areas exhibiting large sensitivity to the hydrologic model (Fig. 8).
4. The rain scanner should be located in areas with high precipitation predictability, which can be estimated with the existing rain gauge network.

These utility functions were aggregated and weighted following the principles of compromised programming (Duckstein and Opricovic, 1980). Equal weights were selected.

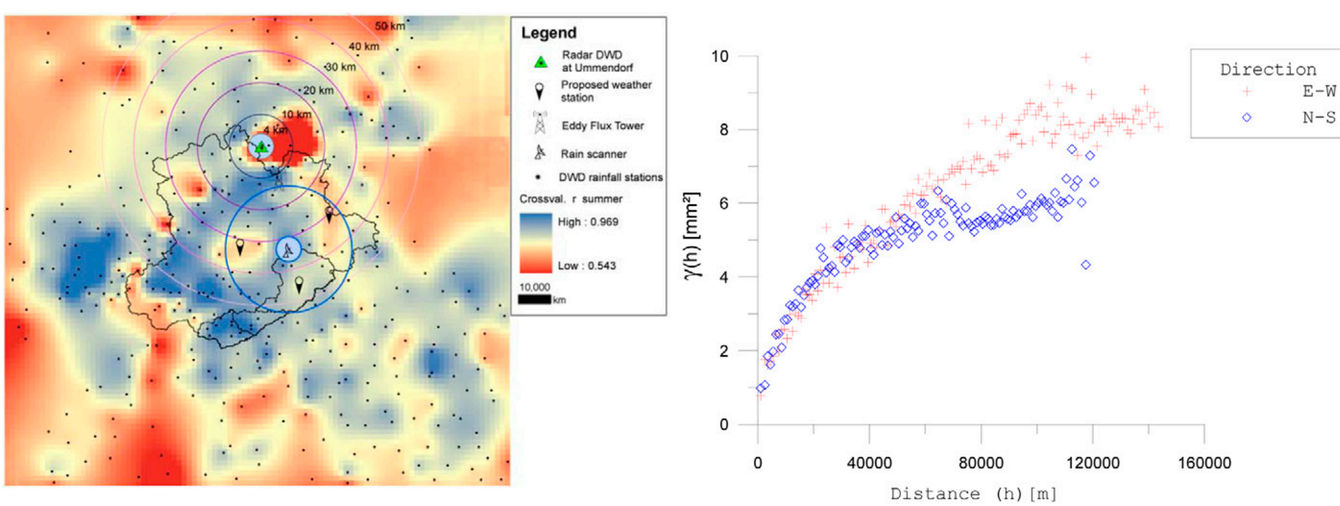

Fig. 7. Jackknifed *r* at every rain gauge interpolated across the domain based on daily records from 1961 to 2006 in summer, predicted at each station with external drift kriging and a spherical variogram, and possible locations of the rain scanner and additional rain gauges also shown (right), and empirical variograms of daily precipitation network for the period 1961 to 2006 along the directions north–south and east–west (right) (DWD = German Meteorologic Service).

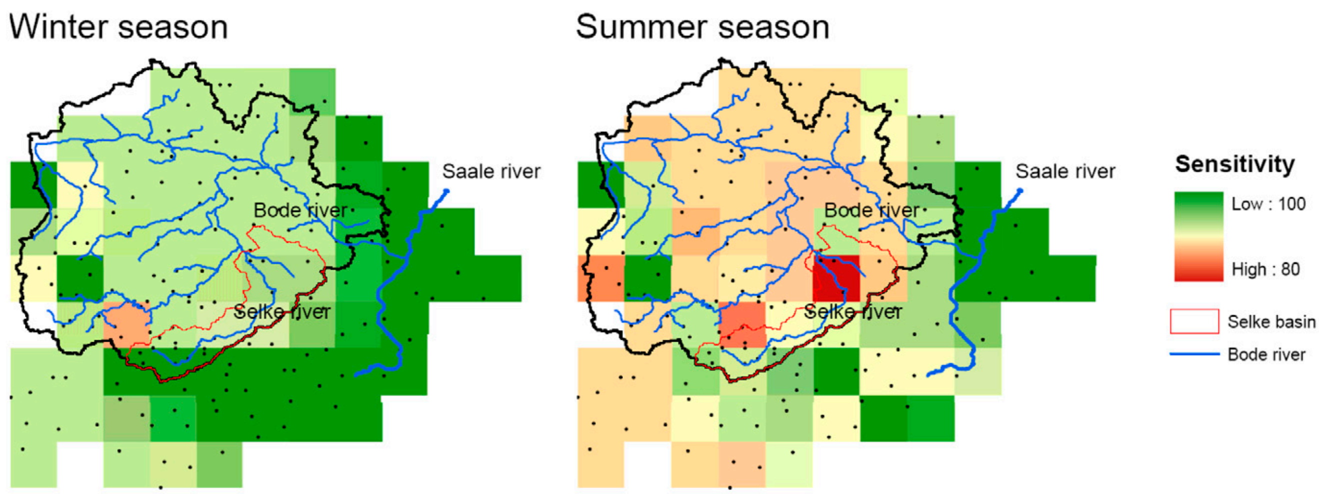

Fig. 8. Cross-validation study to determine the input–output sensitivity at various locations in the Selke River basin in winter and summer.

External drift kriging (EDK) coupled with the mesoscale hydrologic model were used to determine a sensitivity index that estimates the effect of the location of the rain gauges on the model efficiency. The sensitivity index depicted for summer and winter was determined as the ratio between the cross-validated mesoscale hydrologic model efficiency (Nash–Sutcliffe model efficiency, NSE) in the Selke basin with respect to the overall NSE based on daily precipitation records from 1961 to 2006 for winter and summer. In this case, the smaller the index, the larger will be its influence on the model efficiency. The precipitation predictability index was estimated as the jackknifed Pearson correlation coefficient (r) estimated for each existing rainfall station during the period 1961 to 2006. The jackknifed estimation at every station was done with EDK and a composed variogram (nugget and spherical). The searching distance was in all cases at most 70 km (Fig. 7). As a result of this analysis, potential locations for the rain scanner were found (Fig. 9).

It is expected that a coverage of 15 to 20 km^2 per station should be achieved in the Bode basin to be able to resolve convective precipitation cells, which usually have an areal extension between 20 and 50 km^2 (Barry and Chorley, 2003). This estimate determines the upper limit of the number of additional rain gauges in this basin (i.e., about 15 new rain gauges). The exact number and their potential best locations will be found once the rain scanner starts operation. It should be noted that an ad hoc selection of potential locations would lead, with high probability, to a suboptimal solution (Bogárdi et al., 1985). This allocation problem can be formulated as a combinatorial multiobjective optimization problem (Rodríguez-Iturbe and Mejía, 1974; Bogárdi et al., 1985; Kassim and Kottegoda, 1991; Bradley et al., 2002). Robust solutions can be found by simulated annealing using the objective functions mentioned above.

Closing the Catchment-Scale Water Balance

Attempting to close the water balance by measurements at the catchment scale is a challenging task but if successful will yield a valuable data set for the development and evaluation of hydrologic models. Furthermore, in conjunction with modeling, the water balance data will help in determination of the magnitude of measurement errors, determination of how to diagnose these errors, and avoidance of the misattribution of water balance components (Kampf and Burges, 2010).

The monitoring concept of the TERENO Wüstebach research station is presented as an example of a hydrologic observation concept at the subcatchment scale in TERENO. The Wüstebach research station is part of the Eifel/Lower Rhine Valley Observatory. It is a subcatchment (0.27 km^2) of the River Rur basin and is situated in the German low mountain ranges within the National Park Eifel (Fig. 10 and 11).

The mean altitude is 612 m above sea level, with a mean annual precipitation of ~1100 mm (1961–1990) and a mean annual temperature of ~7°C. The main vegetation type is Norway spruce [*Picea abies* (L.) H. Karst.]. The bedrock consists of Devonian shales with sporadic sandstone inclusions and is superimposed by a 3- to 1-m-thick periglacial solifluction layer in which mainly Cambisols and Planosols have developed (Bogena et al., 2010).

Figure 11 presents the hydrologic instrumentation of the Wüstebach research station. In addition, the mean topsoil moisture distribution for the period 1 Aug. to 30 Nov. 2009 is presented in Fig. 11 (data from Bogena et al., 2010).

For monitoring soil state variables (soil moisture and temperature), the wireless sensor network SoilNet was developed in the framework of TERENO (www2.fz-juelich.de/icg/icg-4/index.php?index=739; verified 2 July 2011). A detailed description concerning the SoilNet technology was provided by Bogena et al. (2010). The sensor network in the Wüstebach test site consists of 150 sensor nodes (a combination of multiple sensor nodes in a nearly 60- by 60-m raster and randomly distributed nodes in between). At each measurement location, soil moisture and temperature are measured at three depths (5, 20, As an

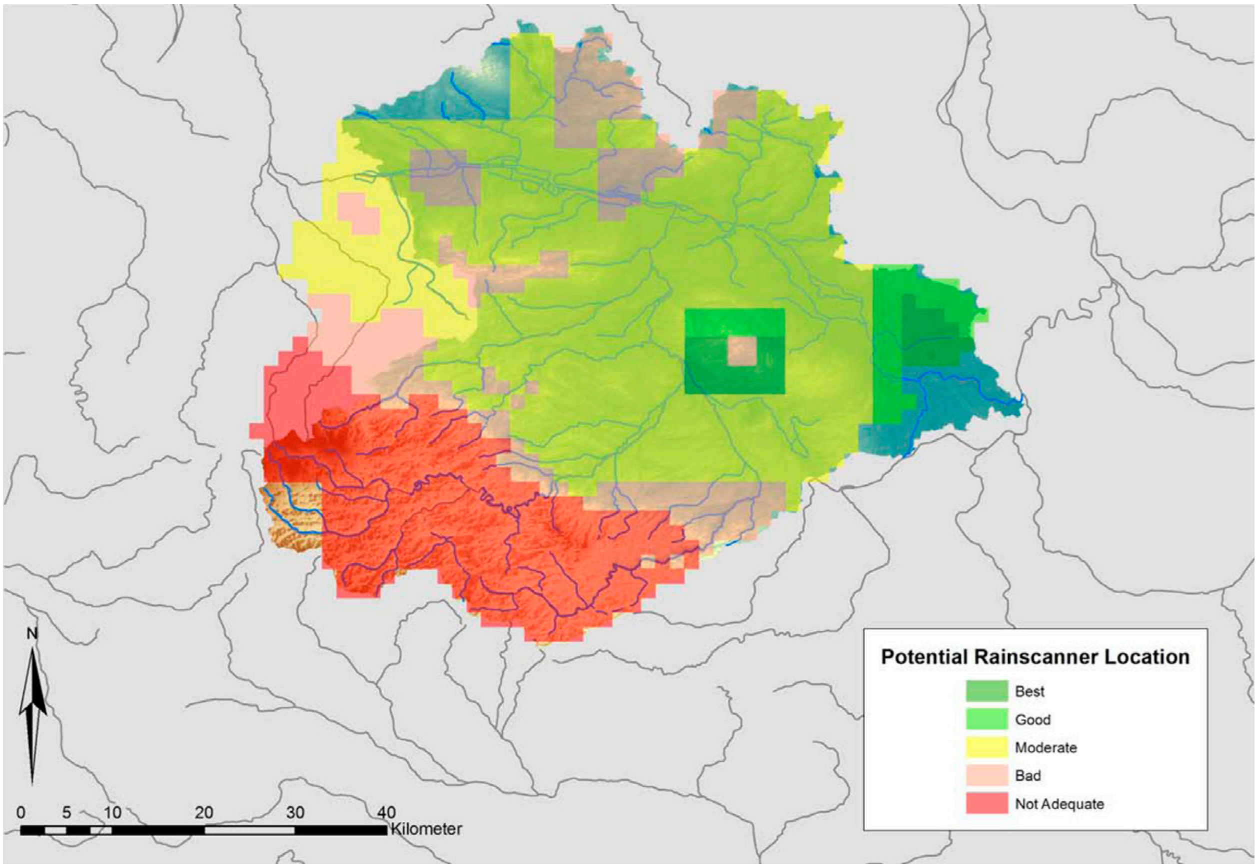

Fig. 9. Potential rain scanner locations; scale: green = best, yellow = good, orange = moderate, dark orange = bad, red = not acceptable.

and 50 cm) using ECH_2O sensors (EC-5 and 5TE, Decagon Devices, Pullman, WA), which were recently evaluated (Bogena et al., 2007; Kizito et al., 2008; Rosenbaum et al., 2010, 2011). Runoff discharge is monitored at two sites (one at the outlet and one within the catchment). For the accurate measurement of river discharge, a combination of Parshall flumes and V-notch weirs is used. In both devices, water flow is measured by the water level using pressure transducers. While the Parshall flume is used to measure normal to high flows (5–300 L/s), the V-notch weir is specifically dedicated to measure low-flow conditions (<5 L/s). Groundwater levels of the near-surface groundwater body are monitored using piezometers installed at eight sites. For the measurements of transpiration flux, two sites were selected. The first one is located near the Wüstebach River and is influenced by groundwater fluctuations. The second site is located on the hillslope and thus is not influenced by fluctuations of the groundwater. At every site, four trees were instrumented with sap-flow sensors to infer transpiration fluxes of the spruce trees. The basic principle utilizes the temperature difference between two needles inserted in sap wood, where the upper needle is heated with a constant supply of energy (Granier, 1987). The temperature difference can be converted with an empirical formula to water flow density. Latent and sensible heat fluxes were measured at a 34-m-high meteorologic tower using the eddy covariance method (Arya, 2001). Furthermore, a lysimeter station is available in the area. The SoilCan Lysimeter concept is presented below..

example for hydrologic observations in TERENO, Fig. 12 shows the results of the hydrometeorologic measurements at the Wüstebach research station for the period from 1 Aug. 2009 to 31 July 2010 (daily averaged high-resolution data).

During the measurement period, a total precipitation of 801 mm and an average air temperature of 7.3°C were measured. The winter period 2009–2010 was characterized by intense snow events (the maximum snow height was 0.6 m). The catchment discharge was 673 mm and the mean depth to groundwater was 0.29 m. The numerous precipitation events in November and December 2009 (in total ~210 mm) resulted in a substantial increase in soil moisture and distinct runoff response, indicating lateral flow processes. The snow coverage in winter 2009–2010 prevented soil freezing, and continuing soil water transport led to a decrease in soil moisture, while subsequent snowmelt events led to an increase in soil moisture. Interestingly, during summer 2010, after a very intense precipitation event (20 mm/h), the soil moisture in the subsoil increased more strongly than in the topsoil. That precipitation event also resulted in a rapid runoff response. Due to a preceding drought, the topsoil was relatively dry (~26% v/v). This indicates that much of the infiltrated rainfall water had bypassed the relatively dry topsoil, possibly due to preferential flow, possibly induced by soil shrinkage and hydrophobicity.

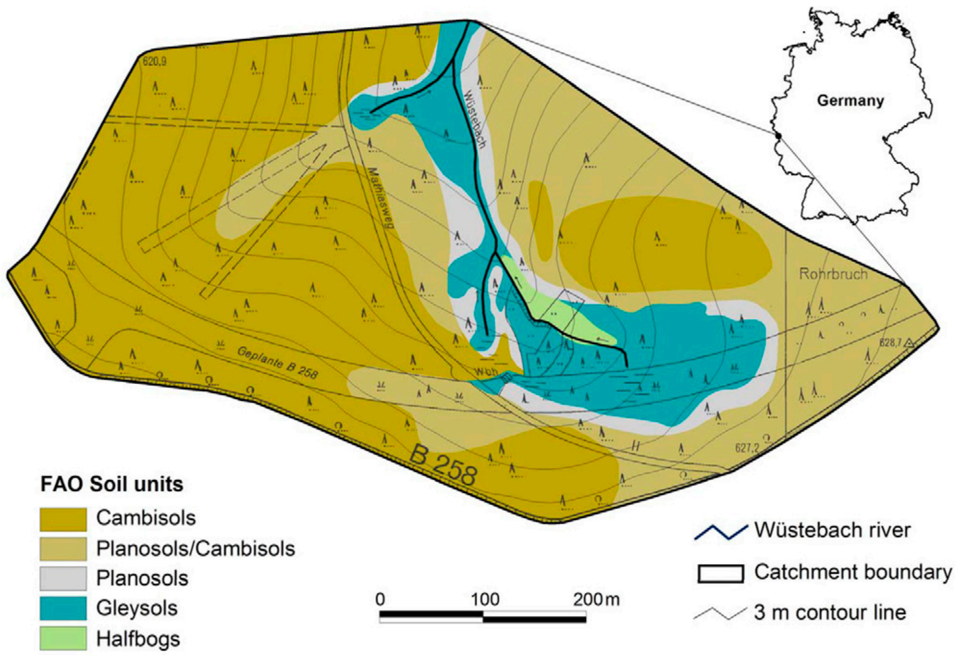

Fig. 10. Soil map of the TERENO research station Wüstebach.

These results illustrate the potential of intensive hydrologic monitoring for process analysis. In conjunction with modeling activities, these observations can support the further development and validation of hydrologic models.

Energy and Trace Gas Flux Measurements

Climate change, resulting from enhanced greenhouse gas emissions, and its effects on Earth systems functioning are some of the most complex and challenging environmental issues. Following the UN Framework Convention on Climate Change (www.unfccc.int, verified 2 July 2011), most industrialized countries aim at reducing greenhouse gas emissions to reduce atmospheric concentrations and to mitigate the effects on, e.g., precipitation patterns, heat waves, storm severity, and sea level rise. Whereas data on emissions from the combustion of fossil fuels are relatively easily accessible, quantifying the net effect of terrestrial ecosystems on greenhouse gas levels in the atmosphere under a changing climate is still a challenging task, fraught with many large sources of uncertainty. To help constrain the uncertainty of the feedbacks and net impacts of terrestrial ecosystems on C cycling and greenhouse gas emissions, long-term ecosystem-scale observations of energy and trace gas fluxes between the Earth's surface and the atmosphere are widely recognized to be of high priority and an important component of the TERENO observatories. To be useful on the regional or larger scale, such observation programs must be comprehensive, continuous during characteristic time periods of ecosystem development (i.e., a decade or longer), represent all important biomes and regions, and adhere to concerted standards for data quality and analysis.

Long-Term Ecosystem-Scale Observations in TERENO Integrated Carbon Observation System

One international observatory network designed with the above-mentioned goals in mind is the Integrated Carbon Observation System (ICOS), "a new European research infrastructure to decipher the greenhouse gas balance of Europe and adjacent regions" (www.icos-infrastructure.eu, verified 2 July 2011). The mission of ICOS is

- to provide the long-term observations required to understand the present state, and predict future behavior, of the global C cycle and greenhouse gas emissions, and
- to monitor and assess the effectiveness of C sequestration and greenhouse gas emission reduction activities on global atmospheric composition levels, including attribution of sources and sinks by region and sector.

The objectives of TERENO's scientific program mesh well with those of ICOS. A selection of TERENO sites with eddy-covariance stations in all observatory regions is currently being built up to include fast laser-based instrumentation for the measurement of CH_4 and N_2O fluxes beyond the standard equipment for energy balance and CO_2 flux measurements. The instrument setup for surface exchange observations over grassland and pasture areas is shown in Fig. 13, including standard meteorologic sensors, seven-component radiation balance, soil heat-flux and moisture profiles, and an eddy-covariance system consisting of a three-dimensional sonic anemometer, open- and closed-path infrared gas analyzers (for fast CO_2 and H_2O concentrations), and a quantum cascade laser spectrometer (for fast CH_4 and N_2O concentrations), plus auxiliary equipment for surface characterization and phenological observations, datalogging, processing, and communication.

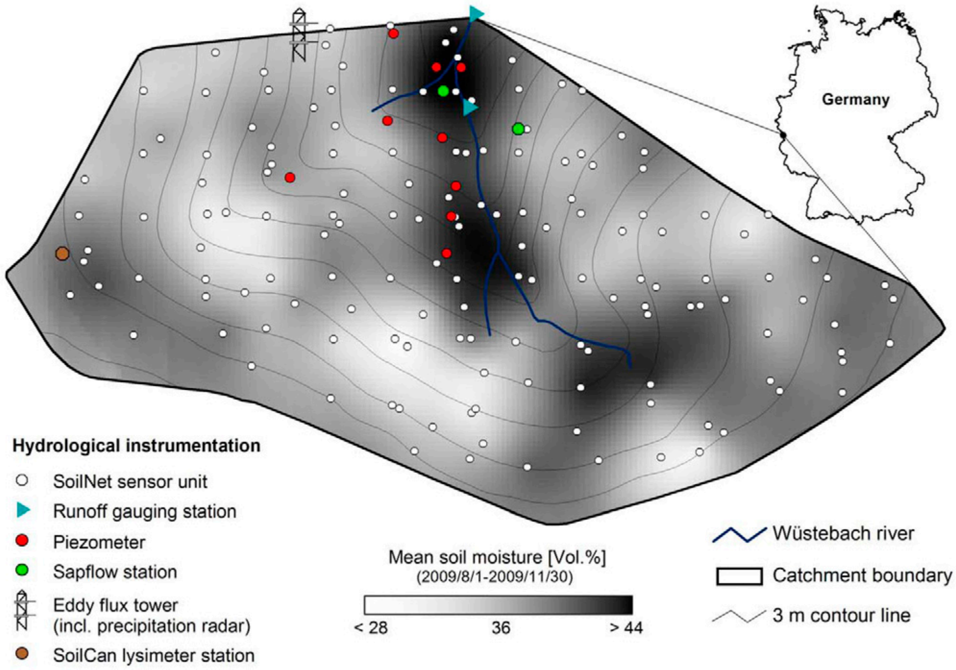

Fig. 11. Hydrologic instrumentation of the TERENO research station Wüstebach.

As an example for surface–atmosphere interaction observations in TERENO, Fig. 14 shows the surface energy fluxes measured at two grassland sites of the Bavarian Alps/Pre-Alps Observatory during 3 d in the beginning of July 2010. These sites are located at different elevations: Graswang at 865 m above sea level and Fendt at 600 m above sea level. Due to the differences in elevation, a south–north precipitation gradient exists (~500-mm increase toward the south and higher elevation) as well as a temperature gradient (~2.5°C toward the north and lower elevation). The criteria for the selection of these locations were their typical vegetation for this region (grassland), an area as homogenous and as flat as possible, suited for eddy-covariance measurements, and differences in elevation between the sites of at least 100 m. Energy- and matter-flux measurements and measurements of environmental parameters started in October 2009 at the Graswang site. The Fendt site went operational in July 2010. The data show that net radiation was very similar at both sites. Evapotranspiration was also comparable, as indicated by the relatively large latent heat fluxes, reaching 400 W/m^2 at midday. The CO_2 fluxes measured at both sites were different, however (Fig. 15). On 8 July 2010, CO_2 uptake at the Fendt site was less than half as large as at the Graswang site, and this difference decreased slightly until 10 July. At the Fendt site, the grass had been cut about 2 wk earlier and was therefore relatively short, about 0.10 m, while the grass canopy height at the Graswang site was about 0.20 m. From these results it may be concluded that CO_2 uptake at the Fendt site was smaller due to a smaller leaf area available for photosynthesis during that period, while the water vapor flux was apparently not limited by the leaf area at either site. It is likely that the difference in leaf surface temperature, which was about 2 K higher at the Fendt site (not shown), may have contributed to the observed difference in net CO_2 uptake, but further observations and analysis are needed to substantiate this notion.

Trace Gas Flux Observations at the Plot Scale

Because uncertainties in estimates of annual greenhouse gas emissions from farmlands are still high (Schulze et al., 2009), there is ongoing need for data from long-time monitoring studies. Furthermore, the Intergovernmental Panel on Climate Change (2006) advises consideration of the impact of specific conditions, e.g., management practice and crop type, when estimating direct N_2O emissions from crop lands, thereby creating an additional need for field monitoring data. At the TERENO station Scheyern (Bavarian Alps/Pre-Alps Observatory) a specific research emphasis lies in the impact of climate change on agroecosystems. Greenhouse gas fluxes from a long-time field experiment have been monitored since 2007.

Observations at agricultural field sites started in 1992 and have been continued since then on soils under extensive as well as intensive farming systems. Agricultural croplands are important emitters of N_2O (Schulze et al., 2009) and therefore have to be seen as a significant source of anthropogenic greenhouse gas emissions. Since the 100-yr global warming potential of N_2O is 298 times that of CO_2, and in addition N_2O catalyzes the decomposition of ozone in the stratosphere (Crutzen, 1981; Ravishankara et al., 2009), N_2O emissions from soils are of particular concern in efforts to mitigate climate change (Intergovernmental Panel on Climate Change, 2007). To achieve a reduction in N_2O emissions from agricultural soils, new management practices need to be developed that can minimize the amount of fertilizer input (Kawashima et al., 1996). Such efforts are in conflict with the increasing worldwide demand for food, however, which creates economic pressure toward more intensive agriculture (Canfield et al., 2010; Mosier, 2001).

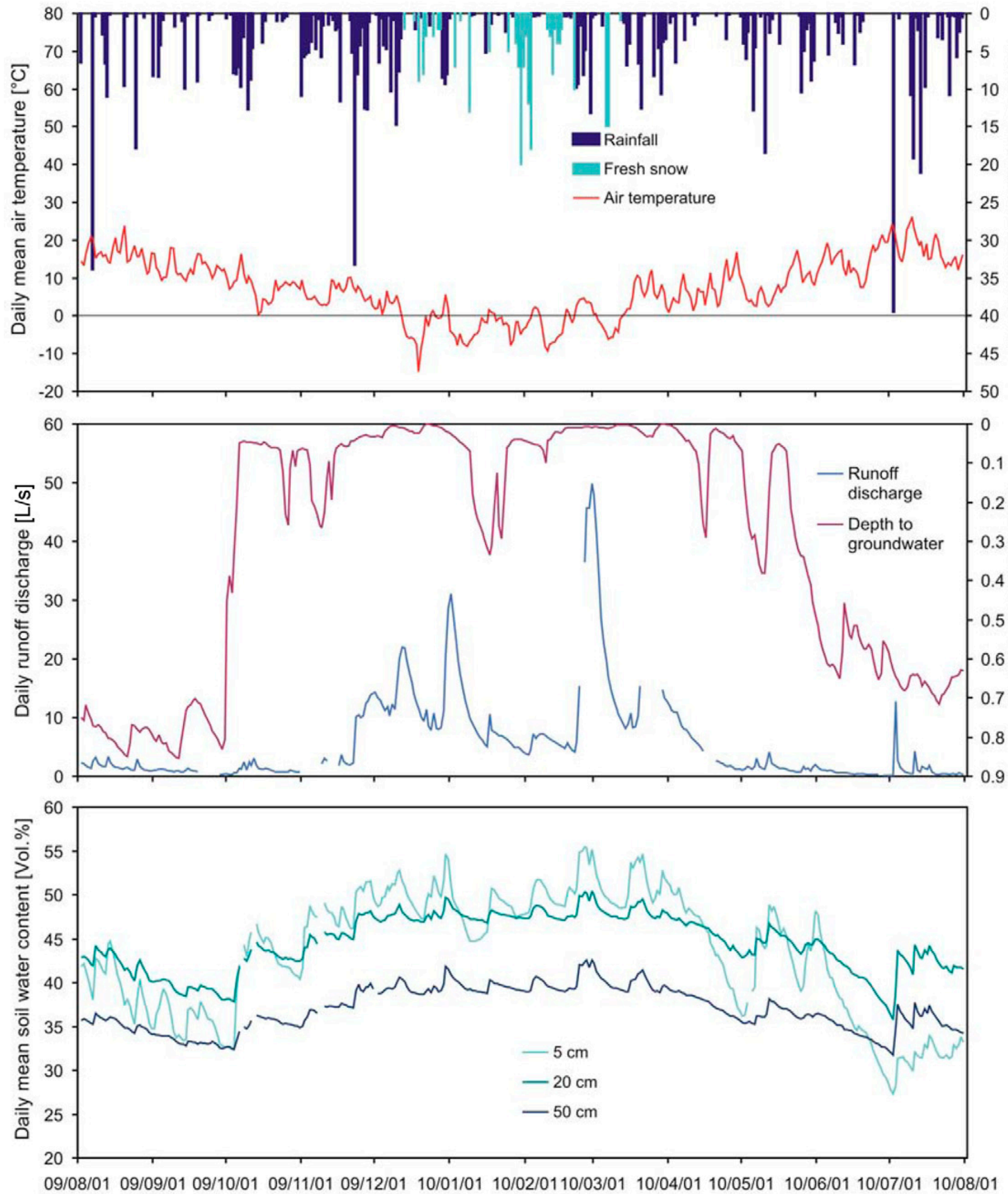

Fig. 12. Hydrometeorologic fluxes and state variables at the TERENO station Wüstebach.

The plot design at the TERENO station Scheyern combines three tillage practices (conventional, reduced, and minimum tillage) and three N fertilization practices (−30%, conventional, +30%). The use of automated chambers (Fig. 16) allows long-term measurements with a frequency of two to three measurements per day and also gives a measure of spatial variation at the plot level. A sufficient spatial and temporal resolution is essential because N_2O emissions are characterized by short emission pulses with a high spatial variation. Upscaling of short-term measurements or of measurements with an insufficient frequency can lead to a severe over- or underestimation of annual emissions (Flessa et al., 2002; Wolf et al., 2010). In addition to the gas flux measurements, water content, temperature, and redox potentials are measured in situ.

Long-term Monitoring of Climate Change Effects using Lysimeters

From the point to the regional scale, a lysimeter is the smallest unit representing a comprehensive view of processes in terrestrial systems and is widely used to study solute transport and water flow in soils. The naturally layered, undisturbed soils in lysimeters, together with their vegetation cover, allow the observation of long-term effects caused by climate change.

The TERENO-SOILCan network is a cutting edge initiative of the German Federal Ministry of Education and Research that

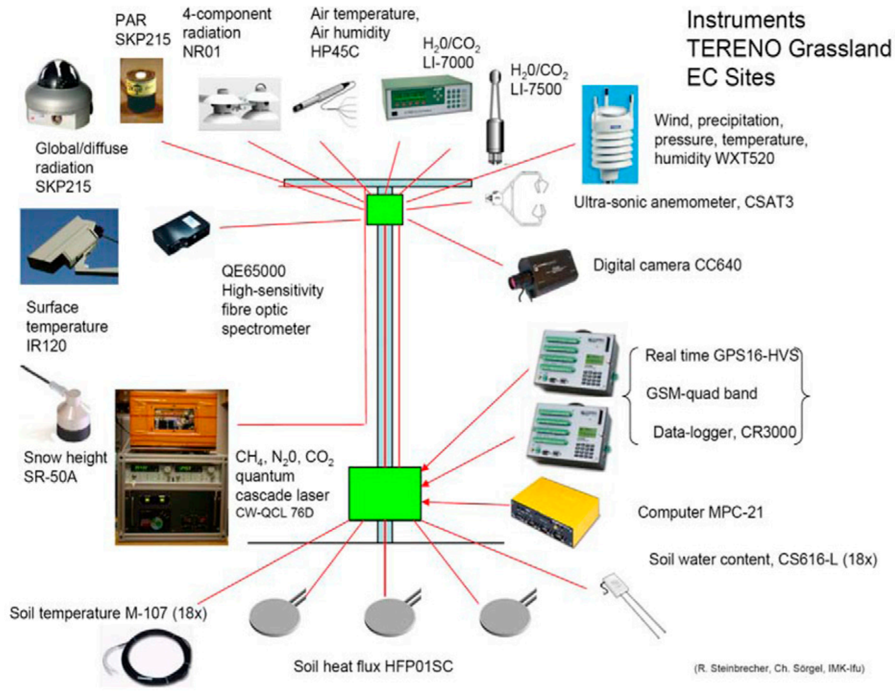

Fig. 13. Instrumentation of TERENO eddy-covariance (EC) energy and trace gas exchange sites.

focuses on the long-term effects of climate change on terrestrial systems. Matter and water fluxes will be studied in a lysimeter network established at all four TERENO observatories covering different climate conditions and land uses across Germany. These comprehensive investigations of terrestrial ecosystem processes and effects caused by climatic conditions will be studied within long-term (>10-yr) research programs.

The development of compatible instrumentation for all four TERENO observatories creates an optimized network of the highly instrumented designated measurement fields, which acts as a prototype for an international observatory network.

The challenges of SOILCan within one observatory are the observation of the long-term effects of climate change on terrestrial systems with a special focus on

- changes in the coupled C and N cycles and C and N storage (temporal dynamics),
- biosphere–atmosphere exchange of greenhouse gases,
- changes in vegetation and biodiversity in the defined lysimeter systems,
- alteration of all components of terrestrial hydrology (water balance, evapotranspiration, precipitation variability, and water retention capacity),
- supplementation of the highly instrumented TERENO test sites, and
- bridging of the gap between single and field measurements (upscaling).

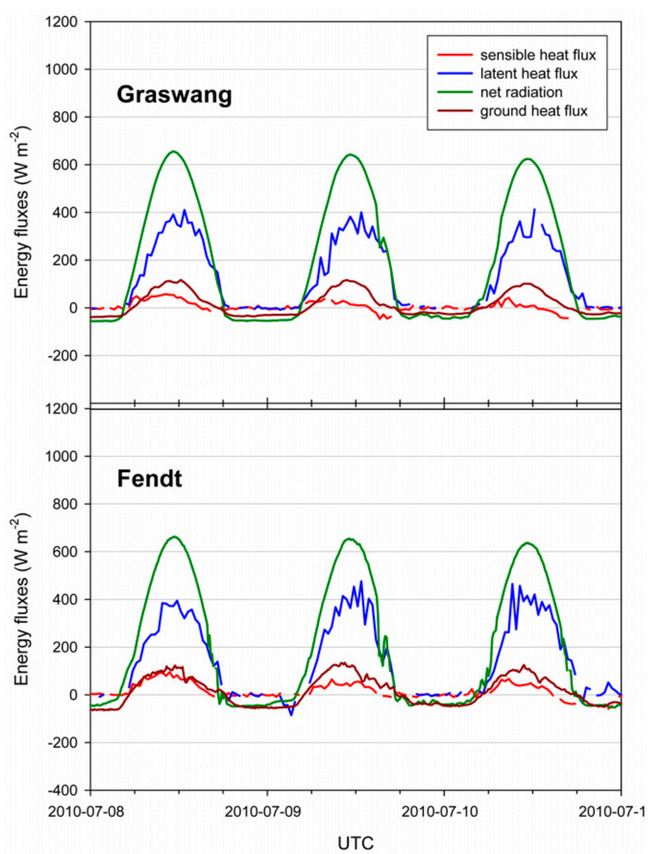

Fig. 14. Energy fluxes at the TERENO stations Graswang and Fendt (8–10 July 2010).

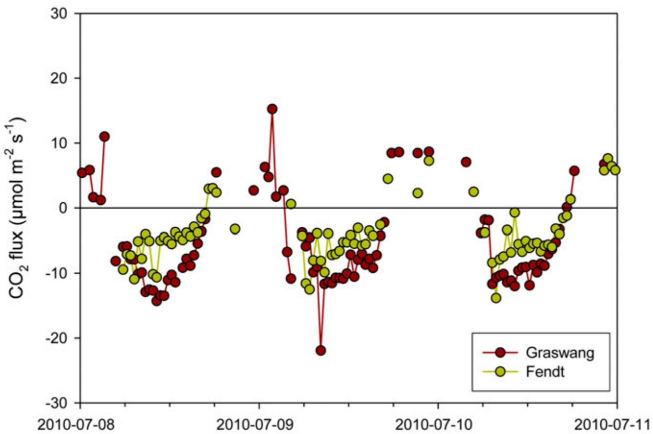

Fig. 15. Carbon dioxide fluxes at the TERENO stations Graswang and Fendt (8–10 July 2010).

The SOILCan network aims to acquire long-term data sets regarding changes in terrestrial systems as a function of climate change, which are still scarce but essential for the development and improvement of models dealing with biosphere–atmosphere–hydrosphere exchange processes.

On the basis of the climate-feedback concept of the Institute for Meteorology and Climate Research (IMK-IFU, Karlsruhe, Germany), a 3-yr period of intensive planning and construction of a total of 126 lysimeters at 12 different test sites was completed in September 2010. The main lysimeter stations are located at the TERENO sites Fendt, Rottenbuch, Bad Lauchstaedt, and Selhausen (Fig. 17), where lysimeters were installed that were obtained from other test sites within the observatory along the temperature and precipitation gradient. For comparison among the different observatories, lysimeters were transported to the Eifel/Lower Rhine Valley and Harz/Central German Lowland observatories. Figure 17 presents the differences in the average annual temperature and the average annual precipitation among the different test sites within and between the TERENO observatories. The gradients of the average annual temperature vary between 0.6 and 5.5°C. The differences in mean annual precipitation at the different test sites vary between 70 and 1120 mm.

At the different test sites, six lysimeters were arranged in a hexagonal design around the centrally placed service unit hosting analytical and data recording devices. This equal geometry guarantees the same conditions for all lysimeters in one lysimeter unit and is a prerequisite for comparative studies. Each lysimeter vessel is made of stainless steel, with a surface area of 1.0 m^2 and a length of 1.5 m (Fig. 18). The lysimeters' lower boundary condition can be controlled with a unit of parallel suction pipes, which were installed at the end of the filling procedure in an inverted lysimeter. Using measurements of the matric potentials by tensiometers inside and outside the lysimeters,

Fig. 16. Trace gas flux observation with automated chambers on field plots at the TERENO station Scheyern.

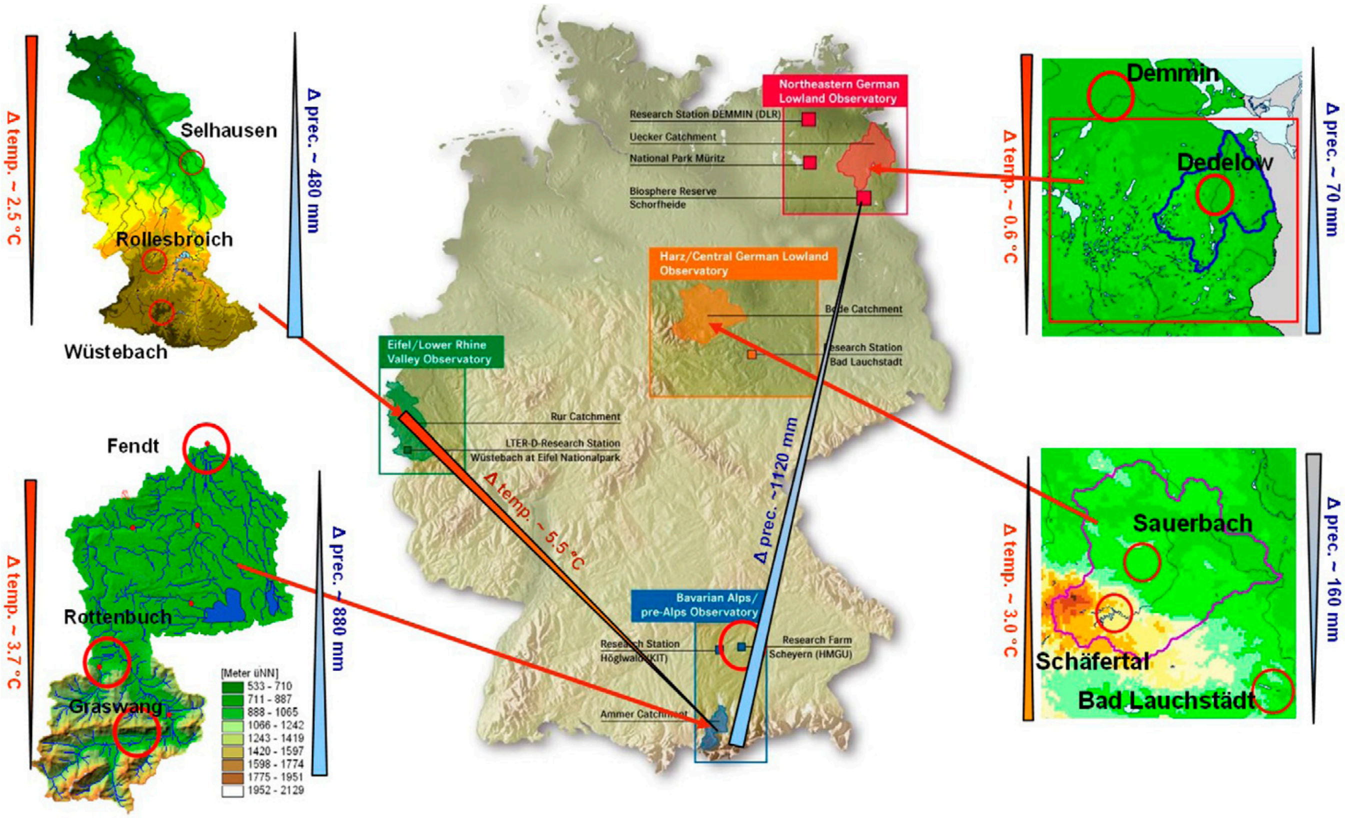

Fig. 17. The different locations of lysimeter stations, showing the different temperature (temp.) and precipitation (prec.) gradients within and between the TERENO observatories.

the vacuum line is adjusted to control the parallel suction pipes. In periods when the water content of a lysimeter is higher than in the encircling control plot, water will leach via the parallel suction pipes into a collecting tank. If the water content of a lysimeter is lower, water is injected back into the lysimeter from the tank. The different components of the water balance of each lysimeter are measured by precision weighing in addition to various sensors and probes.

Because temperature is the main driving force for all hydrologic and biogeochemical processes, the temperature profile has to be the same inside and outside the lysimeter. The porous concrete rings that host the lysimeters establish a thermal equilibrium between the lysimeter soil and the surrounding field along the whole soil profile. All lysimeters were filled with undisturbed soil monoliths in a way that avoided compaction or disturbance by, e.g., stones and roots or because of the perpendicular movement of the vessel, by minimized friction of the vessel in combination with an observation at the cutting edge. Matric potential sensors, tensiometers, temperature sensors, heat flux plates, time domain reflectometry probes, and CO_2 sensors were installed at different soil depths to measure different parameters within the "black box" soil. A weather station next to each lysimeter station completes the facility with respect to complementary measurements of atmospheric conditions. All measured data are logged on site and sent via general packet radio service (GPRS) to a central server.

Conceptual Approach for Biodiversity Monitoring and Research

The TERENO concept for biodiversity monitoring and research is to be compliant with other biodiversity monitoring schemes and to be innovative in terms of developing and testing new schemes. Because it is part of the German network for long-term ecosystem research LTER-D (http://www.lter-d.ufz.de/index.php?en=15578, verified 2 July 2011) and the LTER-Europe network (www.lter-europe.net, verified 2 July 2011), there is an urgent need for the tuning of indicators, parameters, and methods to increase the use value of the network. The lack of a common conceptual ground for the selection of indicators and parameters within LTER sites in general has been recognized as a major drawback for the analysis of long-term data. This is being tackled by the LIFE+ project ENVEurope (www.enveurope.eu, verified 2 July 2011) with a special focus on the integration and coordination of long-term ecological research and monitoring initiatives at the European level. This project explicitly uses the LTER network as an integrated and shared system for ecosystem monitoring and is developing a generic conceptual framework for indicator selection at the ecosystem level. This is intended to be adopted by LTER sites and thus will be considered for TERENO sites also.

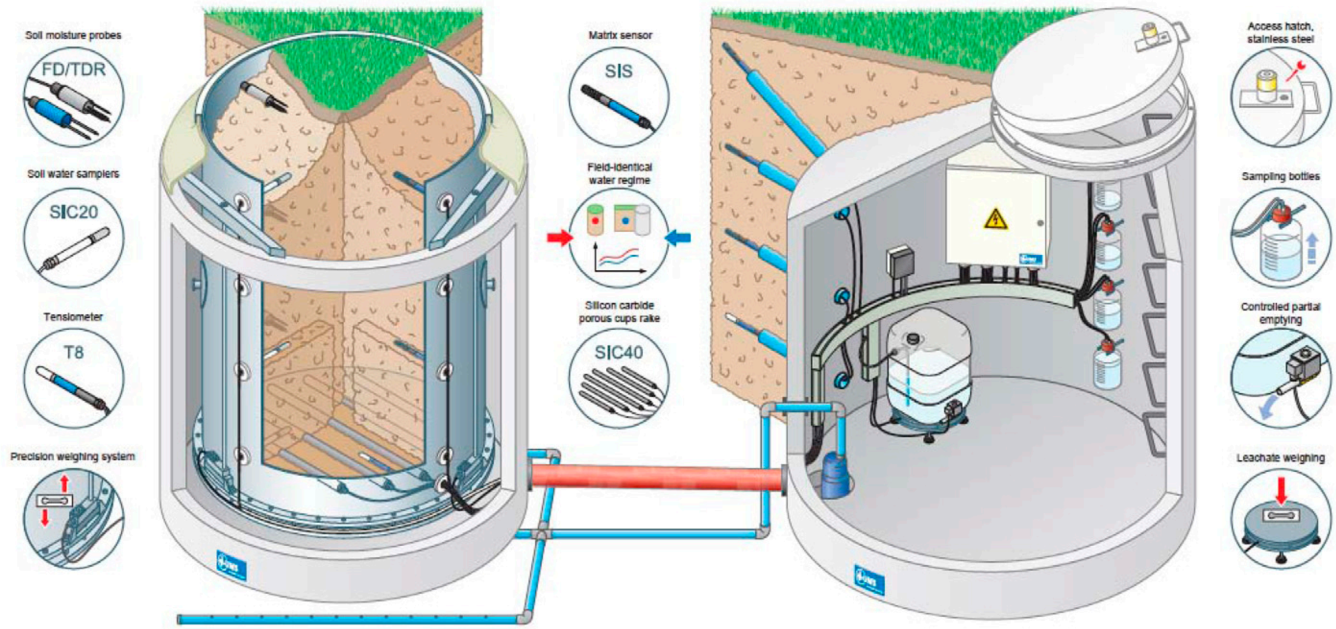

Fig. 18. Sectional drawing of a lysimeter hexagon with the central service pit and one lysimeter (courtesy of UMS GmbH Munich, 2010, used by permission).

Biodiversity comprises diversity at different levels: of ecosystems (and habitats), of species communities, of species, and of genes within populations of the same species. It is an important component of ecosystems but needs to be complemented by other ecosystem features linked to processes and functions to obtain a complete picture of the ecosystem state. The central questions of biodiversity monitoring, observation, and experimentation within the TERENO concept are

- the impact of climate change on species phenology, species ranges, as well as communities, ecosystems, and ecosystem processes,
- the impact of land use on the same components of biodiversity,
- changes in pollinator communities of selected plant species along gradients of land use,
- local adaptation and gene flow (pollen and seeds) within the sites and landscapes and changes in the population genetics of plants (via range and quality of pollen exchange and inbreeding),
- the role of changes in matter flow caused by land use changes (the impact of nutrients as well as pollutants on biodiversity),
- the role of species loss and immigration of alien species, and
- the role of interactions among land use change, climate change, and species loss and gain.

Basic requirements for ecological indicators have been well defined and can be found, for example, in Müller and Burkhard (2010). Indicators should be easily measurable, be able to be aggregated, and depict the investigated relation between the object of indication and the indicator in an understandable manner. These variables should comprise optimal sensitivity, include normative loadings to a defined extent only, and provide a high value for early warning purposes. Müller and Wiggering (2004) provided a detailed list of further requirements for indicators. The concepts to be considered for the selection of indicators include (i) ecosystem integrity as a basic concept, (ii) ecosystem services, and (iii) the Driver–Pressure–State–Impact–Response (DPSIR) model (European Environment Agency, 2006) as a framework linking environmental and human systems. Considering the relationship between ecosystem integrity and ecosystem services, ecosystem integrity (respective ecosystem structures and functions) is the base for the provision of ecosystem services. Human decisions and actions (e.g., land use) again have an impact on the state of the environment. Figure 19 shows the linkages among the concepts.

The focal components that should be taken into account to represent ecosystem integrity are ecosystem structures and ecosystem functions (ecosystem energy balance, ecosystem water balance, and ecosystem matter balance). For a detailed justification, see Müller and Burkhard (2010). Table 1 shows the focal components and indicators as well as potential key variables for an indicator system including the biodiversity component.

A focal point for research related to biodiversity in TERENO is the Harz/Central German Lowland Observatory. Due to its size (about 25,000 km^2) and geographical characteristics, it offers different scales enabling biodiversity and socioeconomic research within different landscapes and environmental gradients like precipitation, temperature, land use, or urbanization. A field-site network used for monitoring and experiments has been established along climatic and land use gradients and in adaptation to the ongoing abiotic monitoring activities. The focus is on seminatural sites (grasslands and forests) and landscape elements (hedges and field margins) within agricultural landscapes and on the

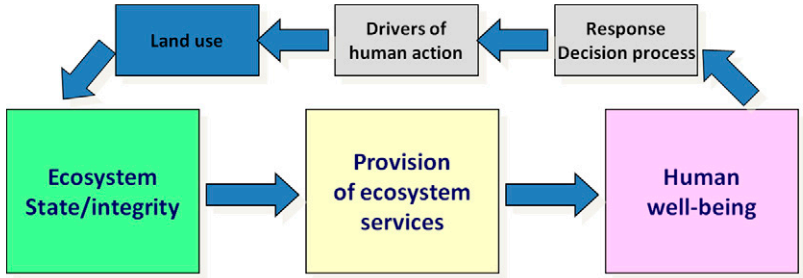

Fig. 19. Ecosystem integrity as the base for the provision of ecosystem services and finally, human welfare, based on the Driver–Pressure–State–Impact–Response (DPSIR) model (B. Burkhard, unpublished data, 2010).

agricultural matrix, too. Six core sites with a size of 4 by 4 km are intensively investigated and additional selected activities (e.g., collection of certain plants or insects) take place at several satellite sites. A prerequisite for the selection of core sites was the availability of historical data, e.g., about land use and vegetation, and the representative character of the site within the whole landscape. Based on old data including vegetation mapping, historical habitat situations were reconstructed (Fig. 20). The reconstructed land use map shows the dramatic changes in land use, in habitat patterns, as well as in landscape structures in general and delivers important information regarding land use–climate–biodiversity interactions.

The monitoring actually covers selected organism groups: (i) vascular plants, most important as primary producers and overall biodiversity indicators); (ii) bees and hoverflies, important pollinators and thus ecosystem service agents; (iii) butterflies, classical indicators of habitat quality and of importance as pollinators; and (iv) birds, highly mobile and sensitive indicators for landscape structures and the whole landscape context and integrative indicators at the landscape scale. Important criteria for the selection of organism groups were different and complementary indicator value qualities and the availability of historical and present data. In this way, popular organism groups (e.g., birds and butterflies) had to be included because data gained by citizen scientists are an important source to complete data sets from institution-based records. Additionally, the genetic patterns and structures within selected species and populations will be monitored as excellent indicators for the selective power of environmental change.

Outlook

The TERENO initiative aims to provide long-term observational data on the terrestrial system in Germany combined with dedicated large-scale experiments and innovative integrated modeling approaches based on an integrated network concept. We expect that the integrated observation of different compartments of the terrestrial system combined with experiments will allow a better understanding of the impact of land use and climate change on the evolution and adaptation of the terrestrial system. The available data and validated terrestrial models will be used to define adaptation strategies needed to cope with the effect of climate change in Germany within the next decades. This is the time scale at which decisions with respect to adaptation need to be taken and implemented. The assessment of the impact of these changes is replete with very large uncertainties, however, hampering the identification of adaptation strategies. The TERENO initiative will provide the relevant data and tools to reduce this uncertainty. The establishment of cross-network standards in environmental monitoring and experimentation opens up excellent possibilities for comparative studies and creates the conditions that will allow the transfer of knowledge to unobserved sites. The TERENO observatories were established with the aim of better integrating the various scientific disciplines active in terrestrial research by exploring synergisms and providing opportunities for capacity building. They will, however, also foster cooperation with local, national, and international authorities and organizations to better integrate monitoring data to provide a solid basis on which management and political decisions can be made. Through the establishment of a data platform and a common data policy, TERENO will make available its data to the scientific community.

Table 1. Set of "optimum" indicators to represent ecological integrity (Müller, 2005; Müller and Burkhard, 2007).

Focal component	Indicator	Potential key variable
Biotic structures	biodiversity	e.g., number of selected species
Abiotic structures	biotope heterogeneity	e.g., index of heterogeneity, habitat diversity
Energy balance	energy capture, entropy production, metabolic efficiency	gross or net primary production; entropy production after Aoki; entropy production after Svirezhev and Steinborn; output by evapotranspiration and respiration; respiration per biomass
Water balance	biotic water flows	transpiration per evapotranspiration
Matter balance	nutrient loss, storage capacity	Leaching, e.g., of NO_3; soil organic C; intrabiotic N

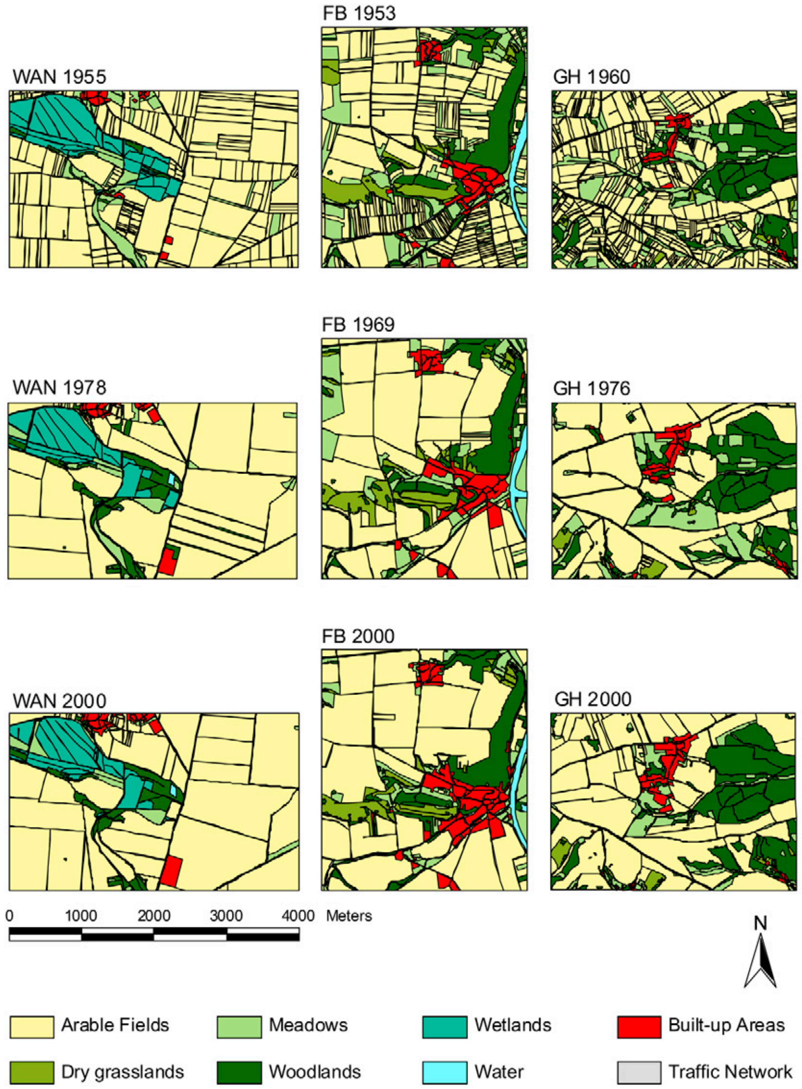

Fig. 20. Land use and habitat maps of the three biodiversity study sites (WAN, FB, and GH) within the Harz/Central German Lowland observatory during three time periods (Baessler et al., 2010).

From 2011 on, TERENO will establish a set of observatories in the Mediterranean region based on the concept outlined here. The region is expected to be strongly impacted by climate change, especially with respect to water management issues.

The TERENO observatories consider themselves to be a community platform open for national and international partners. The openness to other research institutions and the effective cross-linking to international research networks is an essential part of the TERENO research strategy that aims to support the earth and environmental science communities in addressing their specific research questions.

The major focus of TERENO lies in ecosystem controls over energy, water, and matter fluxes in the terrestrial system consisting of the subsurface environment, the land surface including the biosphere, the lower atmosphere, and the anthroposphere. This definition is mostly consistent with the definition of the "critical zone." Despite many points in common with other Critical Zone Observatories, there are also some differences. Thus, for example, the linkage between ecosystem processes and longer term processes of pedogenesis and landscape evolution is a key component of research activities, e.g., in the U.S. Critical Zone Observatory Program or the European initiative SoilTrEC (eusoils.jrc.ec.europa.eu/projects/soiltrec/, verified 2 July 2011), while the main research emphasis of TERENO is on the contemporary time scale. In the context of soil-landscape modeling, however, the integration of geomorphologic and geochemical studies is on the TERENO agenda for the near future. This will provide a further conceptual interface between TERENO and other "critical zone" observation activities.

Acknowledgments

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