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Special Section: Hydrological Observatories

Core Ideas

- TERENO-NE investigates the regional impact of global change.
- We facilitate interdisciplinary geo-ecological research.
- Our data sets comprise monitoring data and geoarchives.
- We are able to bridge time scales from minutes to millennia.

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Interdisciplinary Geo-ecological Research across Time Scales in the Northeast German Lowland Observatory (TERENO-NE)

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The Northeast German Lowland Observatory (TERENO-NE) was established to investigate the regional impact of climate and land use change. TERENO-NE focuses on the Northeast German lowlands, for which a high vulnerability has been determined due to increasing temperatures and decreasing amounts of precipitation projected for the coming decades. To facilitate in-depth evaluations of the effects of climate and land use changes and to separate the effects of natural and anthropogenic drivers in the region, six sites were chosen for comprehensive monitoring. In addition, at selected sites, geoarchives were used to substantially extend the instrumental records back in time. It is this combination of diverse disciplines working across different time scales that makes the observatory TERENO-NE a unique observation platform. We provide information about the general characteristics of the observatory and its six monitoring sites and present examples of interdisciplinary research activities at some of these sites. We also illustrate how monitoring improves process understanding, how remote sensing techniques are fine-tuned by the most comprehensive ground-truthing site DEMMIN, how soil erosion dynamics have evolved, how greenhouse gas monitoring of rewetted peatlands can reveal unexpected mechanisms, and how proxy data provides a long-term perspective of current ongoing changes.

Abbreviations: DEMMIN, Durable Environmental Multidisciplinary Monitoring Information Network; DIC, dissolved organic carbon; DLR, Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center); DOC, dissolved organic carbon; ET evapotranspiration; GFZ, German Research Center for Geosciences; GNIP, Global Network for Isotopes in Precipitation; OSL, optically stimulated luminescence; SOC, soil organic carbon; TERENO, Terrestrial Environmental Observatories.

Human societies are facing ongoing climate change, and it is obvious that this change has various manifestations across spatial and temporal scales (e.g., Luterbacher et al., 2004; Schönwiese, 2008; Büntgen et al., 2013). The scientific community has responded to these changes by performing dedicated experiments (e.g., Osmond et al., 2004; Knorr et al., 2005) and by establishing regional environmental research networks to monitor, analyze, and predict the impact of climate change on different compartments and matter cycles of the Earth's environment, e.g., the International Long-Term Ecological Research Network (ILTER) (Vanderbilt and Gaiser, 2017) and the TERrestrial ENvironmental Observatories (TERENO) (Zacharias et al., 2011).

Uncertainties of climate impact projections are large and point to the need to better understand past and current impacts to constrain impact assessments for the coming decades. One of the first results obtained by TERENO was the observation that a decadal trend of lake level decline in this region, which seemingly supported the worst climate change impact scenarios, came to an abrupt end in 2011 (Kaiser et al., 2014a). Lake levels and groundwater tables in Northeast Germany had decreased since the early 1990s. This alarming trend led to modeling studies on the consequences of climate change for the regional water balance and water supply (e.g., Gerstengarbe et al., 2003; Rachimow et al., 2008; Germer et al., 2011; Hattermann et al., 2011; Lischeid and Natkhin, 2011). Scenarios of savannah-like aridification with bleak consequences for the water balance, agriculture, forestry, and ecosystems disseminated by the media unsettled local stakeholders. The decrease was in line with the model scenarios projecting drier conditions for large parts of Northeast Germany for the 21st century (Zebisch et al., 2005). However, in 2011 this trend stopped and reversed due to a sustained increase in precipitation, especially in summer (Schumann et al., 2013; Miegel et al., 2014). Within 3 yr, lake levels recovered; however, since 2013 lake levels have started to decline again. This poorly understood short-term variability (Richter, 1997) discloses the lack of knowledge of ongoing processes of landscape change. Clearly, it exemplifies how extreme events can change a system substantially. It also indicates the existence of various regional to global forcing factors operating in frequency domains spanning from seasons to several decades and probably even centuries. To comprehensively understand the water budget and its dynamics in all compartments including the hydrosphere, atmosphere, biosphere and pedosphere, better process understanding and information on all time scales are urgently needed, especially on a regional scale (Blöschl et al., 2013; Hüttl et al., 2011).

The observatory TERENO-NE has been set up to focus on the northeastern German lowlands, for which a high vulnerability to climate change is expected. The effects of increasing temperatures and low amounts of precipitation projected for the coming decades are amplified by soils exhibiting relatively low water storage capacities (Hattermann et al., 2011; Buth et al., 2015) and drought-related effects, for example increasing water repellency (Buczko et al., 2007; Lemmnitz et al., 2008). The warmer and drier climate in the Northeast German lowlands is predicted to result in an increasingly negative climatic water balance for this region (Germer et al., 2011; Grünewald et al., 2012; Buth et al., 2015).

The general research focus within TERENO-NE and the overarching theme of all study sites presented here concentrate on the potential impacts of climate and land use changes on regional water and material cycles. The aim is to provide multi-spatial and multitemporal scale monitoring data as well as experiments and modeling frameworks that help to derive a better understanding of the influence of climate and land use change on the regional terrestrial environment. The research of TERENO-NE also comprises the investigation of long proxy records of climate change and landscape evolution derived from natural archives such as lake sediments and tree rings.

Observed recent trends can be reliably evaluated only in the context of profound knowledge of long-term trends and their underlying processes. Instrumental time series are too short to reflect the entire range of processes and amplitudes of natural and anthropogenic changes. Achieving reliable projections for possible future changes, therefore, necessitates a process-based understanding of the dynamics of the climate system and its impact on the geo-, bio-, pedo-, and hydrospheres (Wanner, 2016). The use of natural archives allows us to investigate landscape change under warmer climatic boundary conditions in the past as an analog for possible future scenarios. Natural archives such as lake sediments and tree rings are at the crucial interfaces of the hydrological and nutrient cycles and record regional changes in the thermal regime, the precipitation variability, the dynamics of surface and subsurface runoff systems and of erosion and sediment transport processes, as well as of evapotranspiration (ET). In addition to the natural driving mechanisms, anthropogenic influences on the landscape have been substantial, especially since the beginning of agriculture. Changes in land use and settlement strategies had long-lasting effects on landscape development (Vavrus et al., 2008). In the last centuries, major changes in the hydrological systems such as intensive drainage as well as floodplain sedimentation of eroded soils resulted in the present-day landscape. These anthropogenic changes are an important factor that control landscape responses to the assumed drier climate in the coming decades (Raab et al., 2008; Kaiser et al., 2012b).

Because the effects of climate change are expected to occur on all time scales, monitoring and experimental sites in TERENO-NE were designed so that they are able to detect and quantify both short- and long-term effects and impacts on the terrestrial system. The long-term focus facilitates in-depth evaluations of the effects of regional and global as well as natural and anthropogenic changes in the northeastern German lowlands and help to develop technological, political, and economic instruments for mitigation and adaptation strategies (Bens et al., 2012).

Here we present the Northeast German Lowland Observatory TERENO-NE operated since 2010 by the Helmholtz Centre Potsdam—German Research Centre for Geosciences (GFZ). Our aim is to provide a general overview and description of the research concept and monitoring program with the main components of the current infrastructure. Furthermore, selected examples are provided of the interdisciplinary research in TERENO-NE aiming to advance our comprehension of complex regional water and material cycles.

The Observatory TERENO-NE

Large parts of northeastern Germany are dominated by a geologically young lowlands landscape that formed after the retreat of the Fennoscandian inland ice about 20,000 to 15,000 yr ago and experienced diverse landscape dynamics afterward (Böse et al., 2012; Kappler et al., 2018a). Glacial deposits of Weichselian age are widespread, with different landforms dominantly consisting of sand and loam. Typical features are lakes, peatlands, and kettle holes (Böse, 2005; Lischeid et al., 2018). The main parent materials for soil development are glaciofluvial sandy deposits and sandy loamy glacial diamictons (tills). The resulting soil types at dry sites, e.g., on moraines, till, and outwash plains, are mainly Cambisols, Luvisols, and Podzols, characterized by generally lower water-holding capacities. At slightly wetter sites, e.g., in river and lake basins as well as in peatlands, Gleysols and Histosols occur (European Soil Bureau Network, 2005). The regional climate is generally characterized by relatively dry conditions, with annual sums of precipitation of around 600 mm and mean annual temperatures of about 7.5°C (Deutscher Wetterdienst, 2017). The difference between the absolute minimum (−24.1°C) and maximum temperatures (34.9°C) is an indicator of subcontinentality, although according to the Köppen climate classification the area has a maritime temperate climate (Cfb). While parts of the TERENO-NE observatory are heavily impacted by anthropogenic influences (e.g., large monoculture farms and forests, vast drained peatlands), others are unique near-natural habitats, some of them registered in the UNESCO World Heritage list (e.g., Müritz National Park).

A specific requirement for a "multi-impact" observatory like TERENO-NE with its inherent complexity is the need to observe and investigate a broad variety of processes in river catchments and in different subsystems including lake and peat systems, soils, and forests, with different degrees of human interference ranging from near-natural landscapes to intensive agricultural land use, and at different spatial and temporal scales.

Obviously, this variety of landscape features and processes cannot be captured at only one location. Instead, a network of monitoring stations according to the specific requirements of each research question and related work package was selected.

The network consists of the peatland Hütelmoor, a coastal mire at the Baltic Sea, the Polder Zarnekow, a flow-through fen in the catchment of the Peene River, the DEMMIN Test Field site representing a typical agricultural landscape, Lake Tiefer See, selected for its unusual depth of 63 m, Lake Fürstenseer See–Hinnensee surrounded by near-natural forests in the Müritz National Park, and the peaty kettle hole near the hamlet Christianenhof located in the Quillow River catchment (Fig. 1; Table 1 and Supplemental Table S1). In addition, within the monitoring network, natural archives (lake sediments, tree rings, and soil profiles) were explored at the Lakes Tiefer See and Fürstenseer See–Hinnensee as well as in the Quillow River catchment.

Research in TERENO-NE

Water Level Dynamics of a Lake-Dominated Landscape: Lake Fürstenseer See–Hinnensee

Lake level variations are an obvious sign of hydrological dynamics. In northeastern Germany, some recent periods of accelerated lake level decrease (1980–2009) led to scientific and public debate about global warming as a cause for the observed change and catastrophic future scenarios (Germer et al., 2011; Kaiser et al., 2012a, 2014a). Already during this debate it appeared that a decadal-scale trend of decreasing lake levels was reversed by a short-term level increase within 2 yr between 2010 and 2012 (Fig. 2), suggesting that lake level change is not simply related to climate but triggered by a complex process chain and that such changes occur at various time scales. The main TERENO-NE site for investigating lake level dynamics is Lake Fürstenseer See–Hinnensee because this lake system has been shown to be particularly sensitive with respect to modern lake level fluctuations and because it has a long record of lake levels and groundwater levels (Heine et al., 2015; Kaiser et al., 2015a; Stüve, 2015).

Located in the forested area of Serrahn, an eastern subsection of the Müritz National Park, Lake Fürstenseer See–Hinnensee is a complex lake basin formed during and after meltdown of the Weichselian ice sheet in the direct forefront of the Pommerian ice margin (Börner, 2015). This outwash plain area is characterized by glaciofluvial sandy, partly gravelly sediments; aeolian and colluvial sands sporadically appear near the shore (Kaiser et al., 2014b). The dimictic lake is located at 63.7 m asl, with a surface area of approx. 2.4 km^2 and a volume of 17.4 million m^3, a perimeter of 19.9 km, a maximum water depth of 25 m, and a mean depth of 6.7 m. The landscape around the lake is mostly flat to undulating, but the northern shores are dominated by steep slopes with altitudinal differences of approximately 50 m within a short distance. Because it is a groundwater-fed lake, the lake level is determined by precipitation, evapotranspiration, and the level of the groundwater table. There are no surficial inflows to this naturally closed lake system except in extremely wet years, when ditches deliver very low amounts of water from Lakes Zwirnsee, Schmarsee, and Plasterin-See. The lake has a low ratio of lake to catchment area and therefore shows immediate and significant lake level responses after precipitation (van der Maaten et al., 2015). About 75% of the Serrahn area is covered by beech, oak, and pine forests of different age cohorts. The forest at the northern shore of Lake Hinnensee is an old-growth, near-natural forest composed mainly of the tree species Scots pine (*Pinus sylvestris* L.), sessile oak (*Quercus petraea* Liebl.), and European beech (*Fagus sylvatica* L.). The Grand Dukes of Mecklenburg-Strelitz used the region for hunting, and silvicultural practices were subordinated to this main aim in the 18th century (Tempel, 2003). It was partly declared as protected area and partly as wilderness area in 1961. It became part of Müritz National Park in 1990, and a core zone (2.68 km^2) was declared a UNESCO World Heritage Site in 2011 (Spiess, 2015). Since the 16th to 17th centuries and until 1990, the lake was artificially connected to adjacent lakes for the operation of water mills (Kaiser et al., 2014b).

In the forest at the northern shore of Lake Hinnensee, we use a comprehensive approach integrating instrumental monitoring data (weather and climate, tree growth and sap flow, lake and groundwater levels, soil moisture and soil temperature, forest throughfall and tree stem flow, leaf wetness, and water storage variations from terrestrial gravimetry) with historical information and tree-ring chronologies.

The topographic situation due to steep slopes at the northern end of the lake allows a gradient-based ecohydrological study of tree growth. Trees of the three common species *Pinus sylvestris*,

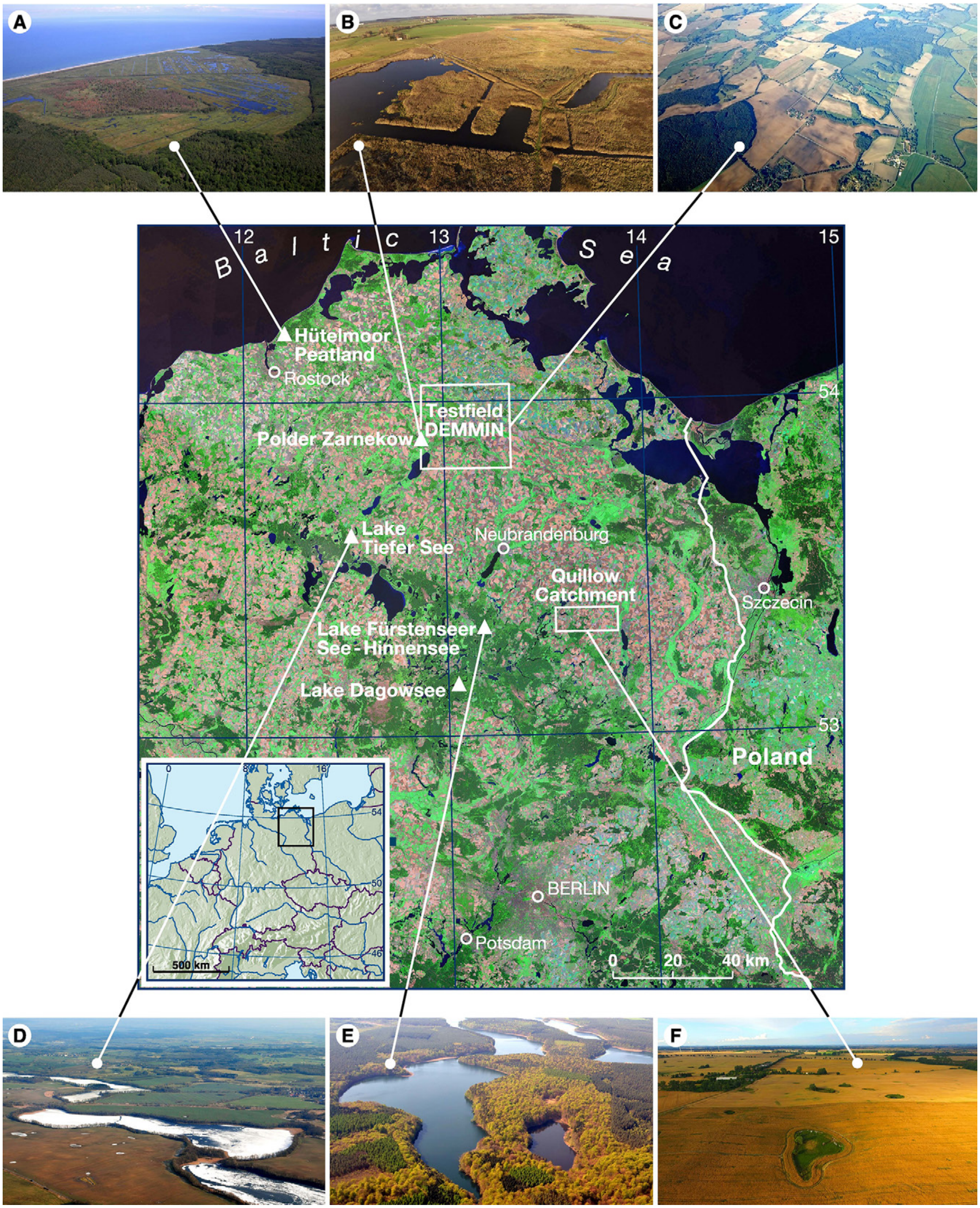

Fig. 1. Map with study and monitoring sites (white frames and triangles) within the Northeast German Lowland Observatory TERENO-NE (satellite data: mosaic of Landsat-ETM scenes 1999–2001, Bands 7,4,2 [RGB]; source: Earth Science Data Interface (ESDI) at the Global Land Cover Facility, 1997–2004, University of Maryland), with aerial views of the TERENO Northeast monitoring sites: (A) Peatland Hütelmoor, a coastal mire at the Baltic Sea rewetted since 1992; (B) Polder Zarnekow, a flow-through fen rewetted since 2004 in the catchment of the Peene River; (C) DEMMIN (Durable Environmental Multidisciplinary Monitoring Information Network) Test field; (D) Lake Tiefer See, part of the Klocksin Lake Chain, a subglacial gully system in the morainic terrain of Mecklenburg, northeastern Germany; (E) Lake Hinnensee, located in the forested area of Serrahn, an eastern subsection of the Müritz National Park; and (F) the Quillow River catchment, located in the Uckermark area, draining to the Baltic Sea—study site Christianenhof with peaty kettle hole. (Photos by Christoph Kappler, Torsten Sachs, Schneeballtoaster CC BY-SA 4.0, Daniel Spengler, Peter Stüve, and Lars Tiepolt).

Table 1. Summary of the research activities in the Northeast German Lowland Observatory TERENO-NE

Site	Objective	Involved disciplines
DEMMIN test field	regional evapotranspiration	remote sensing, pedology, climatology, environmental modeling, soil physics
Quillow River catchment	soil erosion	geomorphology, pedology, climatology, environmental modeling, soil physics
Lake Fürstenseer See–Hinnensee	hydrological dynamics	ecohydrology, biogeochemistry, paleoclimatology, paleohydrology, pedology, tree physiology
Hütelmoor peatland	greenhouse gas fluxes, evapotranspiration, sensible heat	micrometeorology, biogeochemistry, aquatic ecology
Lake Tiefer See	lake level dynamics, varved lake sediment formation	ecohydrology, biogeochemistry, paleoclimatology, paleohydrology, paleobotany, geomorphology
Polder Zarnekow	greenhouse gas fluxes, evapotranspiration, sensible heat	micrometeorology, biogeochemistry, aquatic ecology

Quercus petraea, and *Fagus sylvatica* are growing near the lake close to the groundwater as well as on a steep but stable glacial moraine 10 to 20 m above the groundwater level. The distances between down- and uphill trees are 50 to 150 m. Trees growing near the lake most likely experience wetter soil conditions than trees on the upper parts of the slope, resulting in varying dynamics of water uptake and water stress with varying distance to groundwater.

Trees of all species and topographic positions were equipped with tree physiological monitoring equipment such as point dendrometers (Siegmund et al., 2016) and sap-flow sensors (Peters et al., 2018b). Furthermore, a comprehensive hydro-meteorological monitoring system comprising climate parameters, soil water content, soil water tension, and groundwater levels complemented the forest monitoring (Supplemental Table S1). For example, the link between groundwater and lake was investigated by generating a data set of groundwater inflow rates along most of the shoreline, allowing a view of spatial patterns that are usually hidden from sight (Tecklenburg and Blume, 2017). It was found that while the groundwater is generally flowing into Lake Hinnensee, the hotspots of inflow are at the northern end where the topography is most pronounced.

Besides the monitoring activities, selected trees of the three species were sampled for further dendrochronological analyses. The methods of dendrochronology applied in the current study followed those described by Stokes and Smiley (1968), Fritts (1976), Schweingruber (1983), and Cook and Kairiukstis (1990). Correlation analyses between standardized and age-detrended tree-ring width series and monthly climate and groundwater data were conducted, with the aim to statistically identify the most important growth-limiting factors. Correlations are often low and not significant (Fig. 3). In particular, the broadleaf species *Q. petraea* and *F. sylvatica* did not exhibit significant correlations with the groundwater level. Only *P. sylvestris* showed generally high correlations at the downhill site that were significant in the previous December and current February.

Overall, it is remarkable that all three species showed positive correlations with the groundwater level, suggesting that increased water availability by higher groundwater levels tend to increase tree growth. This is supported by the positive and negative correlation patterns of *F. sylvatica* with precipitation and temperature, respectively. In combination, these patterns suggest that the species' growth is mainly water limited, as similarly reported by Scharnweber et al. (2011) for northeastern Germany. While Scharnweber et al. (2011) stated that lower precipitation also negatively influences the growth of *Quercus robur* L., the correlation patterns of climate and growth for *Q. petraea* only partly suggested water stress. Correlations with precipitation were found to be mainly positive, especially at the uphill site, but correlations with temperature were mixed, significantly both positive and negative.

The precipitation–growth correlation patterns for *P. sylvestris* are more significant at the uphill site, which implies that the uphill trees

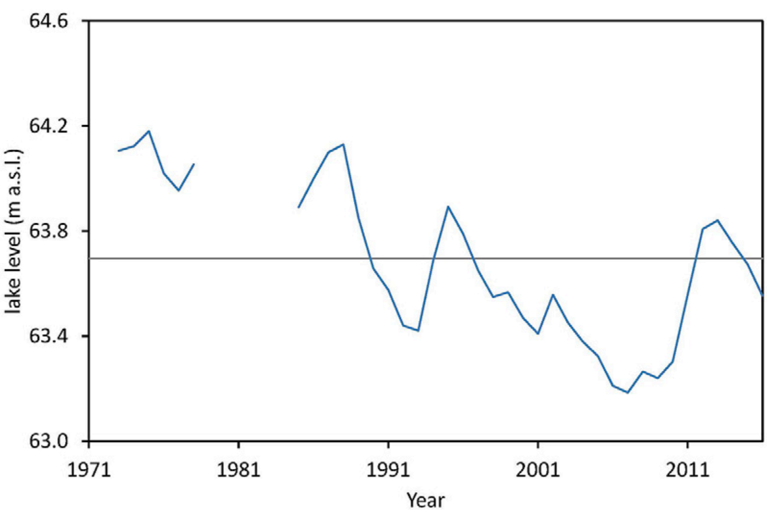

Fig. 2. Lake level of Lake Fürstenseer See, 1972 to 2016 (source: State Agency for Agriculture and Environment, Mecklenburg Lake District).

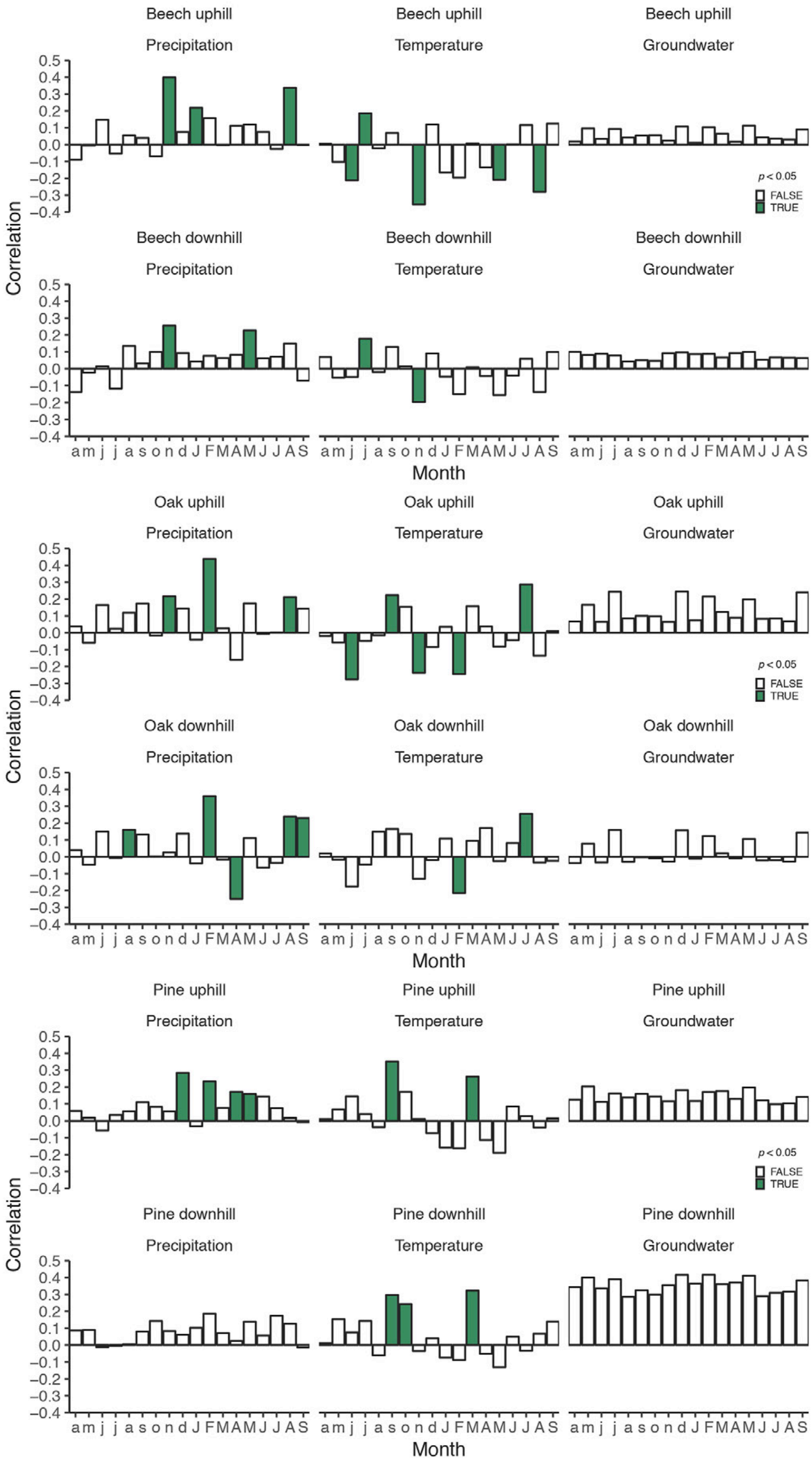

Fig. 3. Climate–growth relationships between tree-ring width and monthly precipitation sums (1900–2016) indicated by Pearson correlation coefficients (*y* axis), monthly means of temperature (1900–2016) and monthly means of groundwater levels (1972–2016) (*x* axis). Lower- and uppercase letters indicate correlations performed with months of the previous and current year, respectively. Green bars indicate significant correlations at $p < 0.05$.

suffer from water stress throughout the growing season. The correlations with temperature for *P. sylvestris* show positive significant values for previous September and October and current May. Correlations during the winter months are nonsignificant but slightly negative. This is in contrast to the results of Balanzategui et al. (2017), who suggested a positive response to high cold-season temperatures for *P. sylvestris* growing under similar site conditions in northern Poland.

While long-term climate–growth correlations are relatively weak for all three species and for both uphill and downhill sites, the direct link between tree water uptake and groundwater can be seen at short time scales such as diurnal variations (Fig. 4). During the daytime, dendrometer and groundwater (sap flow) values decrease (increase), and at nighttime the opposite is true. While during the day trees transpire water through their stomata, the water in the tree stems and in the groundwater directly under the trees cannot be refilled as fast as the water is lost through the leaves into the atmosphere, hence during the day tree stems shrink and groundwater levels decline.

At night, stomata are closed and little water is lost, and thus groundwater levels and tree stem diameter can recover at night (Peters et al., 2018b). This direct connection between trees and groundwater is lost at the uphill site (data not shown here) when the distance between trees and groundwater is larger and the diurnal signal in the groundwater data disappears.

On the one hand, the monitoring data imply a direct connection between groundwater and tree physiology, but on the other hand the statistical analysis of the tree-ring widths and climate as well as hydrological data often does not indicate significant correlations. The correlations with groundwater are only significant for *P. sylvestris* at the downhill site. The discrepancy between monitoring and correlation results needs to be investigated further. In addition, the correlation and regression (not shown here) statistics are too weak for reliable reconstructions. Therefore, in a next step, other tree-ring parameters such as stable isotopes (Schollaen et al., 2014) and wood anatomical cell structures (Liang et al., 2013a, 2013b) need to be explored for stronger and additional climate and hydrological signals contained in the tree rings within TERENO-NE. Recent technical and methodological advances will facilitate the development of long cell structure chronologies. Cell structure measurements will be made on merged micro-images using the image analysis software ROXAS (von Arx, 2013) and the computer program RAPTOR (Peters et al., 2018a) will be used to further processing. The relationships between the various cell structure and stable isotope parameter chronologies on the one hand and climate as well as hydrological data on the other hand will be examined with the CLIMTREG Version 4 program (Beck et al., 2013). CLIMTREG allows the investigation of the relation between the measured wood variables and climate data with a daily temporal resolution rather than using the traditional monthly correlations.

Long-Term Lake Level Changes

The results of our studies on lake sediment and tree ring records provide evidence that natural and human-induced changes

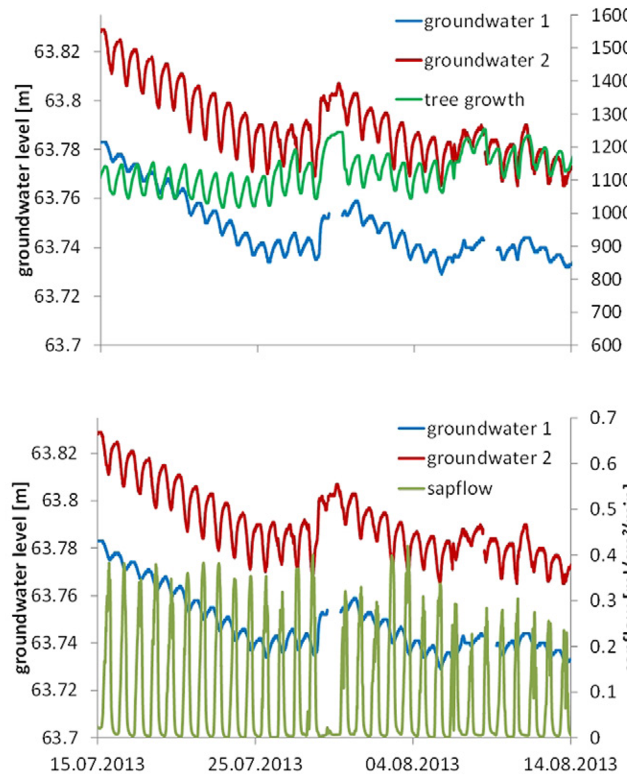

Fig. 4. Comparison of dendrometer, sap flow, and groundwater data monitored at the *Fagus sylvatica* downhill site of Lake Hinnensee.

in vegetation or anthropogenic modification of drainage systems strongly influenced lake level variations in the past (Kaiser et al., 2012b; Dietze et al., 2016). Human alterations of landscape hydrology particularly increased in the 13th and 14th century with a widespread construction of water mills (Kaiser et al., 2018a). Probably in combination with wetter climatic conditions at the onset of the Little Ice Age, these alterations resulted in a lake level rise at Lake Fürstenseer See of up to 3 m, as evidenced by onshore geomorphological studies (Kaiser et al., 2014b) that clearly exceeded fluctuations of 1.3 m observed in recent decades and probably represents one of the highest lake levels during the last 10,000 yr. With the change in forest management practices toward conservation during the 18th century (Schwabe et al., 2015), the water level of Fürstenseer See fluctuated at lower rates. In this respect, even the aforementioned phase of declining lake levels from the 1980s until the late 2000s, in the public debate often related to both global warming and local drainage as well as rewetting measures, was not unusual. Although we have no data from Lake Fürstenseer See itself, we discovered emerging tree stems on the retreating shorelines of nearby Lake Redernswalder See (Kaiser et al., 2015b). Tree-ring dating of these stems proved that these trees were growing in situ from the 1920s to the 1950s during periods with low lake levels comparable to the most recent low. Since the 1950s, the lake rose to the high levels in the 1980s when our instrumental lake level data started. The reasons for these decadal-scale oscillations still remain elusive, but modes of atmospheric variability like the North Atlantic Oscillation might play a role. More recently, in situ drowned trees have also been found in water depths of 2 to 5 m in Lake Giesenschlagsee (Kaiser et al., 2018b), located not far from Lake Fürstenseer See. Radiocarbon ages revealed that these trees grew there about 10,000 to 11,000 yr ago and thus reflect a major early Holocene low water level. Such low water levels distinctly below the recently observed lake levels are in good agreement with regional lake level reconstructions (Kaiser et al., 2012b; Dietze et al., 2016). Based on a combination of sediment facies data from a transect of cores from the shoreline to the deepest part of Lake Fürstenseer See and acoustic sub-bottom profiling, water levels 3 to 4 m lower than present lake levels were reconstructed for the early Holocene (>9700 yr before present). Possible causes include (i) subsurface remains of permafrost formed during the last glaciation (Błaszkiewicz et al., 2015) that could have limited water infiltration, (ii) the warmer and drier climate, and (iii) the development of pine forests that more efficiently consume water compared with other tree species on sandy soils (Vincke and Thiry, 2008; Hüttl and Bens, 2012). Lake levels remained generally low but fluctuated until about 6400 yr before present before rising to a short-term high of about 4 m above modern levels at around 5000 yr before present (Dietze et al., 2016). At that time, forests were dominated by beech and oak whose stems route considerably more water toward the ground, thus contributing more positively to groundwater recharge (Vincke and Thiry, 2008; Hüttl and Bens, 2012) than early-Holocene pine stands. The long-term trend from lower early-Holocene to higher mid- to late-Holocene lake levels probably was additionally driven by an increasingly wetter and cooler climate due to changes in the amount and seasonal distribution of solar irradiation caused by long-term changes in the Earth's orbit (i.e., decreasing summer and increasing winter insolation) (Wanner, 2016). Lake levels remained high until initial human impact started to open the landscape (Küster et al., 2014), which probably contributed to sustaining high water levels (Dietze et al., 2016).

To summarize, lake level changes represent complex feedbacks affected by catchment configuration, vegetation history, and human impact, superimposed by climate change at multiple temporal scales (Kaiser et al., 2012b; Dietze et al., 2016) and experienced significantly higher amplitudes in the range of ± 4 m than observed today (Fig. 5), even during times when humans did not impact natural drainage systems. Even though sediment archives commonly reveal mainly centennial to millennial rather than decadal-scale changes, this is proof of concept that geoarchive investigations provide essential contributions to the knowledge of mechanisms and amplitudes of environmental change.

Moreover, our results imply that underlying long-term trends and mechanisms can cause future lake level shifts that would not be expected from short-term observations, emphasizing the need for an improved time-scale-dependent process understanding of climatic and land cover change to inform forest and water management in a warming world. In particular, a gap in knowledge still exists about evaporation processes from lake surfaces that is essential for assessing the climate impact in a lake-dominated landscape like northeastern Germany.

Seasonal Evaporation from a Deep Lake: Lake Tiefer See

Lake Tiefer See is part of the Klocksin Lake Chain, a subglacial gully system in a morainic terrain located in the natural park Nossentiner/Schwinzer Heide. Today, the lake is connected to Lake Hofsee in the south, while the connection to Lake Flacher See in the north has been channelized in a tunnel after construction of a railway dam between the two lakes. Lake Tiefer See has a surface area of about 0.75 km^2, and the catchment area of about 5.5 km^2 is dominated by glacial till. Although the catchment is mainly used for agriculture, the direct shoreline of the lake is covered by a fringe of trees and there is no anthropogenic infrastructure such as buildings and roads at the lakeshore. The lake has a maximum depth of 62 to 63 m and no major inflow and outflow. The present-day lake water is mesotrophic, and the circulation mode is either mono- or dimictic, depending on the formation of the winter ice cover (Kienel et al., 2013). The study site is characterized by a warm-temperate climate at the transition from oceanic to continental conditions. Mean monthly temperatures range from 0°C in January to 17 to 18°C in July, with maxima up to 30°C and minima down to −5°C. Mean monthly precipitation varies between about 40 mm during winter and 60 mm in summer, with a mean annual precipitation of 565 mm. Lake Tiefer See was selected as an intensive monitoring site because its sediments consist of seasonally formed laminations (varves) that are an ideal tool for the high-resolution reconstruction of climate and landscape changes (Dräger et al., 2017). Thereby, we can extend our instrumental observations for many millennia back into the past. Sedimentation mainly takes place in spring and early summer when regular diatom blooms and biochemical calcite precipitation forms distinct layers during the main phase of lake productivity (Kienel et al., 2013, 2017). Furthermore, microscale volcanic ash particles have been detected in the Holocene sediment record of Lake Tiefer See and linked to eight Icelandic volcanic eruptions, the last major one of the Askja volcano occurring in 1875 (Wulf et al., 2016). These findings allow precise synchronization of this key climate and environmental archive to other sediment records in the circum-Baltic region and beyond. The recent detection of three major solar minima during the last approximately 6000 yr in the sediments through novel ^{10}Be analyses (Czymzik et al., 2018) will foster investigation of the impacts of solar-driven decadal-scale climate perturbations on the regional environment. Furthermore, the high temporal resolution of the sediments has been used for tracing changes in historical land use in great detail (Theuerkauf et al., 2015). The analysis of the stable isotope composition of lake water ($\delta^{18}O$, δD) is a suitable tool to provide insights into lake water hydrology and especially evaporation processes (e.g., Steinman et al., 2010). In addition, knowledge of the controls on the lake isotope system is a prerequisite for reconstructing past climate change using $\delta^{18}O$ values of carbonates in the sedimentary record. In particular, calcite commonly is precipitated in the epilimnion of hard-water lakes in northeastern Germany (Heine et al., 2017), and its stable isotopic composition reflects past lake water conditions and temperatures (Leng and Marshall, 2004). We have

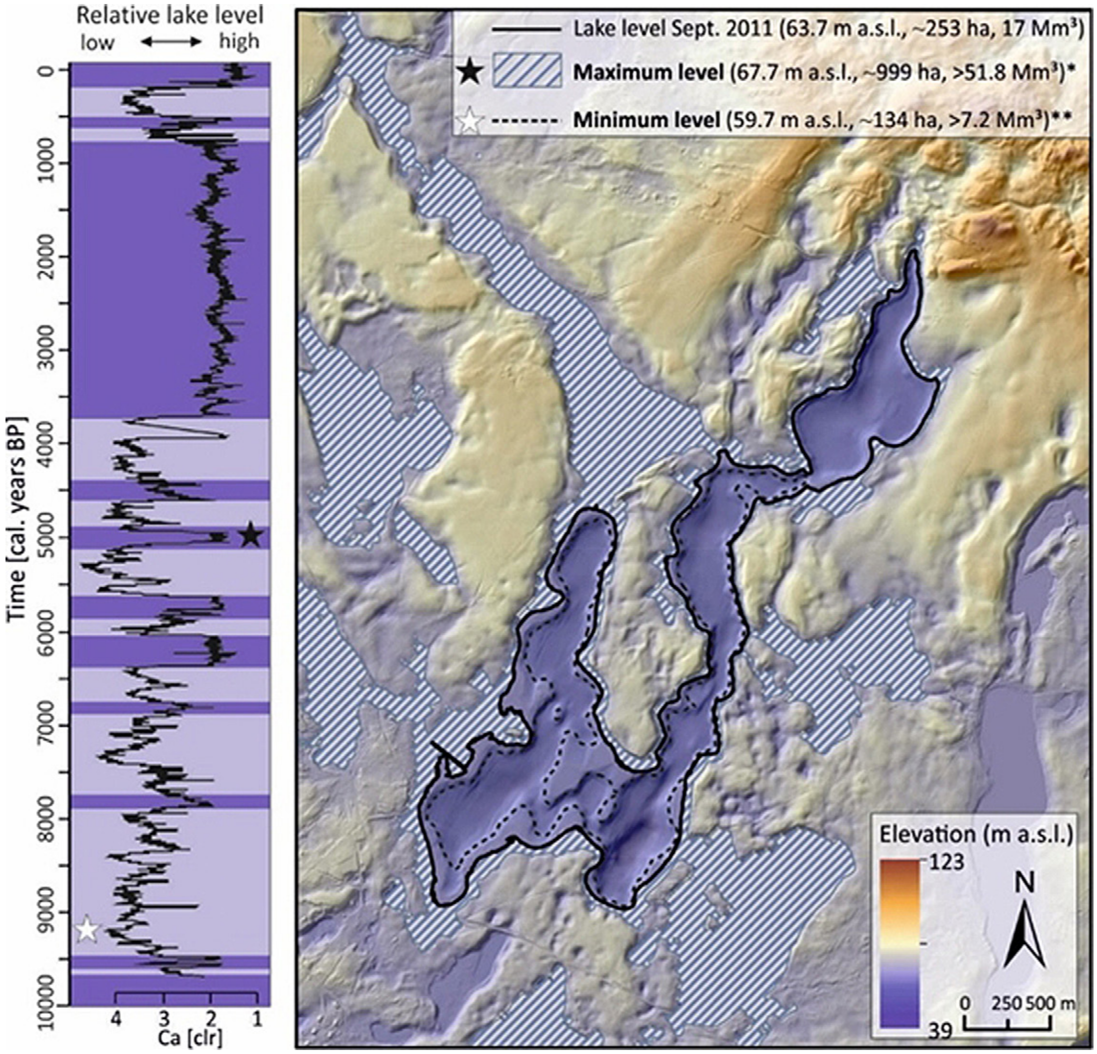

Fig. 5. Holocene lake level changes at Lake Fürstenseer See–Hinnensee: relative fluctuations reconstructed for the last 10,000 yr, with dark (light) blue bars representing periods of relatively higher (lower) lake levels (left). The black (white) star indicates the reconstructed absolute maximum (minimum) lake extensions that are shown on the map (right) (after Dietze et al., 2016).

selected Lake Tiefer See for water isotope monitoring because the sediments consist of calcite varves (Kienel et al., 2013, 2017) that allow even seasonal climate and environmental reconstruction for many millennia back into the past (Dräger et al., 2017). Since 2012 we have comprehensively monitored lake water and recent sediment formation using continuously measuring sensors, sediment traps at different water depths, and a weather station installed on a platform on the lake (Fig. 6).

Lake water has been sampled monthly at water depths of 1, 3, 5, 7, 20, and 50 m since 2012 near a monitoring platform on the deepest part of the lake. Water temperatures were measured using temperature loggers installed at 1-m spacing down to the 15-m water depth and 5-m spacing down to the 55-m depth. Meteorological data measured on site in 10-min intervals include temperature, relative humidity, solar radiation, rainfall, and wind speed. Rainwater has been collected also in monthly increments since December 2016. In addition, we use temperature, precipitation, and $\delta^{18}O$ values from the nearby Global Network for Isotopes in Precipitation (GNIP) station in Neubrandenburg (about 50 km to the east of Lake Tiefer See, period 1997–2002) (International Atomic Energy Agency, 2018).

Aliquots of filtered lake and rain water (1.8 mL) were added to glass vials capped with silicone Teflon septa and analyzed using a cavity ring-down spectrometer from Picarro. The stable isotope ratios ($\delta^{18}O$ and δD) were measured with an L2130-i and L2120-i analyzer equipped with an A0211 vaporizer and V1102-i.

All samples were measured two to four times in high-precision mode. Data correction was performed offline following the procedure described by van Geldern and Barth (2012). The isotopic ratios are reported using the delta notation in per mil (‰) relative to the international Vienna Standard Mean Ocean Water (VSMOW) and are calibrated using two laboratory reference standards. The analytical precision is <0.02‰ for $\delta^{18}O$ and <0.3‰ for δD. The isotopic composition of regional rainwater (GNIP Station Neubrandenburg) (International Atomic Energy Agency, 2018) has an annual range from −14 to −4‰ $\delta^{18}O$ and from −100 to −30‰ δD, with light values during the colder wintertime and

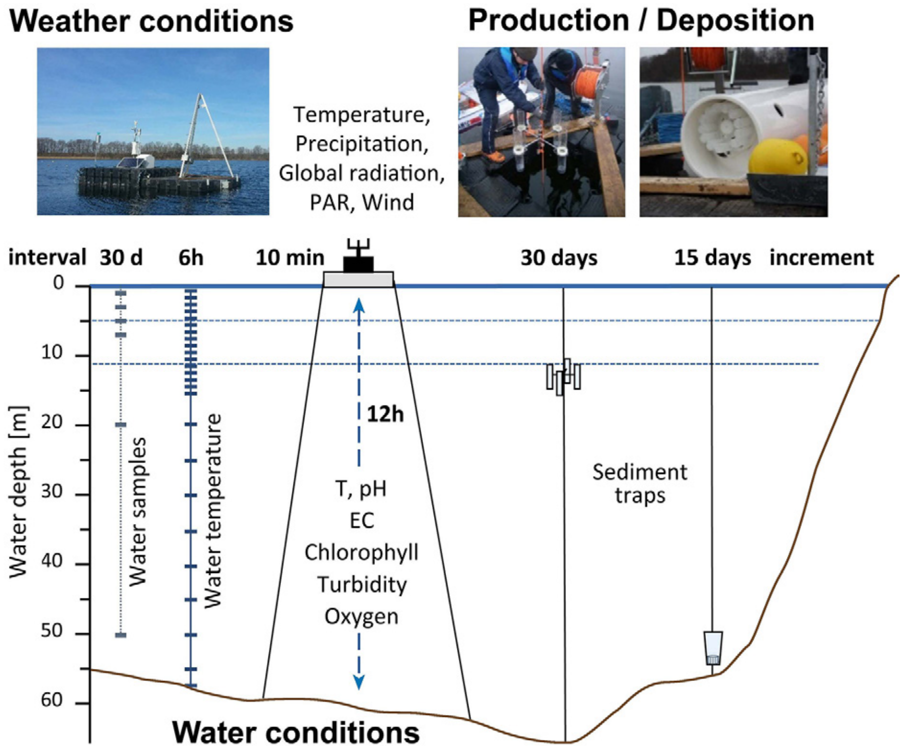

Fig. 6. Schematic monitoring setup at Lake Tiefer See.

heavier values during summer (Fig. 7). The $\delta^{18}O$ values in rainwater samples collected at our monitoring station at Lake Tiefer See in 2016 and 2017 show similar values (−12.9 to −5.5‰ $\delta^{18}O$, −96.8 to −35.8‰ δD). The relationship of $\delta^{18}O$ and δD from both the GNIP Neubrandenburg and Tiefer See stations differs slightly from the global meteoric water line ($y = 8x + 10$) and results in a local meteoric water line of $y = 7.5x + 3.6$ (Fig. 7). The $\delta^{18}O$ values of the epilimnic lake waters (average of samples from 1–5-m water

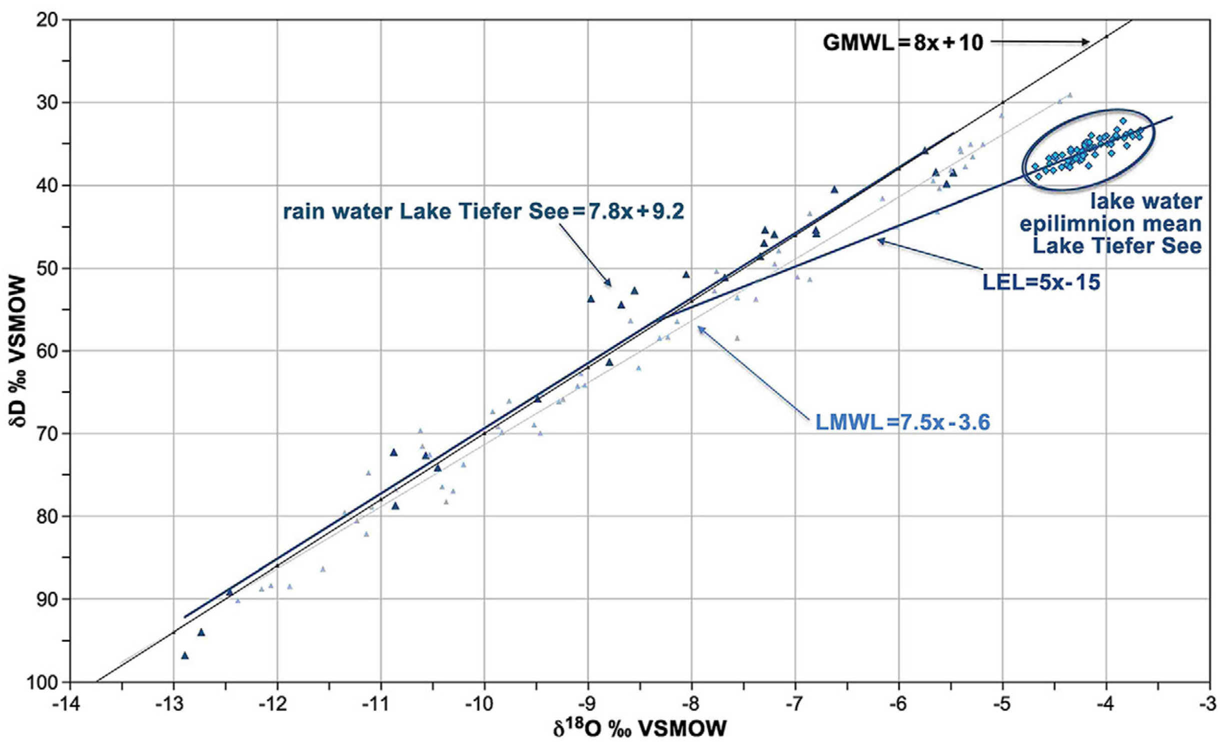

Fig. 7. Global meteoric water line (GMWL), local meteoric water line (LMWL from Neubrandenburg 1997–2002) (International Atomic Energy Agency, 2018), and local precipitation (rainwater, Lake Tiefer See, 2016–2017) as well as epilimnic lake water (mean lake water depths of 1, 3, and 5 m). Slopes between the LMWL and the lake water indicate the evaporation trend.

depth) seasonally vary at low rates between −5 and −3.5‰, with increasing values during summer stratification, higher temperatures, and lake level decrease due to evaporation (Fig. 8).

The seasonal 1.5‰ enrichment of $\delta^{18}O$ indicates an evaporative loss of surface water of up to 10% during the summer, corresponding to the observed lake level drop of 50 cm for neighboring Lake Hofsee, which is hydrologically linked to Tiefer See. Furthermore, the $\delta^{18}O$ values of both the mean epilimnic and deep water (−4.3‰, Fig. 9) are generally more positive than the annual rainwater mean ($\delta^{18}O$: −8.4‰) from Tiefer See.

On the one hand, this proves an evaporative enrichment of the surface water as expressed also in the local evaporation line $y = 4.8x - 15.5$ (Fig. 7). On the other hand, the enriched deep water $\delta^{18}O$ suggests a long water residence time in the lake due to the lack of major in- and outflows and low groundwater inflow, with an expected $\delta^{18}O$ value close to that of the mean annual rainfall.

Regional Evapotranspiration of an Agriculturally Dominated Landscape: DEMMIN Test Site

The impact of climate change on rainfall events and evapotranspiration has not been conclusively determined, and global circulation model applications currently simulate spatially varying and diverse trends for evapotranspiration. Thus the impact of climate change on evapotranspiration needs to be much better understood to develop adaptations in water use and water management (Abtew and Melesse, 2013). Current methods for retrieving evapotranspiration are based on point measurements, eddy covariance measurements, or point and catchment modeling, all of which can provide high temporal resolution but lack spatial information. Other methods are based on remote sensing data and offer high spatial resolution, but due to the availability of optical remote sensing data have irregular temporal resolution (Numata et al., 2017; Zhang et al., 2016). All of these methods have specific advantages and limitations. To combine the high temporal resolution and accuracy of point measurements with the spatial coverage and resolution of remote sensing data, our objective is to link these data sources with appropriate modeling techniques for retrieving high-resolution maps of daily evapotranspiration for the Durable Environmental Multidisciplinary Monitoring Information Network (DEMMIN) area.

The DEMMIN test field is a study area of about 900 km² located around the city of Demmin (53°54′ N, 13°3′ E). The test site is a typical representative of the young morainic soil landscape of northern Germany. Furthermore, lakes and river systems are tightly connected with the near-surface groundwater table. The relief is relatively flat in the north and undulating to hilly with steep slopes in the south. Because of the significant changes in relief, the parent substrate material, and the distance from the groundwater table, soil types are spatially variable.

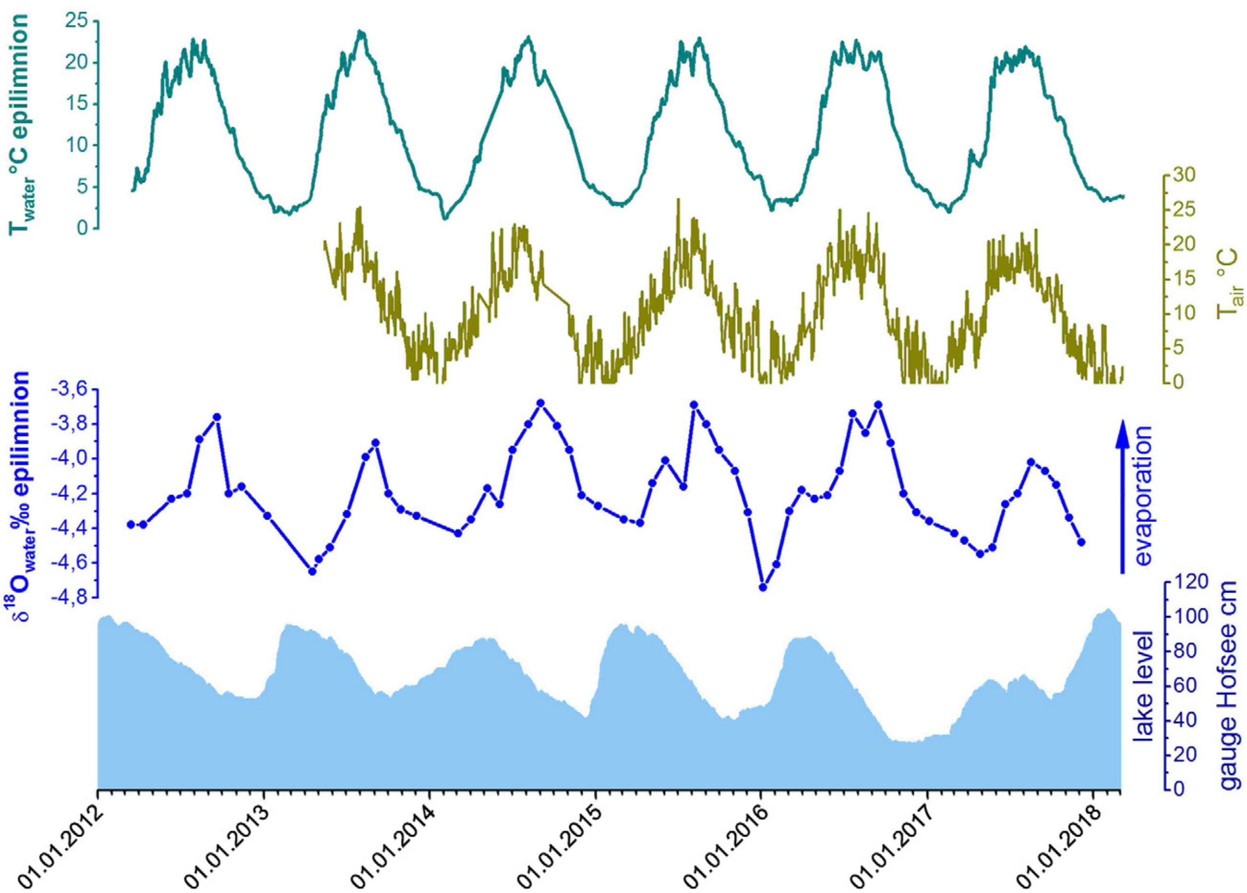

Fig. 8. Seasonal variation (2012–2017) of $\delta^{18}O$ values of the mean epilimnion water of Lake Tiefer See in relationship to air and surface water temperatures as well as lake level fluctuations of the connected Hofsee.

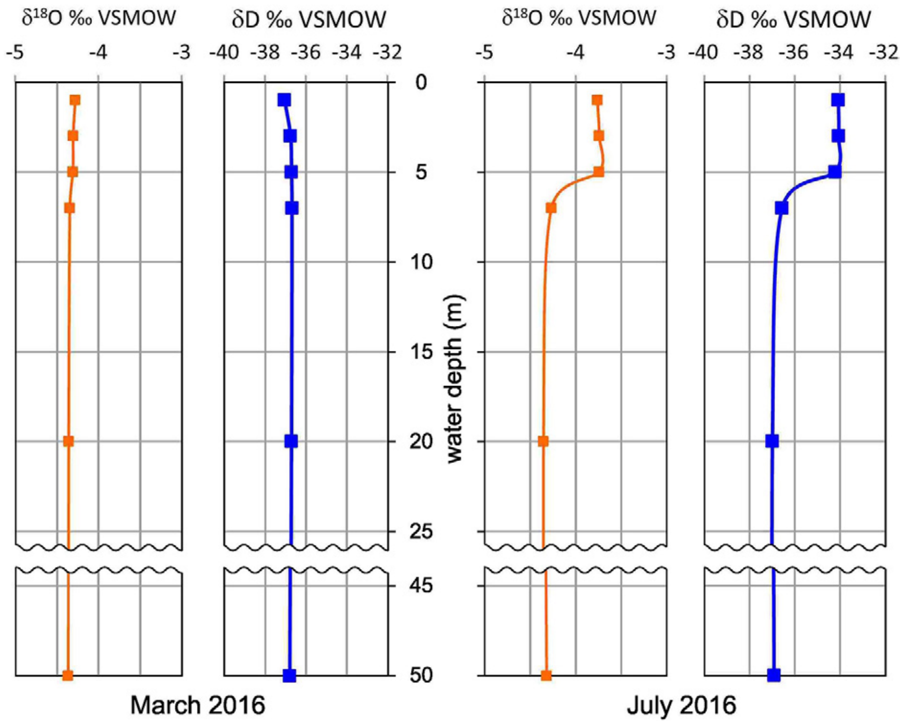

Fig. 9. Isotopic depth profiles for lake mixing (spring March 2016) and for summer stratification (July 2016) at Lake Tiefer See.

The test site is part of the sparsely populated but agriculturally intensive region within the state of Mecklenburg–Western Pomerania.

DEMMIN was formed based on a partnership between the German Aerospace Center (DLR) and farmers from the Demmin region in 2000 as the national calibration and validation test site for Earth observation in agricultural areas (Borg et al., 2009). In 2011, the existing network of climate stations was expanded by the GFZ, Forschungszentrum Jülich, and DLR in the framework of the TERENO project. Currently, 43 climate stations that are measuring environmental parameters (e.g., up- and down-welling shortwave radiation, up- and down-welling longwave radiation, relative air moisture, air temperature, wind direction and speed, precipitation, leaf moisture, as well as soil moisture and soil temperature at different depths), and about 190 SPADE soil moisture sensors under agricultural fields are operational. Administration and data transfer to GFZ for all stations are operated by DLR. In addition to the environmental measurement network, a lysimeter hexagon was installed by FZJ and DLR to further investigate regional evapotranspiration rates. These permanent measuring infrastructures are supplemented by campaign-based measurements for the determination of soil (e.g., surface soil moisture, organic matter) and crop (e.g., phenology, leaf area index, crop height, biomass) parameters. As a precondition for the combination of different data sources, it is necessary to understand data sources and processes at different scales. Here, different methods for the retrieval of ET at the DEMMIN site are presented based on modeling at point, airborne, and regional (satellite-based) scales. The study focuses on ET retrieval for agricultural areas because the high temporal dynamic of annual crops from bare soil conditions over climax stadium to dry vegetation has the highest demands on a model. For the modeling of evapotranspiration at point scales, the METVER model of the German weather service is applied to each of the 62 climate stations at DEMMIN. METVER is a simple one-dimensional water budget model optimized for farmland. It includes crop-specific hydrological parameters for >30 species of fruit, crop, and other plant species from the agricultural, horticultural, and forestry sectors (Müller and Müller, 1988a, 1988b, 1988c; Böttcher et al., 2010). The METVER model facilitates predictions of soil moisture changes. To do so, METVER uses meteorological, plant, and soil input data, all available at DEMMIN. One of the key parameters for ET retrieval is soil moisture, which is measured at DEMMIN with a network of about 100 soil moisture stations (climate stations plus soil moisture stations).

The modeled and measured soil moisture, as an example, shows good correlation for the period from 2013 to 2016 for the Heydenhof BF1a soil moisture station (Fig. 10). The METVER model is only able to model the complete soil column up to a defined depth. To retrieve modeling results that are comparable to the in situ measurements at depths of 50 to 70 cm, two separate METVER model runs, one from 0 to 50 cm and one from 0 to 70 cm, have been performed. The presented results show the difference between the two METVER models and is representative for the depth of 50 to 70 cm. Nevertheless, there are still some artifacts left because of precipitation events, which is reflected in more dynamic variations compared with the measured soil water content at 50 cm. The ET retrieved from METVER shows that the actual ET does not reach the potential ET from the beginning of March until end of October for all years. The difference between potential and actual ET varies within and among the 4 yr and is dependent on weather and vegetation. More comprehensive analyses of the data from 2015 and 2016 shows similar behavior for the measured soil water content at a depth of 50 to 70 cm but very different

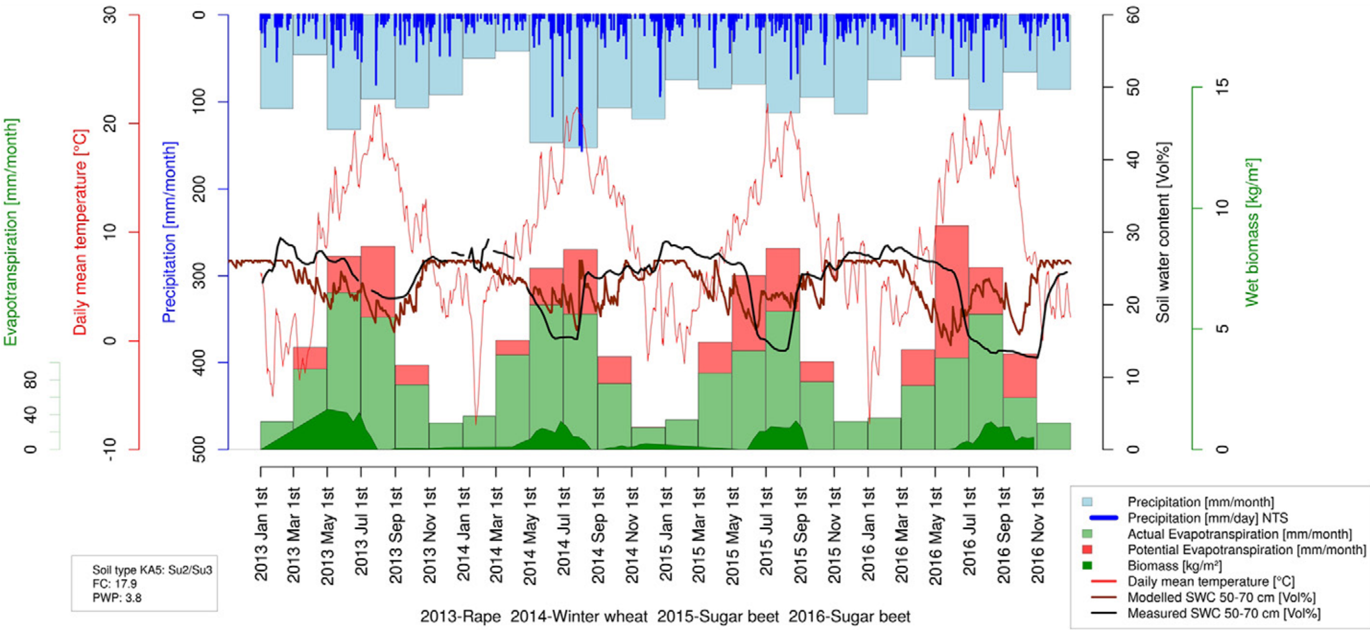

Fig. 10. Results for measured and METVER-modeled soil moisture and evapotranspiration for the Heidenhof BF1 station.

shapes of the modeled soil water content. These diverse values are probably caused by high differences in precipitation between the two years from March to the end of May (2015: 131.2 mm; 2016: 67.2 mm). Especially the water deficit in 2016 is clearly resulting in high differences between potential and actual ET.

For the estimation of ET based on remote sensing data, a more detailed analysis of the energy fluxes within the climate system is necessary. These fluxes can be expressed as part of the surface energy balance:

$$\mathrm{ET_a} \sim \mathrm{LE} = R_\mathrm{n} - G - H$$

where LE is the latent energy used for the phase transition of water from liquid to gas and therefore allows direct conversion to the amount of evapotranspiration, R_n is the net radiation (the balance of incoming solar shortwave radiation and reflected longwave radiation from Earth's surface), depending on incoming and outgoing radiation, G is the sensible heat flux absorbed by the soil and plants (a function of vegetation, radiation, and soil properties), and H is the sensible heat flux, the energy used for heating the surrounding air (a function of the temperature difference, heat transport, and heat capacity).

Quantifying these energy fluxes directly from remote sensing data is not possible in a direct approach (Anderson and Cahalan, 2005; Loeb et al., 2009). The uncertainties involved do not allow sufficient precision for estimating this parameter directly (Liou and Kar, 2014). For this reason, linking remote sensing data with modeling approaches is necessary.

For estimating evapotranspiration from remote sensing data, an adapted version of the METRIC model (Allen et al., 2007; Olmedo et al., 2016) was used, where remote sensing data, in situ data, and further information about the area of interest are combined. The method applies several empirical relationships to estimate the components of the surface energy balance. A key element of this method is the calibration of the retrieved ET so that the ET at estimated extreme pixels is set to zero and a maximum of 105% of the reference ET.

This method was applied to multispectral image data (MicaSense) acquired during an airborne campaign in 2017 that also collected multitemporal datasets of multispectral and thermal data. Figure 11 shows the main land-use types of a small test area of the flight campaign. The area is covered mainly by bare soil, a maize (*Zea mays* L.) field, and a wheat (*Triticum aestivum* L.) field, which is harvested during the day. The surface temperature in the morning is relatively homogeneous. Dependent on the land use, the temperatures are increasing differently, resulting in the highest surface temperature for bare soil areas (+10 K) and moderate heating of vegetation-covered areas (+5 K). Interestingly, the distinction between growing maize and ripe wheat is very low. The reasons for that have to be analyzed further. The temperature differences are characteristic of how radiant energy is converted into latent and sensible heat for different land use types and thus influences the energy balance. Although the surface temperatures differ between 7:00 AM and 12:00 PM, the results for the ET calculation are very similar.

For accurate extrapolations of actual ET to the landscape scale, the coupled in situ and modeled data at the point and local (airborne) scales need to be linked to spatial information based on satellite remote sensing data (Fig. 12). The energy fluxes that are influenced by ET and can be estimated based on thermal satellite data of, e.g., Landsat-8 or Sentinel-3, are decidedly influenced by the present status of the Earth's surface. The soil and crop conditions are strongly affecting ET and a good estimate of these parameters can increase the accuracy of ET estimation. In

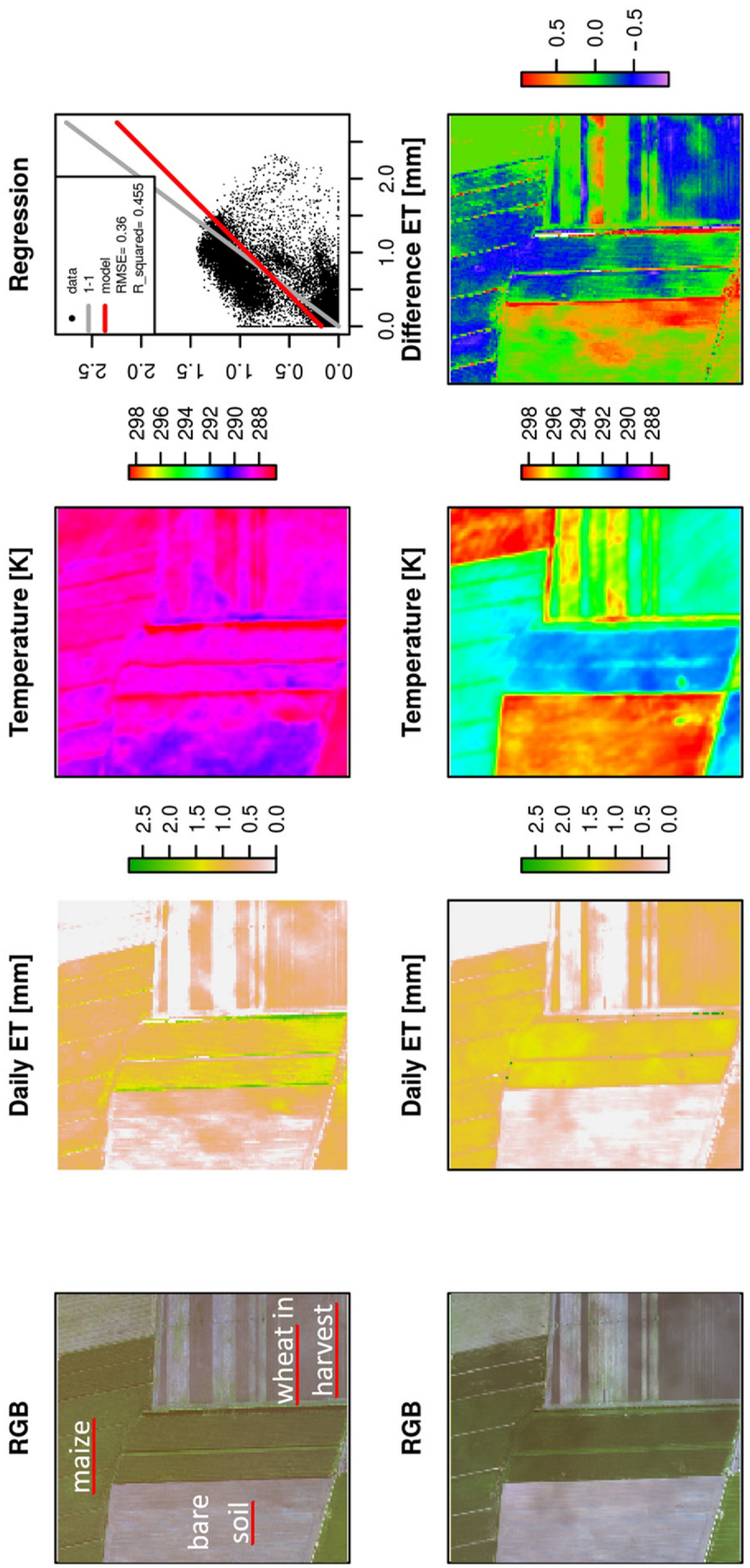

Fig. 11. Upper row: acquisition time 15 Aug. 2017, 7 AM, true color, temperature, evapotranspiration (ET), and regression of both acquisitions; lower row: acquisition time 15 Aug. 2017, 12 PM, true color, temperature, ET, and difference of ET between 7 AM and 12 PM.

terms of soil parameters, we are currently focusing on soil organic matter content. Therefore, a time series derived from satellite data focusing on bare soils of agricultural fields was analyzed to indicate the spatial distribution of loamy and sandy soils. The soil types are linked to higher or lower organic matter contents and resulting variations in water-holding capacity. Further soil parameters like grain size distribution or soil moisture content would also be of high interest and could improve the ET modeling. Retrieving these parameters with high spatial resolution is currently not possible in sufficient quality based on remote sensing data. This might change with future developments in synthetic aperture radar or thermal remote sensing data analysis.

For the estimation of soil organic matter, the multitemporal soil pattern analysis of Blasch et al. (2015a) that was developed using representative calibration test sites within the DEMMIN test site was used. The method detects a stable soil pattern based on multitemporal, multispectral remote sensing data and combines these results with laboratory analysis of soil organic matter for various calibration sites at DEMMIN. This enables the creation of an area-wide distribution map of the topsoil organic matter content for all the agrarian fields of the DEMMIN area (Blasch et al., 2015b; Blasch, 2016).

Besides soil parameters like the presented distribution of organic matter, vegetation plays an important role for remote-sensing-based ET retrieval. Heupel et al. (2018) developed a progressive classification approach for farmland. The algorithm identifies crop types based on their phenological development and their corresponding reflectance characteristics in multitemporal satellite images of the four sensors Landsat-7 and -8, Sentinel-2A, and RapidEye. It distinguishes crop types not only retrospectively but progressively during

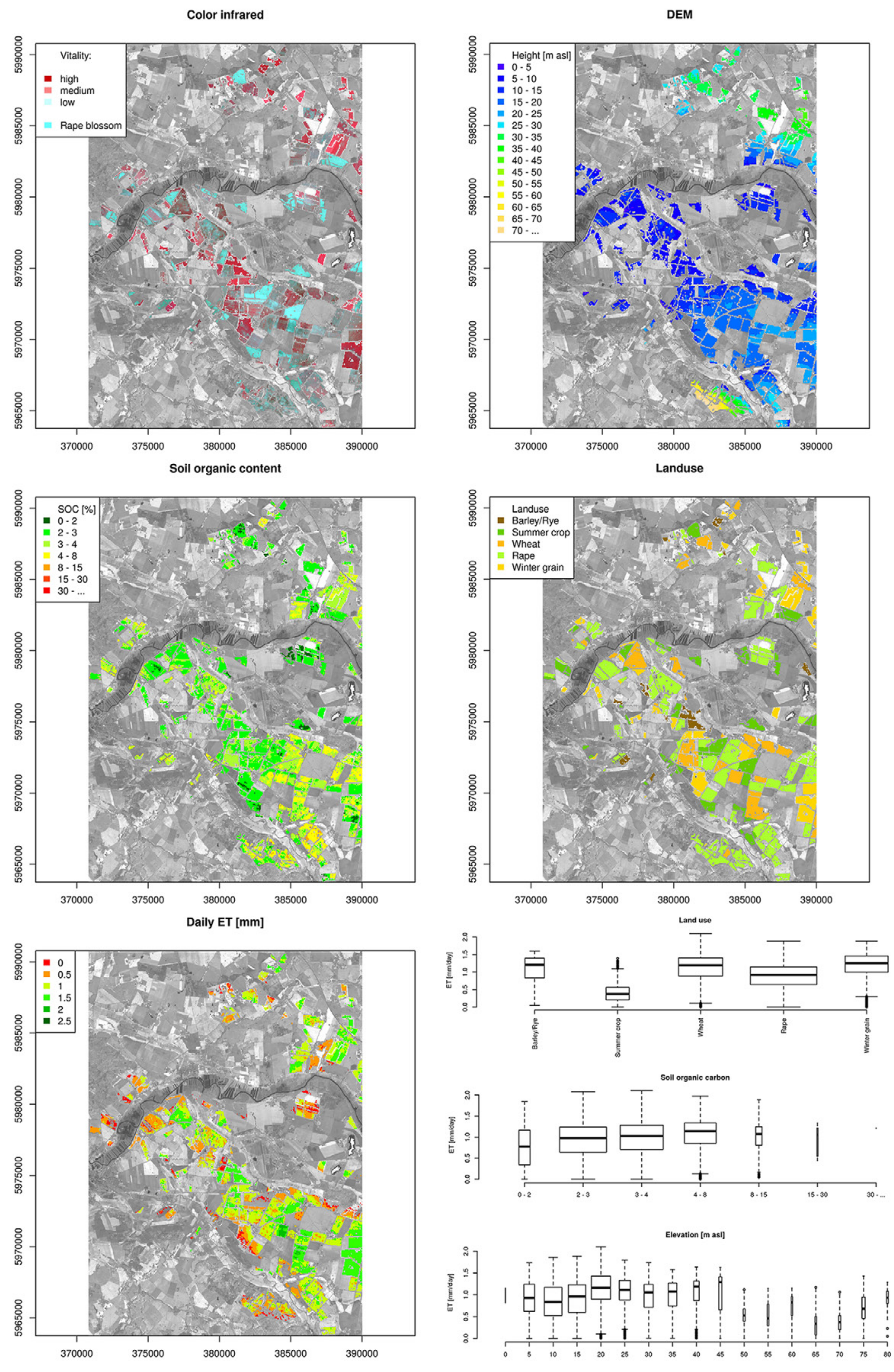

Fig. 12. Landsat 8 color infrared image from 5 May 2016 (top left), digital elevation model (DEM; top right), topsoil organic C content (SOC; center left), multitemporal land use classification with input data up to 5 May 2016 (center right), evapotranspiration estimated from Landsat-8 satellite data (bottom left), and evapotranspiration for different land uses, SOC classes, and elevations (bottom right).

the growing season starting in early spring. Binary fuzzy *c*-means clustering resulted in the differentiation of seven crop types using eight decision rules at particular time periods. This approach enables the inclusion of the most possible actual land use information into the ET modeling process.

The previously listed products in combination with sensor network data, terrain height, and phenological information can provide valuable variables for the parameterization of the METRIC model. The link between several of these sources can be seen in Fig. 13. It shows a color infrared image from 5 May 2016 and a digital elevation model of the crop field in the top row. Very conspicuously colored in bright turquoise, the rape (*Brassica napus* L.) fields in full flower are visible in this image. The center row shows the topsoil organic content from Blasch et al. (2015b) and the result from a progressive land use classification from Heupel et al. (2018) based on the satellite images up to 5 May 2016. The lower row shows the spatial ET estimated using Landsat-8 satellite data in combination with in situ meteorological data from 5 May 2016 and a boxplot of the ET dependent on agricultural land use, surface soil organic matter content, and terrain height. The ET of growing agricultural crops was compared and differences were found. The researchers saw a clear distinction between bare soil fields of impending summer crops with low ET and cereals (barley [*Hordeum vulgare* L.], rye [*Secale cereale* L.], wheat, and unspecified winter grain) with quite similar ET rates of about 1.5 mm d^{-1}. These are comparable results due to the similar phenological development of these crops. In comparison, the results for rape are a bit lower and also the range of ET values is much higher compared with the cereals. We assume that this is a result of the algorithm that uses the normalized difference vegetation index (NDVI) as a precondition for the parametrization of the METRIC model. Because of the flowering of the rapeseed, the NDVI values of the fields were reduced by 0.2. The flowering influences the albedo, which is increased compared with non-flowering plants and thus has an impact on the energy balance. These facts show that it is of high importance to have detailed knowledge about crop types, phenological stages, and their effects on the data for robust area-wide ET modeling. Regarding the topsoil organic content, a slow increase of mean ET with soil organic C (SOC) is visible and will need to be further investigated. Due to the increase in water storage with SOC, this result is assumed to be plausible.

The presented results show the link between different data sources at point and regional scales for ET modeling. As examples, two acquisitions (5 May 2016 and 15 Aug. 2017) have been analyzed at different scales (satellite, airborne), with comparable results between remote sensing data based ET retrieval and the long-term modeling results based on METVER at the point scale (see Fig. 12).

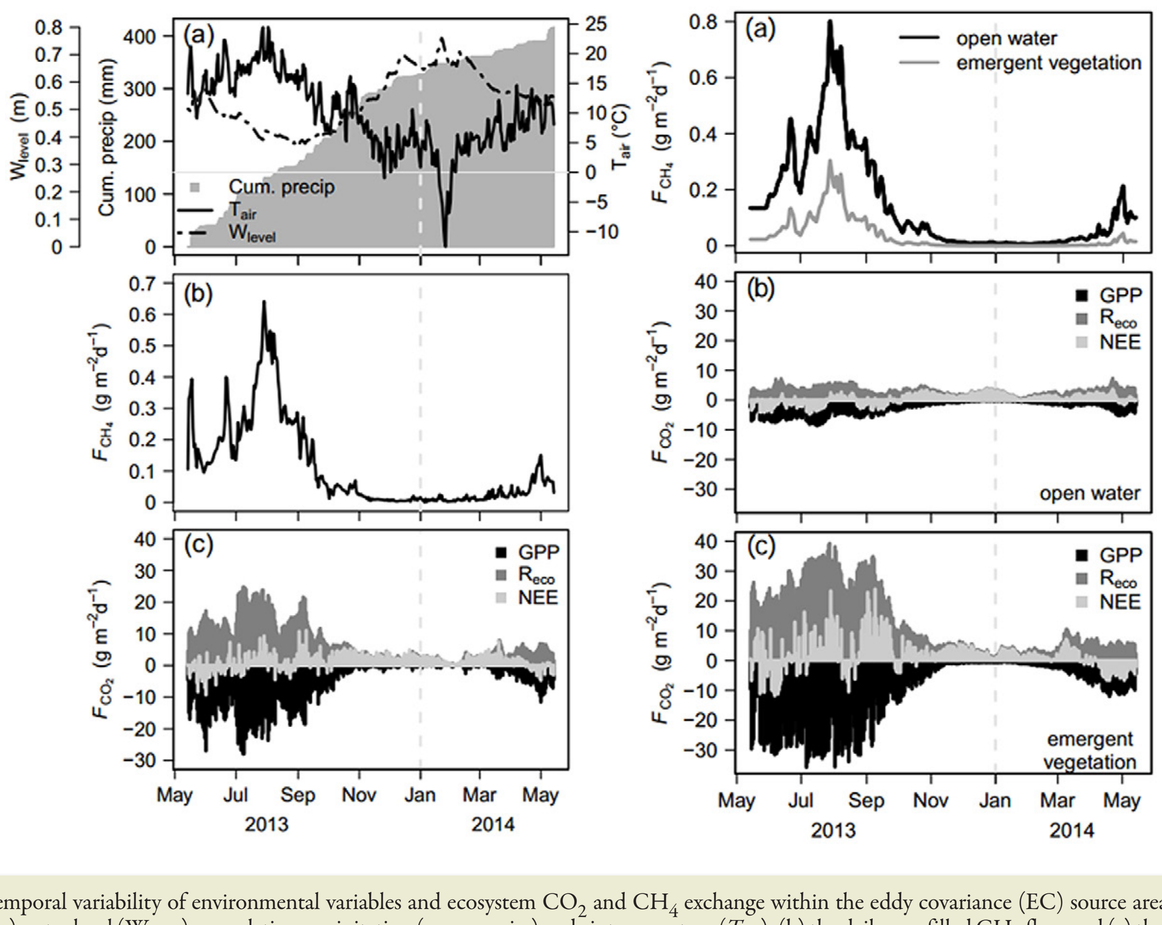

Fig. 13. Temporal variability of environmental variables and ecosystem CO_2 and CH_4 exchange within the eddy covariance (EC) source area: seasonal course of (a) water level (W_{level}), cumulative precipitation (cum. precip.) and air temperature (T_{air}); (b) the daily gap-filled CH_4 flux; and (c) the daily gap-filled net ecosystem exchange (NEE) and component fluxes (modeled ecosystem respiration R_{eco} and gross primary productivity GPP) (Franz et al., 2016).

Soil Water–Vegetation–Atmosphere Exchange Processes: Greenhouse Gas Dynamics in Two Rewetted Terrains: Hütelmoor Peatland and Polder Zarnekow

Although only covering 3% of the Earth's terrestrial surface, peatlands play an important role as effective, long-term C sinks in the Earth system, storing 25% of the SOC. This corresponds to approximately 75% of all the C found in the atmosphere and twice the amount stored in the world's forests. The drainage and conversion of peatland into managed lands, such as farmland, turns these efficient CO_2 sinks into strong emitters of this greenhouse gas, significantly contributing to the radiative forcing of the Earth. This is the case despite the fact that drainage reduces the natural emissions of CH_4, a much more powerful greenhouse gas (Petrescu et al., 2015).

In the glacially formed landscape of northern Germany, peatlands formerly covered 13% of Mecklenburg–Western Pomerania before >95% of this area was drained over the course of land use intensification. The CO_2 emissions from peatland areas used for agriculture are estimated to account for up to 4.5% of Germany's total CO_2 output and for 20 to 30% of the emissions produced by the state of Mecklenburg–Western Pomerania (Ministerium für Landwirtschaft, Umwelt und Verbraucherschutz Mecklenburg-Vorpommern, 2009).

Therefore, as part of climate and water protection efforts, a total of 370 km^2 of degraded peatland is currently being rewetted in Mecklenburg–Western Pomerania alone. In the initial stage of rewetting, however, large amounts of CH_4 can be produced and released. The time frame within which and the extent to which rewetting efforts can contribute to restoring degraded peatland areas to climate-cooling greenhouse gas sinks therefore depends on how long this phase of increased CH_4 release lasts and how strong the CO_2 sink is relative to the CH_4 source. Within TERENO-NE, the objectives therefore are to quantify and understand the production, release, and sequestration of the greenhouse gases CO_2 and CH_4 in a heavily disturbed and rapidly changing ecosystem under restoration.

The nature reserve Hütelmoor is a coastal, mainly minerotrophic fen complex in Mecklenburg–Western Pomerania (northeastern Germany) that is separated from the Baltic Sea by a narrow (~100 m) dune dike. Episodic flooding from storm events delivers sediment and brackish water to the site (Weisner and Schernewski, 2013). The vegetation is a mixture of salt-tolerant macrophytes. The dominant plants are interspersed with open water bodies (Koch et al., 2017). Intense draining and land amelioration practices began in the 1970s, which lowered the water level to 1.6 m below the ground surface and caused aerobic decomposition and concomitant degradation of the peat (Voigtländer et al., 1996). The upper peat layer varies in depth between 0.6 and 3 m and is highly degraded (Hahn et al., 2015). Active draining ended in 1992, but dry conditions during summertime kept the water table well below the ground surface (Koebsch et al., 2013) until concerns of prolonged aerobic peat decomposition prompted the installation of a weir in 2009 at the outflow of the catchment (Weisner and Schernewski, 2013).

The Polder Zarnekow intensive site is located in the valley of the Peene River at the southwest corner of the DEMMIN test area. It is a degraded minerotrophic fen with a peat depth reaching up to 10 m, which was drained in the 18th century. An extensive amelioration program and its use as grassland in the second half of the 20th century led to a decline of the water table to >1 m below the surface, decomposition and mineralization of the upper 30 cm of peat, and surface subsidence. The latter resulted in the establishment of a shallow water body after rewetting was intensified in 2004 to 2005 by opening the polder's dikes. This water body with submerged and floating vegetation is surrounded by emergent vegetation, primarily *Typha latifolia* L. (Hahn-Schöfl et al., 2011).

The micrometeorological eddy covariance method at an average measurement height of 2.63 m above the fluctuating water surface was used to quantify the ecosystem–atmosphere exchange of CH_4 and CO_2 at half-hourly resolution. The eddy covariance setup includes an ultrasonic anemometer for the three-dimensional wind vector (u, v, w) and sonic temperature (HS-50, Gill), and both enclosed-path and open-path infrared gas analyzers for CO_2/H_2O and CH_4 concentrations, respectively (LI-7200 and LI-7700, LI-COR Biogeosciences), which were all logged at 20 Hz. Additional meteorological and environmental variables recorded every minute included net radiation, air temperature and humidity, two-dimensional wind direction and speed, incoming and reflected photosynthetic photon flux density, water level, precipitation, soil heat flux as well as water temperature at the sediment–water interface, and soil temperature at depths of 10, 20, 30, 40, and 50 cm below the water column. Nine years after rewetting, large CH_4 emissions (53 g CH_4 m^{-2} yr^{-1}) from the open water area were found, four times larger than from the surrounding vegetation (13 g CH_4 m^{-2} yr^{-1}) (Franz et al., 2016). However, surprisingly, both the open water and the surrounding vegetation were also net sources of CO_2 (158 and 750 g CO_2 m^{-2} yr^{-1}, respectively) (Fig. 13).

Unusual meteorological conditions with a warm and dry summer and a mild winter might have facilitated high respiration rates, particularly from temporally non-inundated organic mud in the vegetation zone. The very large CH_4 emissions, on the other hand, were the subject of concurrent biogeochemical and microbial investigations. These found a well-developed methanogenic community, while the CH_4–oxidizing methanotrophic communities were much less abundant, suggesting a possible explanation for the magnitude of the fluxes (Wen and Unger et al., 2018).

Soil Erosion and Matter Fluxes in an Agricultural Landscape: The Quillow River Catchment

Soils play a major role in the global C cycle and are highly susceptible to climate change and land-use impacts (Lal, 2003; Prechtel et al., 2009). During the past two decades, studies dealing with soil erosion-induced C fluxes have received great attention due to conflicting results (Doetterl et al., 2016). These large uncertainties are partly caused by different data sources and/or modeling approaches used to derive global estimates. However, even on the field scale, the feedbacks between redistribution processes and their effect on C dynamics are still not sufficiently understood (Doetterl et al., 2016). Therefore, process-oriented monitoring systems were installed at the

Dedelow (CarboZALF-D, Sommer et al., 2016; Pütz et al., 2016) and Christianenhof field sites, both located in a hummocky till plain and intensively used agricultural landscape. Different methods were combined to study the complexity of soil erosion and corresponding C dynamics across different time scales (Fig. 14).

The catchment of the Quillow River covers an area of 168 km^2 and is located in the hummocky glacial landscape of the Uckermark area. The elevation varies between 18 and 120 m asl. The hilltops and slopes consist mainly of sand-covered till and intercalated layers of glaciofluvial sand, whereas the valleys are filled by fine-grained fluvial sand, peat, and gyttja. Locally, dendritic gully systems have incised steep slopes, with gully lengths of up to 120 m and depths of up to 8 m. The removal of topsoil by combined tillage and water erosion has created spatial patterns of truncated soil profiles (Luvisols, Calcaric Regosols) at hummock positions and colluviated soils at hollow sites (Gleyic-Colluvic Regosols, Terric Histosols) with modified thicknesses and properties of soil horizons (Sommer et al., 2008). Only 10 to 15% of the area consists of soils unaffected by soil erosion. The Quillow River catchment belongs to the Upper Ucker River catchment draining to the Baltic Sea. The catchment can be regarded as an assemblage of mostly drainless subcatchments, first connected by artificial ditches probably built since the 13th century. A patchwork of small drainless depressions, called (glacial) kettle holes, occurs. Within the Quillow River catchment, 1176 kettle holes have been identified (Lischeid et al., 2017). Many of them are at least occasionally filled with water, whereas the rest are filled with mineral soil and peat (Nitzsche et al., 2017). Kettle holes are biological and biogeochemical hotspots. They originated mostly from melting of buried stagnant ice, usually called *dead ice* (e.g., Kaiser et al., 2012b). After the melting of these ice remains, water-filled basins of varying size could appear, which were later often replaced by mires and, if small enough, completely covered by colluvial sediments. Input from the surrounding terrestrial environment occurs either by the groundwater system, by interflow, by surface runoff, or by direct input via deposition or anthropogenic discharge. Consequently, kettle hole sediment cores reveal a legacy of land use effects (Kleeberg et al., 2016). The present-day land cover of the Quillow River catchment consists of arable land and pasture (70%), wetlands and lakes (16%), forest (11%), and settlements (3%) (Schneider, 2014).

The focus at the study sites is on recent and past erosion rates, the separation and quantification of soil redistribution due to water and tillage erosion, and the identification of the main drivers and characteristics for lateral SOC redistribution. Four subcatchments (in total 0.04 km^2) of a peaty kettle hole at Christianenhof were instrumented and have been continuously monitored since 2015. The monitoring quantifies surface runoff and corresponding sediment and C delivery into the kettle hole. Moreover, spatially distributed rainfall intensity and kinetic energy (1-min temporal resolution) are measured and land management operations are recorded (Fig. 14).

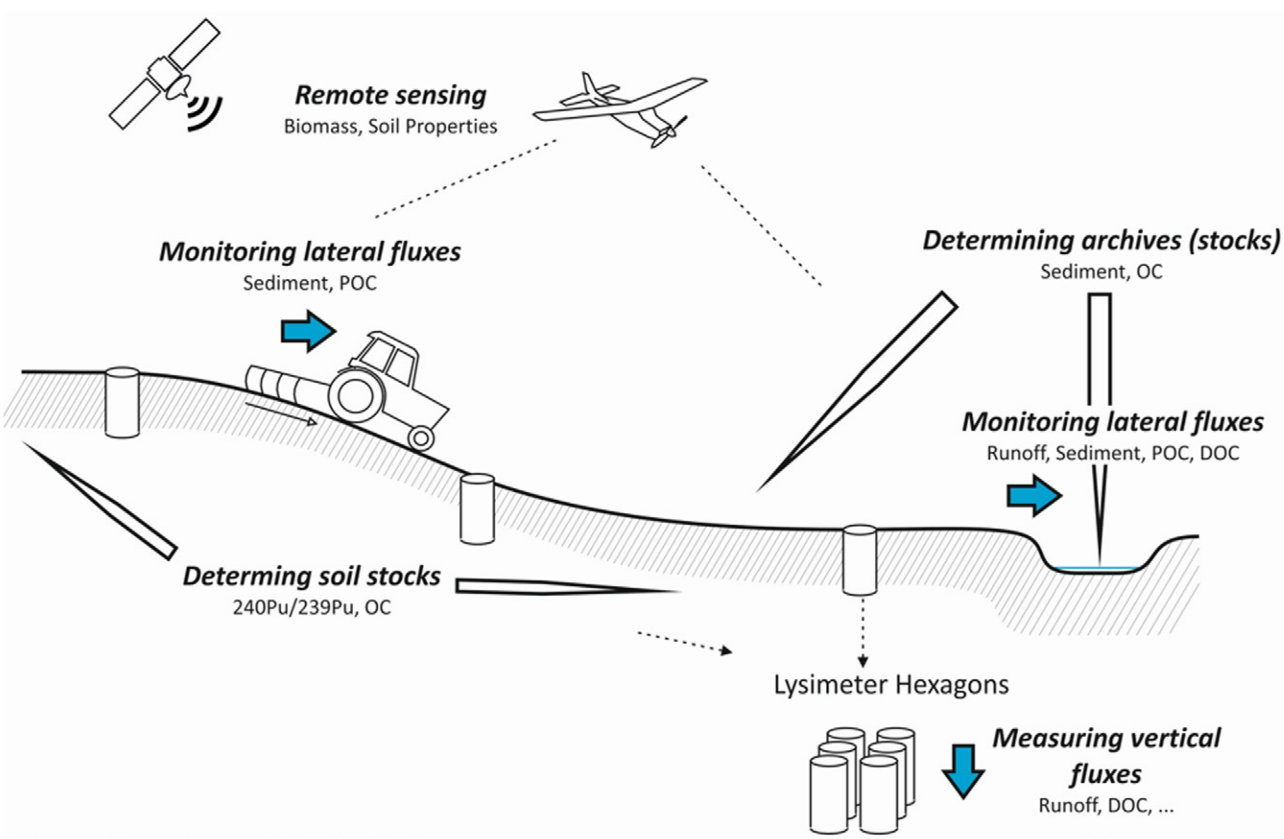

Fig. 14. Conceptual model of the research approach to soil erosion and matter fluxes in the Quillow River catchment; OC is organic C, POC, is particulate organic C, and DOC is dissolved organic C.

A soil inventory, analyzing soil nutrients (C and N), soil aggregates, and incorporated C as well as basic soil physical properties (bulk density and texture) was performed. This information was spatially interpolated (geostatistics) and compared against model results of water and tillage erosion rates. For this purpose, the conceptual WaTEM/SEDEM model (Van Oost et al., 2000) as implemented in SPEROS-C (Fiener et al., 2015) was used to simulate soil redistribution patterns in the kettle hole catchment from 1963 to 2016. To analyze process-based effects of soil redistribution on SOC dynamics, a coupled process-oriented and event-based soil erosion and C turnover model was developed (MCST-C; Wilken et al., 2017a, 2017b). The MCST-C model was applied on a unique 100-yr, high-resolution rainfall dataset to analyze the effect of event size (Wilken et al., 2017a). Subsequently, the model was used to compare the role of water erosion processes vs. tillage erosion on C dynamics (Wilken et al., 2017b).

For the detection and quantification of soil erosion-induced changes in the water balance and leaching of dissolved organic and inorganic C (DOC and DIC, respectively), a novel monitoring approach was applied. Two lysimeter hexagons, as part of the TERENO-SoilCan project (Pütz et al., 2016), quantified water and matter dynamics of uneroded, eroded, and colluvial soils at the pedon scale. A pair of cylindrical weighing lysimeters (1 m^2, 1.5 m long, UMS-METER Group AG) were filled with intact Luvisol monoliths from the Dedelow (Dd) and Holzendorf (Hd) sites and defined as Hexagon 1 (Fig. 15). A second lysimeter hexagon was filled with pairs of eroded Regosols from sites Hd, Grünow, and Christianenhof. For the soils of Hexagon 1, the depth to the C horizon, inversely related to the profile truncation, ranged between 0.65 and 0.70 m (Dd_5, Dd_3), 0.8 m (Dd_1, Hd_4, Hd_2), and 1.15 m (Hd_6). Precipitation (*P*), drainage (*D*), and actual evapotranspiration (ET_a) rates were evaluated for a 3-yr period (April 2011–March 2014) (Herbrich et al., 2017a), considering the temporal autocorrelation of the high-resolution time series of lysimeter mass changes (Herbrich and Gerke, 2016). In addition to the monitoring approach, column percolation experiments and one- and two-dimensional numerical simulations have been performed to quantify the soil water balance depending on erosion-affected pedogenetic changes in the soil profiles (Rieckh et al., 2014, 2015; Filipović et al., 2018).

Furthermore, monitoring data and process investigations were combined with depositional records derived from soil geoarchives of the wider catchment, providing a long-term record that covers the late Holocene. Therefore, sedimentary sequences containing colluvial sediments and fossil soils were sampled for optically stimulated luminescence (OSL) dating, portable OSL reader measurements, and radiocarbon dating in the whole Quillow River catchment (Kappler et al., 2018b).

The spatial distribution of SOC distinctively shows that tillage erosion in the kettle hole catchment is the dominant driver of soil and C redistribution (Fig. 16). The lowest SOC concentrations are found at the convex hilltops where almost no water erosion but the greatest tillage erosion takes place. Furthermore, tillage erosion resulted in a concave footslope area consisting of hydrological sinks that surround the kettle hole. The monitoring data indicate that the footslope sinks

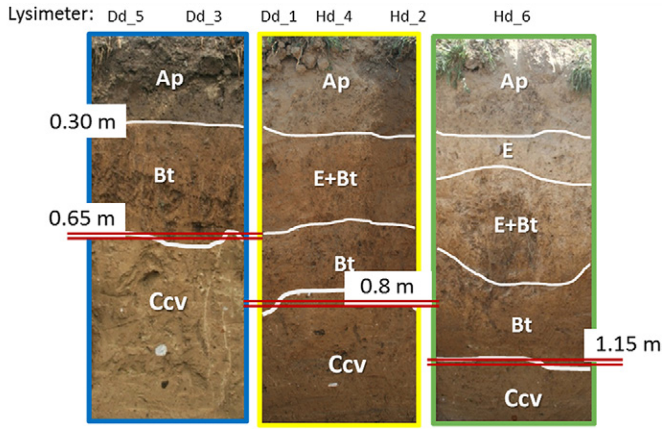

Fig. 15. Sequence of eroded Luvisols from the Uckermark area with different stages of soil profile truncation and indication of lysimeter numbers (green framed profile: most complete Luvisol profile; yellow frame: average truncation, has still remnants of E-horizon material; blue frame: most truncated profile without any E horizon). The reddish lines indicate the depths to the C horizon, consisting of the soil parent material, which is glacial till. The depth of the intact soil profile is approximately 1.4 m.

lead to a substantially limited hydrological and sedimentological connectivity with the kettle hole. Hence, enhanced deposition occurs at the footslope sinks and leads to high SOC concentrations (Fig. 16).

The process-oriented soil erosion and C turnover modeling studies using MCST-C (Wilken et al., 2017a, 2017b) underlined (i) that event size is highly important due to the preferential transport of SOC and corresponding SOC enrichment processes in delivered sediments; (ii) the intra-field catchment connectivity controls sediment delivery and corresponding SOC enrichment processes, as catchments with reduced sedimentological connectivity show enhanced SOC enrichment in delivered sediments; (iii) soil aggregation reduces sediment and SOC transport distances due to the encapsulation of highly mobile SOC-rich fine particles; and (iv) in general, tillage erosion induced a substantial in-field SOC sequestration compared with model runs without erosion.

These combined erosion processes have resulted in spatially variable truncated and colluviated soil profiles underneath the agromechanically seemingly leveled soil surface of a field. The erosional soil profile modifications were found to have interrelated effects on crop growth and water and element balances in the soil–plant–atmosphere system. The leaching of DOC and colloids was strongly different in more and less eroded soils (Rieckh et al., 2015). The root development of winter wheat observed using the minirhizotron technique (Herbrich et al., 2017b) was temporally different at the three contrasting hillslope positions and reduced at the most eroded truncated Haplic Regosol soil profile (Fig. 15, left). Simulations (one-dimensional) of water and dissolved C leaching (Rieckh et al., 2014; Gerke et al., 2016) suggested increasing drainage rates at eroded hummocks and upward fluxes at colluviated hollow positions compared with uniform crop development scenarios. Even the soil water retention dynamics can differ depending on soil management and erosional soil modifications (Herbrich and Gerke, 2017), and

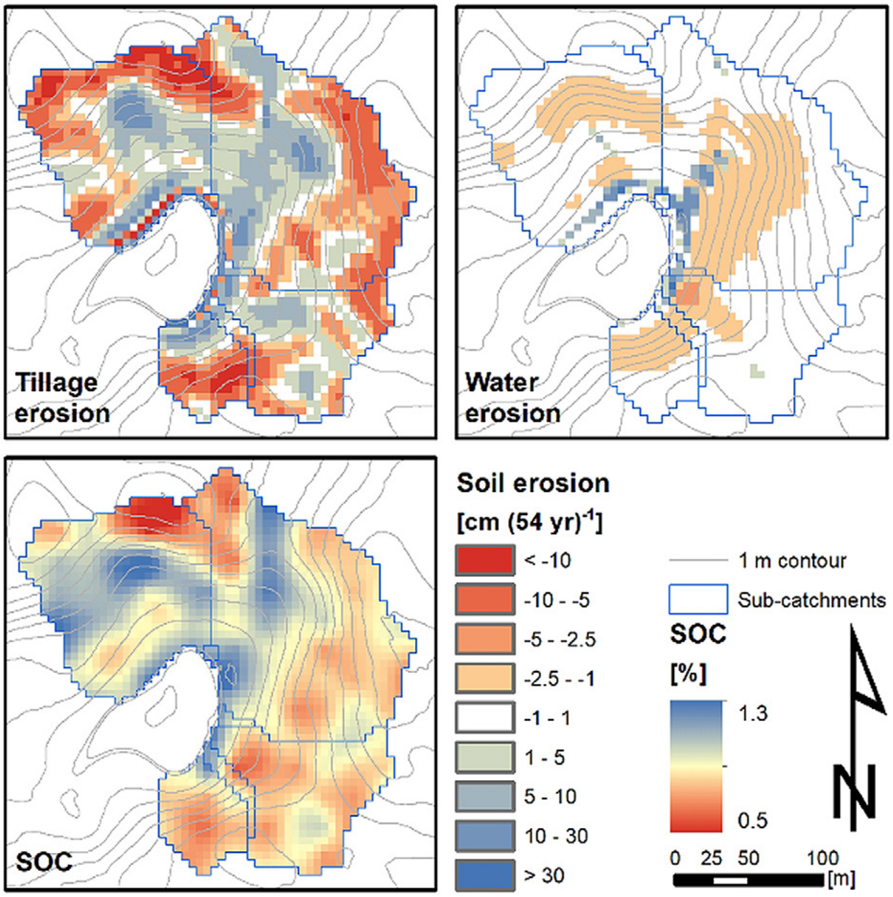

Fig. 16. Spatial distribution of topsoil soil organic C (SOC) and modeled tillage and water erosion in the monitored kettle hole at Christianenhof over 54 yr; negative and positive values of erosion indicate soil loss and gain, respectively.

subsurface lateral flow may occur along sloped boundaries between Bt and C horizons (Filipović et al., 2018).

The lysimeter monitoring demonstrated that the water balance components (Table 2) differed among the lysimeters (Herbrich et al., 2017a, 2017b). The 3-yr cumulative amount of drainage D (ET_a) ranged from 170 mm (1903 mm) for the least eroded (Hd_6) to 312 mm (2071 mm) for the most eroded (Dd_5) Luvisol (Fig. 15). However, if related to precipitation P, the differences in balance components between individual lysimeters became less significant (Table 2). Only for lysimeters from Hd sites a trend of decreasing D and increasing ET_a with increasing thickness of the solum (i.e., E and B horizons) could be found. The effluent concentrations of DOC (5 ± 0.5 mg L^{-1}) and DIC (62 ± 5 mg L^{-1}) were relatively constant in time at the 1.4-m depth for all lysimeters. The decrease in DOC concentration of the soil solution with depth, which seems to have depended on the DOC sorption in the Bt horizon, somehow reflected the thickness of this horizon. Nevertheless, leaching rates of DOC and DIC were mainly controlled by differences in the water flux rates (Table 2).

Information on long-term soil erosion was obtained from soil profiles with colluvial layers (Kappler et al., 2018b). The OSL ages suggest that the onset of the youngest (i.e., uppermost) and strongest colluvial phase in the study area started around 600 ± 100 yr ago, following several prehistoric colluvial phases (Fig. 17).

Table 2. Annual average water balance components and dissolved organic C (DOC) and dissolved inorganic C (DIC) leaching during the period April 2011 to March 2014 for TERENO SoilCan lysimeters at the ZALF Research Station Dedelow. Three lysimeter rings were filled with eroded Luvisol soil monoliths from Dedelow (Dd) and Holzendorf (Hd). Precipitation measured at the lysimeters (P_{Lys}) was about 20% above that measured at the weather station; evapotranspiration (ET_a), drainage (D_{out}) and re-injected water (D_{in}) add up to D_{sum}, and the soil water storage change (Δq).

Soil	P_{Lys}	ET_a		D_{out}	D_{in}	D_{sum}	D_{sum}	Δq	$ET_a + \Delta q$	DOC	DIC
	mm	mm	%	mm	mm	mm	%	mm	%	g m^{-2}	g m^{-2}
Dd_1	675	659	97.6	87.7	37.0	50.7	7.5	−34.7	92.5	0.34	5.6
Dd_3	680	690	101.6	104.0	56.0	48.0	7.1	−58.7	92.9	0.45	7.1
Dd_5	678	661	97.5	96.0	35.0	61.0	9.0	−44.3	91.0	0.38	5.5
Hd_2	646	624	96.5	73.0	11.0	62.0	9.6	−39.3	90.5	0.33	4.3
Hd_4	668	642	96.1	92.3	13.0	79.3	11.9	−53.3	88.1	0.45	4.7
Hd_6	633	634	100.2	56.7	19.3	37.3	5.9	−38.7	94.1	0.25	3.2

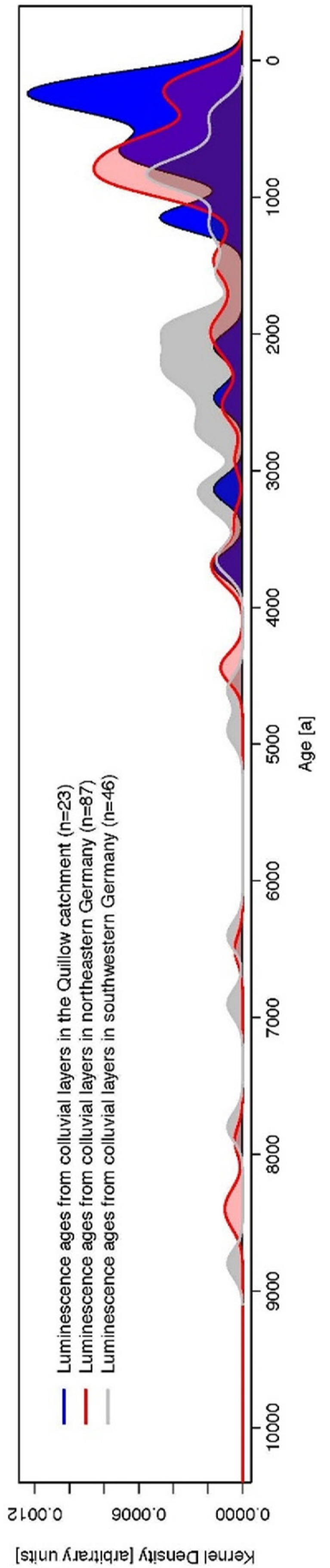

Fig. 17. Kernel density estimates of dated colluvial layers (luminescence ages) indicating historical soil erosion in the Quillow River catchment (blue curve), in the total area of northeastern Germany (red curve), and in southwestern Germany (gray curve).

In most cases, the prevailing thickness of the uppermost colluvial layer indicates an increase in deposition rates of at least one order of magnitude within the last approximately 200 yr. This finding, based on numerical age dating, corroborates the hypothesis on the erosion effects of modern agriculture in the region (Sommer et al., 2008). The results also suggest that phases of increased colluviation and soil erosion also occurred during the late Bronze Age, the Iron Age, and the Middle Ages (Kappler et al., 2018b; Fig. 17). As a methodical improvement, the application of the portable OSL reader method for colluvial deposits facilitated a more precise sampling strategy and provided a more detailed insight into the local depositional dynamics. Furthermore, it allowed the detection of invisible sedimentary hiatuses in homogenously appearing sediments. This was achieved by densely sampled sequences (sampling interval of 10 cm), which yielded continuous, high-resolution records of luminescence signal intensities throughout the profile (Kappler et al., 2018b).

Conclusions and Future Perspectives

Here we have provided an overview of the TERENO Northeast German Lowland Observatory, followed by examples of the interdisciplinary and integrated research at selected sites within the observatory.

Ongoing monitoring of selected lakes and tree species delivers urgently needed insights into lake sedimentation, groundwater recharge, and tree growth dynamics, resulting in a better process understanding, which in turn facilitates an improved understanding of the proxy data. We showed how the monitoring of Lake Tiefer See could improve our understanding of evaporation processes and their impact on the hydrology of lake-dominated landscapes, showing that the seasonal enrichment of $\delta^{18}O$ can be used as a proxy for lake level declines. Furthermore, varved lake sediments indicated that lake levels in northeastern Germany varied much more strongly throughout the Holocene than the fluctuations and trends observed during the last decades. Currently, we are developing new proxies, among them intra-annual cell structures within individual tree rings. This will increase the temporal resolution of the proxy data from seasonal down to sub-seasonal, helping to better recognize long-term trends vs. the impacts of short-term events.

The combination of remote sensing data with ground-truthing data from the DEMMIN test field with the METVER model of the German weather service sheds more light on the regional evapotranspiration dynamics of an agriculturally dominated landscape. Comparable results derived from remote sensing and long-term modeling could be achieved.

In TERENO-NE, greenhouse gas dynamics were monitored in two rewetted peatlands, serving as pilot studies and representatives for other rewetted areas in the temperate lowlands. Remarkably, the rewetted peatlands were found to be net sources of CO_2 and CH_4. Ongoing monitoring will show whether this is true only for the initial phase of the rewetting process or if this will be a long-lasting process that needs to be considered in future land management practices. To increase spatial coverage, TERENO-NE will cooperate more closely with the WETSCAPES project (https://www.wetscapes.uni-rostock.de/en/), creating a cluster of flux towers covering rewetted sites under differing management and water level regimes. Airborne flux measurements will cover the spatial gaps between the sites and help evaluate their representativeness with regard to regional greenhouse gas fluxes.

We also showed how state-of-the-art soil erosion monitoring combined with two lysimeter hexagons and soil redistribution modeling could assist to identify tillage erosion as the much more effective type of erosion. These monitoring and modeling data were combined with depositional records derived from soil geoarchives from the catchment, providing a soil redistribution proxy record that covers the late Holocene. According to this unique record, the strongest soil redistribution took place within the last 200 yr; however, it was also indicated for the late Bronze Age, the Iron Age, and the Middle Ages.

It is noteworthy, that national and international cooperation among universities and research centers are already making use of the facilities at TERENO-NE. Data are provided via standardized exchange formats, and we are offering interested communities data access and opportunities for new cooperation via the data portal TEODOOR (http://teodoor.icg.kfa-juelich.de/).

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