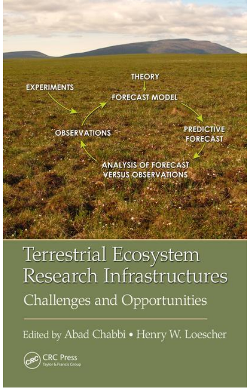

Terrestrial Ecosystem Research Infrastructures
Challenges and Opportunities

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A Blueprint for a Distributed Terrestrial Ecosystem Research Infrastructure

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11

A Blueprint for a Distributed Terrestrial Ecosystem Research Infrastructure

Heye Bogena, Harrie-Jan Hendricks Franssen, Carsten Montzka, and Harry Vereecken

CONTENTS

Abstract

Although there is growing awareness that continuous observation of the various terrestrial subsystems (i.e., atmosphere, hydrosphere, pedosphere, biosphere) is essential in improving our understanding of the complex influences of global change on terrestrial ecosystems, existing networks of long-term research infrastructures tend to address only specific issues (e.g., carbon balance). In this chapter, we advocate the need for long-term, distributed terrestrial ecosystem research infrastructures (TERIs) for a new level of fully integrated, multidisciplinary global change research. TERI networks would offer significant potential to address a wide range of challenging environmental problems. Knowledge gained through these networks will be critical in understanding, detecting, and forecasting changes in terrestrial ecosystems that affect important ecological services upon which society depends. Such a network of integrated observation platforms will provide information necessary for societies to adapt to broad-scale changes such as those associated with land use, demographic, and climate change.

In this chapter, we discuss the blueprint for a network of TERIs. Based on the example of the TERENO infrastructure, we present the complexities and challenges confronting the design and implementation of ecological monitoring networks.

Keywords: Terrestrial ecological monitoring network, Remote sensing, Scaling, Modeling

11.1 Introduction

During the last century, mankind impacted fundamental environmental and physical processes that sustain life on earth in an unprecedented way (McCarthy et al. 2001). We are now starting to observe broad-scale ecological impacts of global climate change, including changes in the timing of ecological processes (Westerling et al. 2006). In particular, polar and high-altitude regions are already showing the highest rate of warming connected to climate change (UNEP and WMO 2011). The increase in global average surface temperature by 0.85°C ± 0.2°C is expected to further increase by 1.5°C–4.8°C until 2100 (IPCC 2013). Through modifications of the earth's surface and global biogeochemical cycles, productive ecosystems have lost to desertification processes, reduced availability and reliability of clean and abundant sources of water and food, increased risks to natural hazards such as floods and fires, and increased disease and exposure to harmful chemicals (Bellamy et al. 2005; Young and Harris, 2005). The specific human influences and drivers of these observed changes are complex and multiscaled in nature (MEA 2005).

There is an increased recognition that ecological research infrastructures, providing long-term information on the development of states and fluxes of the various terrestrial subsystems (i.e., atmosphere, hydrosphere, pedosphere, biosphere), are essential in improving our understanding of these complex relationships between humans and environment and in developing policies and strategies to reduce impacts from anthropogenic change, to develop adaptation strategies and to secure a more sustainable future (Allen et al. 2014, Balvanera et al. 2013; Fraser et al. 2013; IPCC 2013; Peters et al. 2014). However, the existing networks of research infrastructures tend to address specific issues often related to specific subsystems within ecosystems and, as a result, represent different geographies, temporal and spatial scales, and attributes of the environment (CENR 1997). We also lack coordinated monitoring programs that provide integrated, standardized, and quality-checked data across multiple ecological systems at various temporal and spatial scales in order to make studies and comparison more robust.

Moreover, a critical need exists to synthesize biophysical, ecological, social, and economic information to increase our understanding of the significance of interactions among processes that impact upon ecological systems over broader time and space than currently possible. New developments in science and technology provide new opportunities for collecting and organizing data that could greatly expand our monitoring capabilities and, hence, develop new understandings.

In this chapter, we present the challenge of designing and implementing long-term distributed terrestrial ecosystem research infrastructures (TERIs) for a new level of fully integrated, multidisciplinary global change research. We further describe how such infrastructures in combination with remote sensing and prognostic modeling efforts can be used to provide early warning and forecasting of potentially irreversible conditions and trends in processes that maintain important ecological services.

The remainder of this chapter is organized as follows. First, we will address the current challenges in ecosystem research and the need for distributed TERIs. We then describe the TERI implementation and design, which is followed by a presentation of complementary remote monitoring and scale transfer using modeling approaches. To illustrate the TERI concept, we use the existing national TERI (TERENO) as an example. Finally, we present concluding remarks and an outlook.

11.2 Challenges in Terrestrial Ecosystem Research

Up-to-date research networks have mainly focused on specific subsystems, such as land surface, various parts of the atmosphere and the subsurface, and natural ecosystems, without considering their different buffer capacities (e.g., soil nutrient buffer capacity, flood retention zones) and process time scales (Bogena et al. 2006). Although there is a growing awareness of subsurface terrestrial systems (e.g., vadose zone, groundwater aquifers) being affected by global change and the direct impact of human activity, less attention has been paid to important subsurface characteristics and processes (e.g., observed decrease in soil organic matter, expected changes in the soil moisture regime, evapotranspiration, groundwater recharge, and runoff generation). For instance, subsurface lateral flow is widely considered to be an important hydrological flux that is poorly understood and difficult to measure and quantify (Vereecken et al. 2015). In the framework of TERI, high-frequency isotope analysis and hydrogeophysical methods (e.g., multireceiver electromagnetic induction, ground-penetrating radar) could be used to better determine this important hydrologic process from the field to the catchment scale. In addition to the impact of global change, terrestrial systems are strongly influenced by local and direct human activities causing dramatic changes in the terrestrial system functions, which are not yet monitored comprehensively (e.g., changes in land use, deforestation, overfertilization, opencast mining, groundwater withdrawal).

In our view, the increasing anthropogenic impact on the terrestrial systems and their associated changes require a multiscaled, consistent, and longer-term utilization of environmental research from local sites to regional scales with corresponding personnel and financial expenditure. Here we emphasize the importance of regional scale because at this scale, interactions between land surface and atmosphere and land management consequences (e.g., political decisions on bioenergy of fertilizer taxation) can be investigated. On the other hand, comprehensive experimental studies on multisubsystem interactions and scale dependencies are needed to better understand the response of terrestrial systems to changing environmental conditions (e.g., Bogena et al. 2015; Burt et al. 2008; Katul et al. 2012). Numerous experiments (e.g., summarized in Giardina and Ryan 2000) have been conducted in order to evaluate the potential future effects of climate change on soil carbon dynamics. However, these experiments rarely continue for more than a few years and thus never provide information on the response of the large, slower pools that will dominate feedback from the soil to the atmosphere over time scales of decades or more (Powlson 2005). The effects of climate change are much more complex than just an increase of a single parameter, since compensation and acclimatization processes may occur (Davidson et al. 2000). Thus, in order to increase the ecosystem process understanding, that is, in terms of multisystem interactions and scale dependencies, the continued multiscale fully integrated observation of terrestrial states, fluxes, and properties by TERI needs to be combined with more detailed, long-term experimental studies.

11.3 Implementation and Design

As elaborated in previous chapters, the implementation of long-term TERIs is urgently needed to enable a better study of the terrestrial system in order to provide guidance in how (1) to sustain the ability of terrestrial systems to adapt to environmental change as well as their resilience, (2) to maintain ecosystem services, and (3) to provide scientifically justified solutions to land use conflicts. This is underpinned by the strategy paper of the DFG on "long-term perspectives and infrastructure in terrestrial research in Germany—a systemic approach" (DFG, 2013). A terrestrial system in this context is defined as a system consisting of the subsurface environment, the land surface including the biosphere, the lower atmosphere, and human impact on the different scientific areas of study. Since this system is organized along a hierarchy of spatiotemporal scales and structures ranging from the local scale to the regional scale, the TERI concept needs to follow a multiscale approach consisting of a set of spatially distributed, site-based terrestrial observatories. In order to characterize terrestrial-atmospheric feedback and human-use gradients, the spatial scale of each terrestrial observatory (which contributes toward the overall network) should range between 1,000 and 10,000 km^2 including several intensively instrumented super test sites (field or headwater catchment scale). These super test sites need to be representative, that is, they should cover the main types of land use, soil, geology, and topography found in the region of the terrestrial observatory to enable upscaling of local observations (see Chapter 4 for more details on scaling issues). In addition, super test sites can host manipulation experiments on ecosystem response to changing environmental conditions and can be used for testing new observation techniques (e.g., Bogena et al. 2013). Since hydrologic processes exert a fundamental control on aquatic and terrestrial metabolism and nutrient cycling, catchments represent an ideal fundamental unit of the TERI network (Bogena et al. 2006), providing the construct to close or constrain the water, energy, and mass balances (Jensen and Illangasekare 2011). By combining individual terrestrial observatories into the overall TERI network, continental- to global-scale questions between anthropogenic and natural factors can begin to be addressed in a systematic fashion, similar to existing distributed research infrastructures that focus on specific science disciplines, for example, Integrated Carbon Observation System (ICOS) that aims for a European-scale carbon balance.

Natural sites that have minimal human impact should be a core design element of a TERI network as reference sites. A “near” natural site such as state owned (as in Siberia, Russia), wildlands of the Bureau of Land Management (as in the United States), restricted access zones (as in Brazil), private ownership of reserves (as in Costa Rica), natural heritage sites, can provide a baseline understanding of how a least-human-impacted one would behave and allow for robust comparisons with sites of varying degrees of land management and human-impacted systems. These types of comparative analyses will enable spatially integrative understanding of the long-term environmental changes due to human impact. Moreover, a comparative design that includes natural areas will also provide the context to socioeconomic research questions. Albeit the integration of ecosystem science and socioeconomic questions is still nascent (Burkhard et al. 2010) and has not yet been implemented in existing distributed TERIs.

Another requirement for the development of TERI network is the availability of appropriate measurement platform and sensing techniques. The TERI instruments need to be designed for robust, long-term, consistent measurements of important terrestrial fluxes of mass and energy and state variables, for example, soil moisture, and the factors that control these exchanges between the terrestrial subsystems. The observational strategies need to be designed in a way to address the expected changes in the processes at relevant time and space scales. For example, near-real-time measurements by fixed installed instruments enable to assess rapid, short-term process rates such as the effects of diurnal patterns (e.g., evapotranspiration) and fast stochastic changes in system states and fluxes (e.g., runoff discharge, effects of fire, rain pulse events). On the other hand, the measurement design needs to be able to also detect slower processes that occur over seasons and years (e.g., soil compaction, droughts). Finally, TERI measurement capabilities must also have the flexibility to add additional capabilities to address the ability to discover future unforeseen processes and address important processes in the future that are not known today.

A primary challenge is to determine the key process (among disciplines) and the relevant time and space scales by which they occur and to design measurement systems that can effectively quantify these time and space scales. For example, in hydrology, one faces the challenge of large spatial and temporal variability of soil moisture from the soil-aggregate-to-plot-to-field and stand-to-landscape scales (Vereecken et al. 2014). Factors controlling soil moisture include atmospheric forcing, topography, soil properties, vegetation, and human impacts (e.g., irrigation, groundwater withdrawal), which all interact in complex, nonlinear ways. One solution is to deploy a sensor network consisting of a multitude of small sensor nodes embedded in the environment that can quantify spatially heterogeneous phenomena, for example, temperature or soil moisture fields, with high temporal and spatial resolution (Bogena et al. 2010). Such data enable the determination of covariance structures of autocorrelated drivers to assist in upscaling and downscaling of state variables in time and space (Loescher et al. 2007). Slower changes in system states might best be observed at broader scales than local scales, that is, field, stand, ecosystem scales. Such would be the example of measuring the below-canopy microclimate of many ecosystems within the landscape. The physical structure of these systems does not change rapidly and can be assessed on a campaign basis through the use of wireless ad hoc sensor networks (Inagaki et al. 2010). Such ad hoc sensor networks are extremely flexible and can be used temporarily to assess spatial heterogeneity of ecosystem states in areas that are not part of the “fixed” sensor network, thus increasing spatial coverage of TERI. In addition, these ad hoc networks can be deployed in a chronosequence design to substitute time for space. The associated requirement would be for these mobile platforms to be interoperable and the data should have the same or similar uncertainties as the fixed long-term measurements. Moreover, these ad hoc sensor networks can operate periodically on a regular or event-driven basis, thus allowing to capture other nonlinear behaviors in the landscape that otherwise could not be measured, that is, heat islands, shifting agriculture, flooding, wildfires. Due to the large amount of information gathered by such instrumentations, dataflow needs to be accompanied by high-performance computational systems for data acquisition, storage, and processing (see Chapter 4).

In order to link in situ information from local monitoring systems to the regional, continental, or global scale, the TERI design needs to be linked with a hierarchy of process-based models. Local-scale information such as parameter fields can be obtained from a combination of direct measurements (Weihermueller et al. 2009), pedotransfer functions that enable predicting key soil properties and parameters from easily measurable properties and state variables (e.g., Qu et al. 2015; Vereecken et al. 2010). In return, these scale-dependent process-level measurements can be used to drive and validate process-based field-scale models (e.g., Fang et al. 2015). Another approach is to use data assimilation techniques at the next larger scale that updates both states and parameters of the terrestrial systems using local-scale information. To continue to evaluate the efficacy of these model approaches, long-term consistent measures of fluxes of energy, water, and mass (e.g., evapotranspiration, infiltration, groundwater flow, runoff discharge) need to be measured (e.g., selected test sites) in order to further validate these models over years and decades and to test new theories. Being able to incorporate land management with more traditional biophysical models is an active area of research, particularly within a scaling framework. Again, using hydrology as an example, catchment models like WASIM-ETH (e.g., Montzka et al. 2011) or TerrSysMP (Kurtz et al. 2016) are able to reproduce management activities like reservoir use, groundwater withdrawal, and irrigation and place them in a context by which they can be scaled further to the regional or continental scale. Alongside with the mandate to scale to larger areas comes the need to integrate data from a variety of remote sensing sources (see Chapter 3 for more details). A nice example that implements the concept of hierarchical scales and scale transformation is the collaborative research center "patterns in soil–plant atmosphere systems" that uses the Eifel/Lower Rhine observatory of the TERENO initiative (Chapter 5); this is a major research thrust to develop novel approaches in upscaling and use of data assimilation approaches (Simmer et al. 2015).

An important set toward the development of a TERI network is the selection of appropriate sites. A promising approach to identify TERI sites from the continental to the global scale is the Budyko framework (Budyko 1974), which describes an empirical global relationship between the evaporative index and climatic dryness index. The Budyko framework has been used to assess the sensitivity of river discharge to climatic change (Donohue et al. 2011; Renner et al. 2012) and to analyze climate and vegetation controls on the surface water balance and evapotranspiration (Williams et al. 2012). The Budyko framework has also been used to describe and subdivide terrestrial systems with respect to energy- and water-limited systems (van der Velde et al. 2014). In addition, further considerations with respect to dominant vegetation and land management should be included to cover all important ecosystems (e.g., tropical rainforest, temperate rainforest, tropical wetlands, desert, managed temperate forest). In addition, more vulnerable and less vulnerable sites, for example, to climate change, can be compared in order to better understand scaling of ecosystem stability. Ecosystem stability in this sense can range from regeneration via resilience (returning to a previous state in a short term) to constancy to persistence. In Section 4 and 5, we describe how remote sensing techniques and model base scale transfer can support the upscaling of local information obtained by the TERI observations systems.

11.4 Complementary Earth Observation

Earth observation (EO) describes the collection of information about planet Earth's physical, chemical, and biological systems via remote sensing technologies supplemented by earth surveying techniques, encompassing the collection, analysis, and presentation of data. Here we review EO techniques because TERI field measurements are typically used for accurate estimation of biogeophysical parameters at the local scale but are not able to provide area-wide information (Kampe et al. 2010). EO sensors are able to return environmental quantities in order to anchor and scale ecosystem properties and support the in situ instrumentation of TERI to monitor the temporal development of spatial patterns (Lausch et al. 2015; Müller et al. 2014; Rudolph et al. 2015) in a sound observatory concept. On the other hand, the in situ observation of TERI can significantly contribute to the validation of EO data products and to the calibration of retrieval models needed to transfer raw EO measurements into environmental variables (Montzka et al. 2013).

Over the last two decades, we have seen great advances in the development and deployment of remote sensors for EO (CEOS 2015). These include a wide range of biophysical quantities, including temperature profiles, soil characteristics, geology, landforms, elevation, chemical quality of surface waters, and vegetation characteristics (e.g., Eisele et al. 2012). Moreover, advances in computing and digital communication have dramatically increased our ability to process, store, analyze, and integrate remote sensing data. Remote sensors are typically designed to monitor specific environmental variables.

In the following, we present an overview of important remote sensing techniques that are relevant for TERI. In most cases, remote sensors operate in the visible (VIS, 400–750 nm), near-infrared (NIR, 750–1,400 nm), short-wave infrared (SWIR, 1,400–3,000 nm), mid-wave infrared (3,000–6,000 nm), thermal infrared (6,000–15,000 nm), and microwave (MW, 1 mm to 1 m) regions of the electromagnetic spectrum. However, these sensors just record electromagnetic waves, which need to be transferred to the respective environmental variables by retrieval models. There are retrieval models with different complexities, from statistical regression to physically based models where additional parameters are needed (e.g., for more details, see

Verrelst et al. 2015). The challenge is not only to develop a remote sensing system that is able to observe the record (reflectance, emissivity) in adequate spatial and temporal resolution but also to relate the raw data to quantitative environmental properties.

Vegetation monitoring is typically performed in the VIS and NIR bands. Here, multispectral systems such as Landsat (Irons et al. 2012), ASTER (Yamaguchi et al. 1998), RapidEye (Krischke et al. 2000), and Sentinel-2 (Drusch et al. 2012) have been used extensively to characterize land cover status and change. This includes not only the provision of spectral indices but also the derivation of higher-level data such as leaf area index (LAI) (Ali et al. 2015; Delegido et al. 2011; Ganguly et al. 2012; Qu et al. 2015) and physiognomic land cover maps (Homer et al. 2015) for further application in environmental models. For the purpose of long-term monitoring in terrestrial observatories, the Landsat missions provide valuable information dating from now back to 1972. The current Landsat 8 satellite had been launched in 2013, and plans for the launch of the successor Landsat 9 in 2023 already existed. Similar to the in situ component of TERI, the long-term observational strategy is inherent to the Landsat science program, making it an excellent partner to identify environmental changes over several years and decades. However, in high-biomass ecosystems, passive optical sensors typically fail to accurately estimate LAI and aboveground biomass. Light detection and ranging (LIDAR) has been shown to provide valuable information about the vegetation structure. Linking both the biophysical quantities and structure are key design attributes of many environmental research infrastructures and campaign-style research activities.

Higher-resolution VIS and NIR data (<5 m) can be obtained by spaceborne systems such as IKONOS and QuickBird that permit the analysis of more detailed land-surface characteristics, including urban environments and impervious surfaces (Boyle et al. 2014). However, to detect finer-scale environmental characteristics especially in VIS and NIR, high-resolution applications are more and more delivered by unmanned air vehicles (UAVs) due to their high flexibility and availability at reduced costs (Colomina and Molina 2014). With this variety of platforms, EO is able to provide information from local to global scale, where the implementation of scaling strategies gains more and more importance (see also Section 11.5).

Although UAVs are able to increase the spatial resolution of multispectral systems, hyperspectral sensors are able to better resolve the electromagnetic spectrum with hundreds of narrow spectral channels (spectral resolution) from VIS to SWIR at moderate spatial resolution (Govender et al. 2007). Currently, the only operational spaceborne imaging spectrometer covering the full spectral range from 4 to 25 nm is EO-1 Hyperion (Pearlman et al. 2003). With this kind of information, for example, different vegetation species can be separated with high accuracy or the health of forests and crops can be estimated. Moreover, hyperspectral systems enable the remote investigation of soil characteristics, such as the soil chemical composition. Specific absorption features deliver information on the iron oxide, organic carbon, or clay fraction, which correlate well with in situ measurements of soil properties (Babaeian et al. 2015; Lagacherie et al. 2012). Currently, for environmental observatories, airborne sensors provide higher spatial resolution at a better signal-to-noise ratio. Available sensors are AISA Eagle/Hawk (Lausch et al. 2013; Feilhauer et al. 2014) and HySpex (Möckel et al. 2014). The new spaceborne Environmental Mapping and Analysis Program is currently built for launch in 2018 (Guanter et al. 2015). Hyperspectral sensors in combination with LIDARs are the key elements of several already institutionalized remote sensing observatories, such as the Carnegie Airborne Observatory (Asner et al. 2012) and the Airborne Observation Platform (AOP) of the National Ecological Observatory Network (NEON, Kampe et al. 2010). In addition to ground measurements, AOP data at submeter to meter spatial scales will help to bridge scales from organism and stand scales to the scale of satellite-based remote sensing.

Although typical hyperspectral sensors record the spectra in bands of 3–25 nm, a special group of hyperspectral remote sensors started recently to operate with ≤1 nm spectral resolution. The reason for this new development is the existence of solar-induced fluorescence. Approximately 82% of the absorbed light in a leaf is used for carbon assimilation while the remaining part is lost as heat and dissipated as emissions of chlorophyll fluorescence. Fluorescence, the radiant flux emitted, is therefore the most direct measurable variable of photosynthetic efficiency (van der Tol et al. 2014). It is obvious that this information is of high value for terrestrial observatories. An airborne remote sensor is the HyPlant system (Rossini et al. 2015), where a typical hyperspectral imager is combined with a fluorescence imager, a special module that acquires data at high spectral resolution (0.25 nm) in the spectral region of the two oxygen absorption bands (670–780 nm) and is dedicated to measure the vegetation fluorescence signal. Recently, with FLEX, the European Space Agency selected this concept to be established on a spaceborne platform to globally record chlorophyll fluorescence on a $300 \times 300\ m^2$ resolution.

Active microwave data (radar) open a large variety of applications by investigating environmental parameters such as terrain elevation change (Montagh et al. 2013) or vegetation structure (Reigber et al. 2000). A widely used further application is the estimation of near-surface soil moisture at the subcatchment to regional scale, exploiting the different dielectric properties of dry soil and liquid water (Kornelsen et al. 2013). Due to the active transmission, the strength of the radar signal is distinctively higher than for passive microwave sensors, which depend on the weak natural emission of radiation from the earth. Therefore, passive MW systems on spaceborne platforms are typically very coarse (>36 × 36 km), so that for terrestrial observatories airborne systems are preferred (Hasan et al. 2014). New generations of radar instruments will become available within the next years, for example, the U.S.–Indian NISAR mission to be launched in 2020 or the German Tandem-L mission (Moreira et al. 2015) for a planned launch in 2024.

Where in some disciplines the forward simulation of the remote sensor record is far advanced, other disciplines still make use of ground-based manual measurements using remotely sensed parameter maps for regionalization and pattern recognition (e.g., Lagacherie et al. 2012). Here, the grand challenge is to develop and employ fully physical forward models describing the radiative transfer processes from the investigated variable to the sensor record.

11.5 Scaling

Upscaling of water, energy, and matter fluxes is challenging as the relevant processes that govern exchange processes between the land and the atmosphere act on very different time scales. This can be nicely illustrated for processes controlling the terrestrial carbon cycle. For example, whereas variability in photosynthetic activity and associated carbon uptake act on very short time scales related to variations in photon flux density (among others), the slow decay of recalcitrant carbon pools acts on time scales of years to decades. Many of these processes are parameterized with semiempirical equations including parameters that are difficult to determine or not easily available (e.g., Weihermueller et al. 2013). Parameter estimation plays therefore an essential role in improving estimates of ecosystem carbon balances and in future projections of the land carbon source or sink term.

For example, Post et al. (2016a) estimated eight sensitive ecosystem parameters of the Community Land Model (CLM) version 4.5 (Oleson et al. 2013) with the help of 1-year-long time series of net ecosystem exchange (NEE), measured by eddy covariance stations in Germany and France. The parameters were estimated by the DREAM$_{ZS}$ algorithm (Laloy and Vrugt 2012; Ter Braak and Vrugt 2008), a Markov chain Monte Carlo–based algorithm, which is particularly CPU efficient. The estimated ecosystem parameters were evaluated with an additional year of NEE data at the same sites. The evaluation was made in terms of the root-mean-square error of 30-minute NEE measurements, the yearly accumulated NEE sum, the mean daily NEE cycle, and the mean annual NEE cycle. The results showed that the estimated parameters reproduced the measured NEE data in the evaluation period better than the default CLM parameters. The estimated ecosystem parameters were also evaluated at other sites, situated ~500 km away from the estimation sites in eastern Germany, with 1 year of measured time series of NEE data. The estimated ecosystem parameters were evaluated at sites that had the same plant functional type (PFT) as the estimation site. Furthermore, at these evaluation sites, it was found that the estimated ecosystem parameters improved the reproduction of the measured NEE data compared to the default ecosystem parameters. Only for grassland sites, no improvement was found.

Finally, the estimated ecosystem parameters were assigned to the different corresponding PFTs of the Rur catchment in western Germany and a CLM simulation was made for the complete catchment (Post et al. 2016b). Moreover, a CLM simulation with the default ecosystem parameters was carried out. The simulated LAI values were compared with the remotely sensed LAI values by RapidEye. The difference between simulated LAI values and measured LAI values was considerably smaller if the estimated ecosystem parameters were used as input.

This study illustrated the potential of upscaling carbon fluxes by measurements of NEE fluxes at single EC towers. It can be expected that the results further improve for longer NEE time series and the inclusion of other data sources like biomass or LAI. Nevertheless, the study also pointed to the fact that although the characterization of the net carbon balance improved with the estimated ecosystem parameters, the optimized parameters also could mask model structural errors. In the context of a European ecosystem infrastructure, it is expected that upscaling would be improved if at existing sites NEE, respiration, biomass, and LAI would be determined simultaneously. A further extension of the network, covering different types of agricultural crops, would also be an advantage.

In order to monitor the processes controlling matter fluxes in soil–plant–atmosphere systems, the described hydrological and carbon monitoring concepts have to be extended by adding other relevant subsystems (e.g., atmosphere) and by a socioeconomic analysis. This may include the identification of socioeconomic drivers that control the intensification and/or deintensification processes (e.g., demographic and technological change) and the feedback to the ecological system (e.g., on the state of soil, water, and air quality) as well as the analysis of ecological impacts of land use changes across and within sectors (e.g., from agricultural to industrial types or from chemical to energy production).

11.6 TERENO Observatory Network in Germany

In the following, we present the TERENO initiative in Germany as an example for a distributed TERI network. The general aim of TERENO is to conduct integrated and long-term observation studies of climate change and global change impacts on terrestrial ecosystems across Germany (Bogena et al. 2012; Zacharias et al. 2011). TERENO combines observations with comprehensive 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 subsystems. Such a combination is needed since the monitoring of terrestrial systems alone is not sufficient to understand the relevant processes of environmental

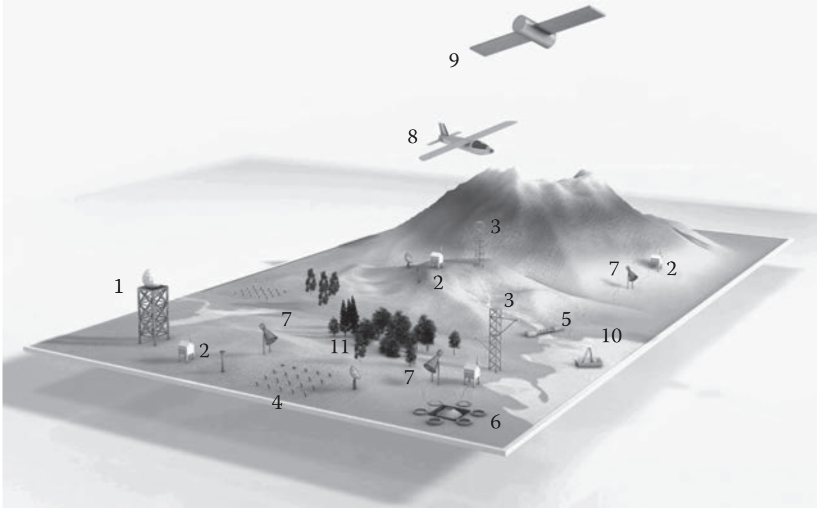

FIGURE 11.1
Schematic view of a typical TERENO observatory platform, including measuring systems for the determination of regional precipitation fields using (1) weather radars and (2) precipitation gauging networks (Diederich et al. 2015), (3) micrometeorological eddy covariance towers (Mauder et al. 2013), (4) sensor networks (Rosenbaum et al. 2012), (5) Runoff monitoring systems (Stockinger et al. 2014), (6) weighable lysimeter systems (Hannes et al. 2015), (7) ground-based and airborne remote sensing platforms, (8) airborne campaigns (Hasan et al. 2014), (9) satellite-borne data (Rötzer et al. 2014), (10) geoarchiving systems (Kienel et al. (2013), and (11) tree growth monitoring systems (Simard et al. 2014).

changes, due to the interrelation of many influencing factors. Within TERENO, four terrestrial observatories were selected because they represent typical landscapes in Germany and other central European countries, which are predicted to be highly vulnerable to the effects of global and climate change. Furthermore, the four terrestrial observatories within these regions can be expected to most appropriately exhibit the dominant terrestrial processes and the different roles of groundwater, surface water, soils, and their links to the atmospheric boundary layer. All of these selected regions either are already affected by climate change or will probably react sensitively in the foreseeable future (e.g., Pfeifer et al. 2015; Vautard et al. 2014). Figure 11.1 gives a schematic overview of the typical instrumentation of a terrestrial observatory as realized in the TERENO network. Mobile measurement platforms are used both for the monitoring of dynamic processes at the local scale and the determination of their spatial patterns at the regional scale.

The TERENO infrastructure is characterized by a high degree of automation and operationalization, for example, for the near-real-time derivation of value-added information products based on in situ data (Borg et al. 2014; Sorg and Kunkel 2015) or on EO data (Missling et al. 2014). During instrumentation of the four terrestrial observatories, local data infrastructures

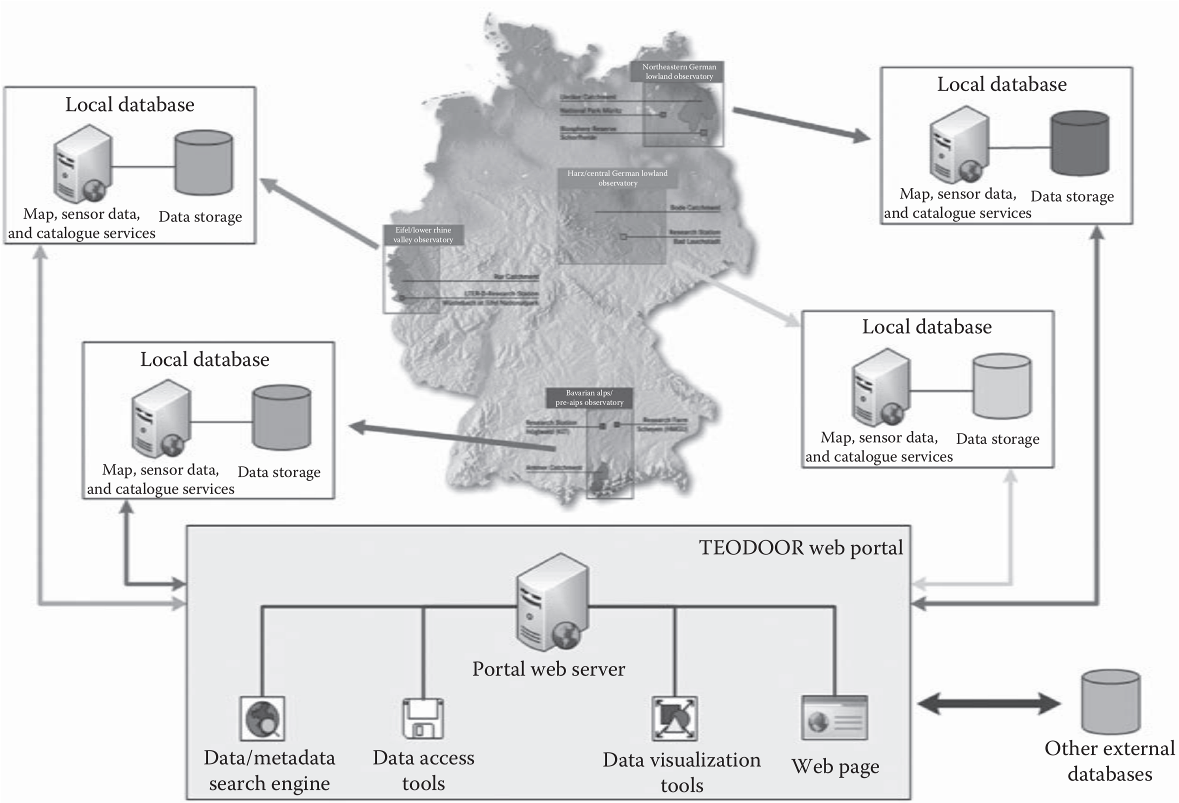

FIGURE 11.2
(**See color insert.**) The design of the TERENO infrastructure for the distribution of the data.

were implemented (Kunkel et al. 2013). The central data portal TEODOOR facilitates the online provision of decentralized TERENO data (Figure 11.2). It is hosted by Forschungszentrum Jülich and can be accessed via https://teodoor.icg.kfa-juelich.de/. TEODOOR uses common standards for the metadata description (e.g., Open Geospatial Consortium [http://www.opengeospatial.org/ogc], Consortium of Universities for the Advancement of Hydrologic Science [https://www.cuahsi.org/#sthash.FcOhNZWf.dpuf]) of data sets based on the INSPIRE directive (2007/2/EC) for spatial data infrastructures (http://inspire.jrc.ec.europa.eu) allowing for a search throughout the entire database. Such standard protocols for accessing environmental data sets are used to guarantee compatibility to the related individual data infrastructures of the TERENO partners. The TEODOOR portal allows versatile community access to data sources. Data governance and data stewardship programs and data architecture and data management programs are much more effective if they are supported by a directive concerning the data management policy. A data policy statement (TERENO, 2015), required for data processing and data exchange, was developed in a common approach by all TERENO partners. A main aspect of the data policy was the definition of the data ownership (intellectual property rights) and data access rights concerning the directives of funding organizations differentiated by types of digital resources, their process status, the data creator, and the data source. As a rule, all data are freely accessible within the TERENO community and accessible also to the public as soon as at least a first quality check was performed on the data and no other usage restrictions are existent, for example, due to ongoing PhD studies or external copyright issues.

11.7 Conclusion

In this chapter, we discussed the challenge in ecosystem research to embrace all subsystems of the terrestrial system in order to better understand the impact of climate and land use change on terrestrial ecosystems. We suggest that a new, multiscale fully integrated TERI network is needed, which capitalizes on the existing experience and knowledge gained from existing networks (e.g., Long-Term Ecological Research, ICOS, NEON) and the recently established critical zone observatories. We advocate that the TERENO example could serve as a blueprint for a distributed TERI as outlined earlier. Such an infrastructure could provide answers to key questions related to ecosystems and terrestrial research from the continental to the global scale, for example, how ecosystems are changing or adapting to global change stressors, identification of the determinants of ecosystem resilience, and threshold interactions resulting in system shifts. In addition, a TERI network can give answers on how to support systems that are more resilient to global change effects and to develop adaptive measures that are needed to sustain ecosystem services.

The ecological science community would strongly benefit from the establishment of a TERI network exploiting the full potential of novel measurement technologies allowing to better falsify hypotheses, to identify underlying organizational principles, to correct biased remote sensing data, and to gain increased insights into the nature of these biases and at the same time reduce the uncertainty in knowledge about states, fluxes, and parameters of the terrestrial system. Linking these observations with remote sensing, large-scale models and data assimilation approaches offer the perspective of predicting the terrestrial water cycle at regional to continental scales or even to global scale.

References

Ali, M., C. Montzka, A. Stadler, G. Menz, F. Thonfeld, and H. Vereecken (2015) Estimation and validation of RapidEye-based time series of leaf area index for winter wheat in the Rur catchment (Germany). *Remote Sensing*, 7(3), 2808–2831.

Allen, D.C., Cardinale, B.J., and Wynn-Thompson, T. (2014) Toward a better integration of ecological principles into ecogeoscience research. *BioScience*, 64, 444–454.

Anderson, J., Martin, M.E., Smith, M-L, Dubayah, R.O., Hofton, M.A., Hyde, P., Peterson, B.E., Blair, J.B., and Knox, R.G. (2006) The use of waveform LIDAR to measure northern temperate mixed conifer and deciduous forest structure in New Hampshire. *Remote Sensing of Environment*, 105, 248–261.

Anselmi, S., Chiesi, M., Giannini, M., Manes, F., and Maselli, F. (2004) Estimation of Mediterranean forest transpiration and photosynthesis through the use of an ecosystem simulation model driven by remotely sensed data. *Global Ecology and Biogeography*, 13, 371–380.

Asner, G.P., Knapp, D.E., Boardman¸ J., Green, R.O., Kennedy-Bowdoin, T., Eastwood, M. et al. (2012) Carnegie airborne observatory-2: Increasing science data dimensionality via high-fidelity multi-sensor fusion. *Remote Sensing of Environment*, 124, 454–465, doi:10.1016/j.rse.2012.06.012.

Asner, G., Scurlock, J.M.O., and Hicke, J.A. (2003) Global synthesis of leaf area index observations: Implications of ecological and remote sensing studies. *Global Ecology and Biogeography*, 12, 191–205.

Baatz, R., Bogena, H., Hendricks Franssen, H.-J., Huisman, J.A., Wei, Q., Montzka, C., and Vereecken, H. (2014) Calibration of a catchment scale cosmic-ray soil moisture network: A comparison of three different methods. *Journal of Hydrology*, 516, 231–244.

Babaeian, E., Homaee, M., Montzka, C., Vereecken, H., and Norouzi, A.A. (2015) Towards estimating soil hydraulic properties by hyperspectral remote sensing. *Vadose Zone Journal*, 14(3). doi:10.2136/vzj2014.07.0080.

Balvanera, P., Siddique, I., Dee, L., Paquette, A., Isbell, F., Gonzalez, A. et al. (2013) Linking biodiversity and ecosystem services: Current uncertainties and the necessary next steps. *BioScience*, 64, 49–57.

Bartuszevige, A.M., Gorchov, D.L., and Raab, L. (2006) The relative importance of landscape and community features in the invasion of an exotic shrub in a fragmented landscape. *Ecography*, 29, 213–222.

Binenko, V.I., Donchenko, V.K., Andreev, V.L., and Ivanov R.V. (2001) Some results and perspectives of using unmanned air vehicles for ecological monitoring tasks. *Ecological Chemistry*, 10, 21–31.

Bogena, H.R., Bol, R., Borchard, N., Brüggemann, N., Diekkrüger, B., Drüe, C. et al. (2015) A terrestrial observatory approach for the integrated investigation of the effects of deforestation on water, energy, and matter fluxes. *Science China: Earth Sciences*, 58(1), 61–75, doi: 10.1007/s11430-014-4911-7.

Bogena, H.R., Herbst, M., Huisman, J.A., Rosenbaum, U., Weuthen, A., and Vereecken, H. (2010) Potential of wireless sensor networks for measuring soil water content variability. *Vadose Zone Journal*, 9(4), 1002–1013, doi:10.2136/vzj2009.0173.

Bogena, H.R., Huisman, J.A., Baatz, R., Hendricks Franssen, H.-J., and Vereecken, H. (2013) Accuracy of the cosmic-ray soil water content probe in humid forest ecosystems: The worst case scenario. *Water Resources Research*, 49(9), 5778–5791, doi: 10.1002/wrcr.20463.

Bogena, H., Kunkel, R., Krüger, E., Zacharias, S., Pütz, T., Schwank, M. et al. (2012) TERENO – Long-term monitoring network for terrestrial research. *Hydrologie und Wasserbewirtschaftung*, 56(3), 138–143.

Bogena, H., Schulz, K., and Vereecken, H. (2006) Towards a network of observatories in terrestrial environmental research. *Advances in Geosciences*, 9, 109–114.

Bohlman, S.A., Adams, J.B., Smith, M.O., and Peterson, D.L. (1998) Seasonal foliage changes in the eastern Amazon Basin detected from Landsat Thematic Mapper satellite images. *Biotropica*, 30, 376–391.

Borg, E., Schiller, C., Daedelow, H., Fichtelmann, B., Jahncke, D., Renke, F., Tamm, H-P., and Asche, H. (2014) Automated generation of value-added products for the validation of remote sensing information based on in-situ data. In Murgante, B. et al. eds., ICCSA 2014, Guimarães, Portugal, June 30–July 3, 2014, *Proceedings Part I*. Vol. 8579 LNCS, Springer, pp. 393–407.

Boyle, S.A., Kennedy, C.M., Torres, J., Colman, K., Pérez-Estigarribia, P.E., and de la Sancha, N.U. (2014) High-resolution satellite imagery is an important yet underutilized resource in conservation biology. *PLoS ONE*, 9(1), e86908.

Burkhard, B., Petrosillo, I., and Costanza, R. (2010) Ecosystem services—Bridging ecology, economy and social sciences. *Ecological Complexity*, 7(3), 257–259.

Burt, T.P., Howden, N.J.K., Worrall, F., and Whelan, M.J. (2008) Importance of long-term monitoring for detecting environmental change: Lessons from a lowland river in South East England. *Biogeosciences*, 5, 1529–1535.

CENR (Committee on Environment and Natural Resources) (1997) Integrating the Nation's environmental monitoring and research networks and program: A proposed framework. *Subcommittee on Ecological Systems*, Washington, DC, 82pp.

CEOS (Committee on Earth Observation Satellites) (2015): Satellite Earth Observations in support of Climate Information Challenges. *The CEOS Earth Observation Handbook*, *Special 2015 COP21 Edition Special*, 37pp.

Clark, J.S., Carpenter, S.R., Barber, M., Collins, S., Dobson, A., Foley, J.A. et al. (2001) Ecological forecasts: An emerging imperative. *Science*, 293, 657–660.

Clevers, J.G.P.W., Schaepman, M.E., Mücher, C.A., de Wit, A.J.W., Zurita-Milla, R., and Bartholomeus, H.M. (2007) Using MERIS on Envisat for land cover mapping in the Netherlands. *International Journal of Remote Sensing*, 28, 637–652.

Colomina, I. and Molina, P. (2014) Unmanned aerial systems for photogrammetry and remote sensing: A review. *ISPRS Journal of Photogrammetry and Remote Sensing*, 92, 79–97, doi:10.1016/j.isprsjprs.2014.02.013.

Davidson, E.A., Trumbore, S.E., and Amundson, R. (2000) Soil warming and organic carbon content. *Nature*, 408, 789–790.

Delegido, J., Verrelst, J., Alonso, L., and Moreno, J. (2011) Evaluation of sentinel-2 red-edge bands for empirical estimation of green LAI and chlorophyll. *Sensors*, 11(7), 7063–7081.

DFG (Deutsche Forschungsgemeinschaft) (2013) Long-term perspectives and infrastructure in terrestrial research in Germany—A systemic approach. DFG-Strategy paper, Bonn, Germany, 29 p. (in German).

Diederich, M., Ryzhkov, A., Simmer, C., Zhang, P., and Troemel, S. (2015) Use of specific attenuation for rainfall measurement at X-band radar wavelengths part I: Radar calibration and partial beam blockage estimation. *Journal of Hydrometeorology*, 16, 487–502.

Diehl, R.H., Larkin, R.P., and Black, J.E. (2003) Radar observations of bird migration over the Great Lakes. *The Auk*, 120, 278–290.

Drusch, M., Del Bello, U., Carlier, S., Colin, O., Fernandez, V., Gascon, F. et al. (2012) Sentinel-2: ESA's optical high-resolution mission for GMES operational services. *Remote Sensing of Environment*, 120, 25–36, doi:10.1016/j.rse.2011.11.026.

Eisele, A., Lau, I., Hewson, R., Carter, D., Wheaton, B., Ong, C., Cudahy, J., Chabrillat, S., and Kaufmann, H. (2012) Applicability of the thermal infrared spectral region for the prediction of soil properties across semi-arid agricultural landscapes. *Remote Sensing*, 4(11), 3265–3286.

Fan, W., Randolph, J.C., and Ehman, J.L. (1998) Regional estimation of nitrogen mineralization in forest ecosystems using geographic information systems. *Ecological Applications*, 8, 734–747.

Feilhauer, H., Dahlke, C., Doktor, D., Lausch, A., Schmidtlein, S., Schulz, G., and Stenzel, S. (2014) Mapping the local variability of Natura 2000 habitats with remote sensing. *Applied Vegetation Science*, 17, 765–779.

Fraser, L.H., Henry, H.A.L., Carlyle, C.N., White, S.R., Beierkuhnlein, C., Cahill, Jr. J.F. et al. (2013) Coordinated distributed experiments: An emerging tool for testing global hypotheses in ecology and environmental science. *Frontiers in Ecology and the Environment*, 11, 147–155.

Ganguly, S., Nemani, R., Zhang, G., Hashimoto, H., Milesi, C., Michaelis, A. et al. (2012) Generating global leaf area index from landsat: Algorithm formulation and demonstration. *Remote Sensing of Environment*, 122, 185–202.

GEOSS (2005) The Global Earth Observation System of Systems (GEOSS) 10-year implementation plan. 11 pp. http://earthobservations.org/

Giardina, C.P. and Ryan, M.G. (2000) Evidence that decomposition rates of organic carbon in mineral soil do not vary with temperature. *Nature*, 404, 858–861.

Govender, M., Chetty, K., and Bulcock, H. (2007) A review of hyperspectral remote sensing and its application in vegetation and water resource studies. *Water SA*, 33, 145–151.

Guanter, L., Kaufmann, H., Segl, K., Förster, S.,Rogass, C., Chabrillat, S. et al. (2015) The EnMAP spaceborne imaging spectroscopy mission for earth observation. *Remote Sensing*, 7(7), 8830–8857.

Haines-Young, R. and Weber, J-L. (2006) *Land Accounts for Europe 1990–2000: Towards Integrated Land and Ecosystem Accounting*. European Environment Agency, Copenhagen, Denmark, ISBN 92-9167-888-0.

Hannes, M., Wollschläger, U., Schrader, F., Durner, W., Gebler, S., Pütz, T., Fank, J., von Unold, G., and Vogel, H.-J. (2015) High-resolution estimation of the water balance components from high-precision lysimeters. *Hydrology and Earth System Science*, 19, 3405–3418.

Hasan S., Montzka, C., Rüdiger, C., Ali, M., Bogena, H., and Vereecken, H. (2014) Soil moisture retrieval from airborne L-band passive microwave using high resolution multispectral data. *Journal of Photogrammetry and Remote Sensing*, 91, 59–71.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States—Representing a decade of land cover change information. *Journal of Photogrammetry and Remote Sensing*, 81(5), 345–354.

Huisman, J.A., Sperl, C., Bouten, W., and Verstraten, J.M. (2001) Soil water content measurements at different scales: accuracy of time domain reflectometry and ground-penetrating radar. *Journal of Hydrology*, 245, 48–58.

Inagaki, M.N., Fukatsu, T., Hirafuji, M., and Nachit, M.M. (2011) Monitoring soil moisture under wheat growth through a wireless sensor network in dry conditions. *Journal of Environmental Science and Engineering*, 5, 428–431.

IPCC (Intergovernmental Panel on Climate Change) (2013) Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.), *Climate Change 2013: The Physical Science Basis*, 1535 pp. Cambridge University Press, Cambridge, United Kingdom and New York, NY.

Irons, J.R., Dwyer, J.L., and Barsi, J.A. (2012) The next Landsat satellite: The Landsat data continuity mission. *Remote Sensing of Environment*, 122, 11–21, doi:10.1016/j.rse.2011.08.026.

Jagdhuber, T., Hajnsek, I., and Papathanassiou, K. (2015) An iterative generalized hybrid decomposition for soil moisture retrieval under vegetation cover using fully polarimetric SAR. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 8(8), 3911–3922.

Jensen, K.H. and Illangasekareb, T.H. (2011) HOBE: A hydrological observatory. *Vadose Zone Journal*, 10(1), 1–7.

Jones, K.B., Bogena, H., Vereecken, H. and Weltzin, J.F. (2010) Design and importance of multi-tiered ecological monitoring networks. In Mueller F. et al. (eds.), *Long-Term Ecological Research: Between Theory and Application*, pp. 355–374, Springer, Dordrecht, the Netherlands.

Jones, K.B., Nash, M.S., Wade, T.G., Walker, J., Neale, A.C., Müller, F. et al. (2008) Cross-European landscape analyses: Illustrative examples using existing spatial data. In Petrosillo, I. et al. (eds.), *Use of Landscape Sciences for the Assessment of Environment Security*, pp. 258–316, Springer, Dordrecht, the Netherlands.

Jongman, R.H.G., Bunce, R.G.H., Metzger, M.J., Mucher, C.A., Howard, D.C., and Mateus, V.L. (2006) Objectives and applications of a statistical environmental stratification of Europe. *Landscape Ecology*, 21, 409–419.

Kampe, T.U., Johnson, B.R., Kuester, M., and Keller, M. (2010) NEON: The first continental-scale ecological observatory with airborne remote sensing of vegetation canopy biochemistry and structure. *Journal of Applied Remote Sensing*, 4(1), 043510, doi: 10.1117/1.3361375.

Kastens, J.H., Price, K.P., Kastens, D.L., and Martinko, E.A. (2001) Forecasting preharvest crop yields using time series analysis of AVHRR NDVI composite imagery. *Proceedings, Annual Convention. American Society of Photogrammetric Engineering and Remote Sensing*, St. Louis, MO, April 23–27, 2001.

Katul, G.G., Oren, R., Manzoni, S., Higgins, C., and Parlange, M.B. (2012) Evapotranspiration: A process driving mass transport and energy exchange in the soil–plant-atmosphere-climate system. *Reviews of Geophysics*, 50, 1–25.

Kerr, J.T., Kharouba, H.M., and Currie, D.J. (2007) The macroecological contribution to global change. *Science*, 316, 1581–1584.

Kienel, U., Dulski, P., Ott, F., Lorenz, S., and Brauer, A. (2013) Recently induced anoxia leading to the preservation of seasonal laminae in two NE-German lakes. *Journal of Paleolimnology*, 50(4), 535–544.

Kornelsen, K.C. and Coulibaly, P. (2013) Advances in soil moisture retrieval from synthetic aperture radar and hydrological applications. *Journal of Hydrology*, 476, 460–489.

Korres, W., Reichenau, T.G., Fiener, P., Koyama, C.N., Bogena, H.R., Cornelissen, T. et al. (2015) Spatio-temporal soil moisture patterns—A meta-analysis using plot to catchment scale data. *Journal of Hydrology*, 520, 934–946.

Krajewski, W.F., Anderson, M.C., Eichinger, W.E., Entekhabi, D., Hornbuckle, B.K., Houser, P.R. et al. (2006) A remote sensing observatory for hydrologic sciences: A genesis for scaling to continental hydrology. *Water Resources and Research*, 42, W07301.

Krischke, M., Niemeyer, W., and Scherer, S. (2000) RapidEye – Satellite based geo-information system. *Acta Astronaut*, 46, 307–312. doi: 10.1016/s0094-5765(99)00219-2.

Kunkel, R., Sorg, J., Eckardt, R., Kolditz, O., Rink, K., and Vereecken, H. (2013) TEODOOR: A distributed geodata infrastructure for terrestrial observation data. *Environmental Earth Sciences*, 69, 507–521.

Kurt, W., He, G., Kollet, S., Maxwell, R., Vereecken, H., and Hendricks Franssen, H.J. (2016) TerrSysMP-PDAF (version 1.0): A modular high performance data assimilation framework for an integrated land surface-subsurface model. *Conditionally accepted for publication in Geoscientific Model Development.*

Lagacherie, P., Bailly, J.S., Monestiez, P., and Gomez, C. (2012) Using scattered hyperspectral imagery data to map the soil properties of a region. *European Journal of Soil Science*, 63, 110–119.

Laloy, E. and Vrugt, J.A. (2012) High-dimensional posterior exploration of hydrologic models using multiple-try DREAM(ZS) and high-performance computing. *Water Resources Research*, 48, doi:10.1029/2011WR010608.

Lausch, A., Blaschke, T., Haase, D., Herzog, F., Syrbe, R.-U., Tischendorf, L., and Walz, U. (2015) Understanding and quantifying landscape structure—A review on relevant process characteristics, data models and landscape metrics. *Ecological Modelling*, 295, 31–41.

Lausch, A., Zacharias, S., Dierke, C., Pause, M., Kühn, I., Doktor, D., Dietrich, P., and Werban, U. (2013) Analysis of vegetation and soil pattern using hyperspectral remote sensing, EMI and gamma ray measurements. *Vadose Zone Journal*, 12, 4, doi:10.2136/vzj2012.0217.

Loescher, H.W., Jacobs, J., Wendroth, O., Robinson, D.A., Poulos, G.S., McGuire, K., Reed, P., Mohanty, B., and Krajewski, W. (2007) Enhancing water cycle measurements for future hydrologic research. *Bulletin of the American Meteorological Society*, 88, 669–676, doi: 101175/BAMS-88-5-669.

Loveland, T.R., Sohl, T.L., Stehman, S.V., Gallant, A.L., Sayler, K.L., and Napton, D.E. (2002) A strategy for estimating the rates of recent United States land-cover changes. *Photogrammetric Engineering and Remote Sensing*, 68, 1091–1099.

Lupo, F., Linderman, M. Vanacker, V. Bartholome, E., and Lambin, E.F. (2007) Categorization of land-cover change processes based on phenological indicators extracted from time series of vegetation index data. *International Journal of Remote Sensing*, 11–12, 2469–2483.

Mauder, M., Cuntz, M., Drüe, C., Graf, A., Rebmann, C., Schmid, H.P., Schmidt, M., and Steinbrecher, R. (2013) A strategy for quality and uncertainty assessment of long-term eddy-covariance measurements. *Agricultural and Forest Meteorology*, 169, 122–135.

McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., and White, K.S. (2001) *Climate Change Impacts, Adaptation, and Vulnerability. IPCC Third Assessment Report*, Cambridge University Press, Cambridge, UK.

Millennium Ecosystem Assessment (MEA). (2005) *Ecosystems and Human Well-Being: Synthesis*. Island Press, Washington, DC.

Möckel, T., Dalmayne, J., Prentice, H.C., Eklundh, L., Purschke, O., Schmidtlein, S. and Hall, K. (2014) Classification of grassland successional stages using airborne hyperspectral imagery. *Remote Sensing*, 6, 7732–7761.

Montzka, C., Bogena, H.R., Weihermueller, L., Jonard, F., Bouzinac, C., Kainulainen, J. et al. (2013) Brightness temperature and soil moisture validation at different scales during the SMOS validation campaign in the Rur and Erft catchments, Germany. *IEEE Transactions on Geoscience and Remote Sensing*, 51(3), 1728–1743.

Montzka C., Pauwels, V.R.N., Hendricks Franssen, H.-J., Han, X., and Vereecken, H. (2012) Multivariate and multiscale data assimilation in terrestrial systems: A review. *Sensors*, 12(12), 16291–16333, doi:10.3390/s121216291.

Moreira, A., Krieger, G., Hajnsek, I., Papathanassiou, K., Younis, M., Lopez-Dekker, P. et al. (2015) Tandem-L: A highly innovative bistatic SAR mission for global observation of dynamic processes on the earth's surface. *IEEE Geoscience and Remote Sensing Magazine (GRSM)*, 3(2), 8–23.

Motagh, M., Wetzel, H.-U., Roessner, S., and Kaufmann, H. (2013) A TerraSAR-X InSAR study of landslides in southern Kyrgyzstan, Central Asia. *Remote Sensing Letters*, 4(7), 657–666.

Müller, B., Bernhardt, M., and Schulz, K. (2014) Identification of catchment functional units by time series of thermal remote sensing images. *Hydrology and Earth System Sciences* 18(12), 5345–5359.

Oleson, K., Lawrence, D.M., Bonan, G.B., Drewniak, B., Huang, M., Koven, C.D. et al. (2013) Technical description of version 4.5 of the Community Land Model (CLM). *NCAR Technical Notes*, Boulder, CO, pp. 420.

Ollinger, S.V., Aber, J.D., and Federer, C.A. (1998) Estimating regional forest productivity and water yield using an ecosystem model linked to GIS. *Landscape Ecology*, 13, 323–334.

Pearlman, J.S., Barry, P.S., Segal, C.C., Shepanski, J., Beiso, D. and Carman, S.L. (2003) Hyperion, a space-based imaging spectrometer. *IEEE Transactions on Geoscience Remote Sensing*, 41(6), 1160–1173.

Peters, D.P.C., Loescher, H.W., SanClements, M.D., and Havstad, K.M. (2014) Taking the pulse of a continent: Role of observatories and long-term research networks to fill critical knowledge gaps. *Ecosphere*, 5(3), 1–23.

Pfeifer, S., Bülow, K., Gobiet, A., Hänsler, A., Mudelsee, M., Otto, J., Rechid, D., Teichmannand, C., and Jacob, D. (2015) Robustness of projected changes in seasonal and extreme precipitation from different ensembles of regional climate change simulations for Germany. *Atmosphere*, 6(5), 677–698.

Post, H., Hendricks Franssen, H.J., Han, X., Baatz, R., Montzka, C., Schmidt, M., and Vereecken, H. (2016b) Upscaling of net carbon fluxes from the plot scale to the catchment scale: Evaluation with NEE and LAI data. *Submitted to Biogeosciences*.

Post, H., Vrugt, J.A., Fox, A., Kumbhar, P., Vereecken, H., and Hendricks Franssen, H.J. (2016a) Estimation of Community Land model parameters with DREAM(ZS) for an improved assessment of net carbon fluxes at European sites. *Submitted to Journal of Geophysical Research-Biogeosciences*.

Powlson, D. (2005) Will soil amplify climate change? *Nature*, 433, 204–205.

Qu, Y., Han, W., and Ma, M. (2015) Retrieval of a temporal high-resolution leaf area index (LAI) by combining MODIS LAI and ASTER reflectance data. *Remote Sensing*, 7, 195–210.

Ramsey III, E., Rangoonwala, A., and Ehrlich, R. (2005) Mapping the invasive species, Chinese Tallow with EO1 satellite Hyperion hyperspectral image data and relating tallow percent occurrences to a classified Landsat Thematic Mapper landcover map. *International Journal of Remote Sensing*, 26,1637–1657.

Reigber, A. and Moreira, A. (2000) First demonstration of airborne SAR tomography using multibaseline L-band data. *IEEE Transactions on Geoscience and Remote Sensing*, 38, 44–46.

Rosenbaum, U., Bogena, H.R., Herbst, M., Huisman, J.A., Peterson, T.J., Weuthen, A., Western, A., and Vereecken, H. (2012) Seasonal and event dynamics of spatial soil moisture patterns at the small catchment scale. *Water Resources Research*, 48(10), W10544.

Rossini, M., Nedbal, L., Guanter, L., Ac, A., Alonso, L., Burkart, A. et al. (2015) Red and far red Sun-induced chlorophyll fluorescence as a measure of plant photosynthesis. *Geophysial Research Letters*, 42(6), 1632–1639.

Rötzer, K., Montzka, C., Bogena, H., Wagner, W., Kidd, R., and Vereecken, H. (2014) Catchment scale validation of SMOS and ASCAT soil moisture products using hydrological modelling and temporal stability analysis. *Journal of Hydrology*, 519, 934–946.

Rudolph, S., van der Kruk, J., von Hebel, C., Ali, M., Herbst, M., Montzka, C., Pätzold, S., Robinson, D.A., Vereecken, H., and Weihermüller, L. (2015) Linking satellite derived LAI patterns with subsoil heterogeneity using large-scale ground-based electromagnetic induction measurements. *Geoderma*, 241–242, 262–271.

Running, S.W., Nemani, R.R., Heinsch, F.A., Zhao, M., Reeves, M., and Hashimoto, H. (2004) A continuous satellite-derived measure of global terrestrial primary production. *BioScience*, 54, 547–560.

Sawaya, K.E., Olmanson, L.G., Heinert, N.J., Brezonik, P.L., and Bauer, M.E. (2003) Extending satellite remote sensing to local scales: Land and water resource monitoring using high-resolution imagery. *Remote Sensing of Environment*, 88, 144–156.

Scholes, R.J., Walters, M., Turak, E., Saarenmaa, H., Heip, C.H.R., Tuama, E.O. et al. (2012) Building a global observing system for biodiversity. *Current Opinion in Environmental Sustainability*, 4, 1–8.

Simard, S., Blume, T., Heidbüchel, I., Heinrich, I., Dreibrodt, J., Güntner, A., and Helle, G. (2015) Interactions and feedbacks of a temperate lake ecosystem in NE Germany. *Geophysical Research Abstracts*, 17, EGU2015-10912.

Simmer, C., Thiele-Eich, I., Masbou, M., Amelung, W., Bogena, H., Crewell, S. et al. (2015) Monitoring and modeling the terrestrial system from pores to catchments – the transregional collaborative research center on patterns in the soil-vegetation-atmosphere system. *Bulletin of the American Meteorological Society*, 96, 1765–1787.

Šimůnek, J., van Genuchten, M.Th., and Šejna, M. (2008) Development and applications of the HYDRUS and STANMOD software packages and related codes. *Vadose Zone Journal*, 7, 587–600.

Smith, R.A., Alexander, R.B., and Schwarz, G.E. (2003) Natural background concentrations of nutrients in streams and rivers of the conterminous United States. *Environmental Science and Technology*, 37, 3039–3047.

Sorg, J. and Kunkel, R. (2015) Conception and implementation of an OGC-compliant sensor observation service for a standardized access to raster data. *ISPRS International Journal of Geo-Information,* 2015(4), 1076–1096.

Stockinger, M., Bogena, H., Lücke, A., Diekkrüger, B., Weiler, M., and Vereecken, H. (2014) Seasonal soil moisture patterns control transit time distributions in a forested headwater catchment. *Water Resources and Research*, 50(6), 5270–5289.

Ter Braak, C.J.F. and Vrugt, J.A. (2008) Differential Evolution Markov Chain with snooker updater and fewer chains. *Statistics and Computing,* 18, 435–446. doi:10.1007/s11222-008-9104-9.

TERENO (2015) TERENO Data policy. http://teodoor.icg.kfa-juelich.de/downloads/TERENO Data policy.pdf/ (accessed 20 Nov 2015).

Treuhaft, R.N., Asner, G.P., Law, B.E., and Van Tuyl, S. (2002) Forest leaf area density profiles from the quantitative fusion of radar and hyperspectral data. *Journal of Geophysical Research-Atmospheres*, 107(D21), 4568–4578.

UNEP and WMO (2011) *Integrated Assessment of Black Carbon and Tropospheric Ozone, Summary for Decision Makers*, http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_SDM.pdf (accessed 4 Feb 2016).

van der Tol, C., Verhoef, W., Timmermans, J., Verhoef, A., and Su, Z. (2009) An integrated model of soil-canopy spectral radiances, photosynthesis, fluorescence, temperature and energy balance. *Biogeosciences*, 6, 3109–3129.

Vautard, R., Gobiet, A., Sobolowski, S., Kjellstroem, E., Stegehuis, A., Watkiss, P. et al. (2014) The European climate under a 2°C global warming. *Environmental Research Letter*, 9, doi:10.1088/1748-9326/9/3/034006.

Vereecken, H., Huisman, J.A., Hendricks Franssen, H.J., Brüggemann, N., Bogena, H.R., Kollet, S., Javaux, M., van der Kruk, J., and Vanderborght, J. (2015) Soil hydrology: Recent methodological advances, challenges, and perspectives. *Water Resources Research*, 51, 2616–2633.

Vereecken, H., Huisman, J.A., Pachepsky, Y., Montzka¸ C., van der Kruk, J., Bogena, H., Weihermueller, L., Herbst, M., Martinez, G., and Vanderborght, J. (2014) On the spatio-temporal dynamics of soil water content at the field scale. *Journal of Hydrology*, 516, 76–96.

Verrelst, J., Camps-Valls, G., Munoz-Mari, J., Rivera, J.P., Veroustraete, F., Clevers, J.G.P.W., and Moreno, J. (2015) Optical remote sensing and the retrieval of terrestrial vegetation bio-geophysical properties—A review. *ISPRS Journal of Photogrammetry and Remote Sensing*, 108, 273–290. doi:10.1016/j.isprsjprs.2015.05.005.

Walker J.P., Houser, P.R., and Willgoose, G.R. (2004) Active microwave remote sensing for soil moisture measurement: a field evaluation using ERS-2. *Hydrologic Processes*, 1811, 1975–1997.

Weihermueller, L., Graf, A., Herbst, M., and Vereecken, H. (2013) Simple pedotransfer functions to initialize reactive carbon pools of the RothC model. *European Journal of Soil Science*, 64(5), 567–575.

Weihermueller, L., Huisman, J.A., Graf, A., Herbst, M., and Vereecken, H. (2009) Multistep outflow experiments for the simultaneous determination of soil physical and carbon dioxide production parameters. *Vadose Zone Journal*, 8, 772–782.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., and Swetnam, T.W. (2006) Warming and earlier spring increases western U.S. forest wildlife activity. *Science*, 313, 940–943.

Yamaguchi, Y., Kahle, A.B., Tsu, H., Kawakami, T., and Pniel, M. (1998) Overview of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). *IEEE Transactions on Geoscience and Remote Sensing*, 36, 1062–1071. doi:10.1109/36.700991.

Young, S.S. and Harris, R. (2005) Changing patterns of global-scale vegetation photosynthesis, 1982–1999. *International Journal of Remote Sensing*, 26, 4537–4563.

Zacharias, S., Bogena, H., Samaniego, L., Mauder, M., Fuß, R., Pütz, T., Frenzel, M. et al. (2011) A network of terrestrial environmental observatories in Germany. *Vadose Zone Journal*, 10(3), 955–973.