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Discussions

High-resolution operational soil moisture monitoring for forests in the Middle Germany

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Abstract. The forests of Central Germany (Saxony, Saxony-Anhalt, and Thuringia) are vital components of the local ecosystems, economy, and recreation. However, in recent years, these forests have faced significant challenges due to prolonged climate-change-induced droughts, causing water shortages, tree stress, and pest outbreaks. One of the key components of the forests' vitality and productivity is the availability of soil moisture. Given the anticipated increase of frequency and severity of droughts events, there is a growing demand for accurate and real-time soil moisture information. This underscores the need for development of an appropriate monitoring tool to make forest management strategies more effective.

The article introduces an operational high-resolution soil moisture monitoring framework for the forests in Middle Germany, which addresses the main limitations and problems of the existing monitoring systems. The key components of this system include advanced LWF-BROOK90 1D water balance model, large database of National Federal Forest Inventory, real-time climate data from German Weather Service, and web information platform for the results presentation with daily updates. This system empowers forest managers and other decision-makers to take targeted, local measures for sustainable forest management, aiding in both drought mitigation and long-term forest health in the face of climate change.

1 Introduction

Forests of Central Germany (Saxony, Saxony-Anhalt and Thuringia) are of ecological, economical and recreational importance in the region. In recent years, climate changes, particularly prolonged droughts in 2018, 2019, 2020 and 2022 (Meusburger et al., 2022; Obladen et al., 2021; Patacca et al., 2023; Spiecker and Kahle, 2023), have significantly affected the forest ecosystem. These droughts have not only directly led to water shortages and associated stress for trees and thus the whole forest ecosystem (Buras et al., 2020), but have caused indirect damage through pest outbreaks, such as the bark beetle (Hlásny et al., 2021). Moreover, it was found that especially under drought conditions, the weakened trees are less resistant to such pests (Vindstad et al., 2019). From 2018 until 2022, pest calamity and droughts have caused a loss of 500 000 hectares of forests in Germany, demanding for 900 million euros for climate-adapted forest management (Bundesministerium für Ernährung und Landwirtschaft, 2023). The quick spread of the insect infestation and other associated (and non-associated) forest damage (i.e.

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windfall) combined with the potential increase of the drought stress due to the climate change highlight the urgency of the situation and the need to develop effective countermeasures for both short- and long-term management strategies (Albrich et al., 2020; Schuldt et al., 2020).

The vitality and productivity of forests are highly dependent on the amount of water available in the soil (Spiecker and Kahle, 2023; Zang et al., 2014). Especially considering the climate change, where drought events and extreme weather conditions are likely to become more frequent and severe (Hanel et al., 2018; Orth et al., 2016; Zhou et al., 2019), it is essential to have reliable estimations of soil water availability in the forests (Meusburger et al., 2022). Up-to-day soil moisture information influences a wide range of forestry decisions from routine forest management and risk assessment to specific mitigation measures on sensitive sites (Sharma et al., 2022; Zweifel et al., 2023). For example, it plays a major role in planning of the planting and trimming actions based on current soil moisture conditions (Scholz et al., 2023). In addition, this real-time data helps with risk management, such as assessing the risks of wildfires during dry periods, the growth of associated pathogens, treefall of stressed and vulnerable trees in wet periods. In ecologically sensitive forest areas, operational data helps to make an appropriate choice of specialised technologies to maintain forest health and resilience. Thus, a precise real-time monitoring system of soil moisture can offer not only effective measures to mitigate drought vulnerability of forests, but also a crucial tool for sustainable forest management in the future.

Currently, few initiatives exist, such as for example North-western Switzerland (https://www.bodenmessnetz.ch) on a local national scale and the International Soil Moisture Network (https://ismn.earth/en/dataviewer, Dorigo et al., 2021) on a global international scale, which provide data on in-situ point-based soil moisture measurements. However, all these networks are still limited to its spatial and temporal coverage due to the very high operational costs. In this context, site-specific operational water balance modelling, especially in combination with climate change scenarios, is gaining attention over the pure measurement-based information platforms. At present, two main platforms exist for this purpose in Germany: the German Drought Monitor (https://www.ufz.de/index.php?en=37937, Zink et al., 2016) and the German Weather Service Soil Moisture Viewer (https://www.dwd.de/DE/fachnutzer/landwirtschaft/appl/bf_view/_node.html). However, despite the big potential of these systems for large-scale soil moisture assessment, they possess significant limitations in terms of their precision and scope for interpretation. The German Drought Monitor demonstrates simulation results from mHM model, converted statistically to a specific soil moisture index representing basically moisture anomalies, which are not adapted to specifics of local scale and different tree species or forest types. In addition, coarse resolution of the output product (4 km) generated from high-resolution soil maps (250 m) make the practical application of this index in forestry difficult (Speich, 2019; Meusburger et al., 2022). The German Weather Service Soil Moisture Viewer is using AMBAV agricultural model parameterized with even coarser soil maps (1 km), shows the plant-available-water only for three types of short vegetation and has a resolution of 1 km. Therefore, despite advances in the development of process-oriented hydrological models for the forests and the availability of the high-resolution datasets for their parameterisation in recent years (Hoermann and Meesenburg, 2000), these systems do not fully utilise their potential. Furthermore, they lack the ability to account properly for the small-scale variability of soil, land use and weather factors.

This motivates us to come up with a high-resolution point soil moisture monitoring system that is updated daily and takes into account important local site information such as for example aspect, slope, soil type and its profile. Thus, this site-specific data allows forest managers and decision-makers to take targeted local-scaled measures for sustainable forest management. In addition, a daily update enables timely detection of anomalies or emerging droughts, allowing for quick adaptation measures. The decisive value of our approach stems from the integration of existing inventory systems, in particular the Federal Forest Inventory, which provides detailed, site-specific and integrated information on the forests of Central Germany. Combining these datasets with an operational climate data, the effects of different tree species on the changes in soil moisture for a local scale can be better understood.

In this paper, we present an operational soil moisture monitoring system for Middle Germany that addresses the shortcomings of existing monitoring products and uses the current state-of-the-art forest hydrological modelling techniques, providing results in real-time for forest practitioners or interested users using a web-platform. We focused on a detailed and transparent technical description of the system architecture and the data representation on the website. Special attention is given to the qualitative and quantitative analysis of the operational climate data used for the model forcing.

2 Study region and forest monitoring data

2.1 Middle Germany region

Historically, the Middle Germany region (Fig. 1) relates to three states – Saxony (SN), Saxony-Anhalt (SA) and Thuringia (TN). The topography of the region ranges from the lowlands (0-200 m) in the north of SN and SA to mountainous regions on the south of SN (up to 1200 m) and TN (up to 1000 m). Prominent elevated geographical features are the Ore Mountains on the border with the Czech Republic, the Harz Mountains in the western part of SA and Thuringian Forest in the south of TN.

The climate conditions of Central Germany are characterised by a moderate continental climate. According to Köppen-Geiger climate classification (Kottek et al., 2006), all three states have predominantly Dfb (hemiboreal) climate type, meaning warm summers and cold winters, with occasional heat spells and typical frost-free periods of 3-5 months. Mean annual air temperature increases from +3-5°C in southern elevated parts to +10-12°C in the flatlands. Pronounced annual cycles introduce a high variability between summer and winter months as well as in between day-night temperatures. Maximum daily values could reach up to +35°C, while minimum daily temperatures can go far below zero (up to -21°C in Ore Mountains). Due to orographic effect, variations in the annual precipitation amounts are high as well. Mountainous regions of TN and SN receive 1100-1500 mm annually, while lowlands in the north get only 500-700 mm per year. Typically, around 70% of annual precipitation falls from May to September and the driest month is October.

According to Copernicus Global Land Service: Land Cover 100m (Buchhorn et al., 2019), total forest coverage of the region is about 36.9% (Fig. 1), from which evergreen needleleaf forests prevail and occupy 17.7%, deciduous broad leaf forests cover 7.6% and the rest are mixed forests (11.6%). The coniferous needle leaf forests are dominated by Norway spruce (Picea abies), Scots pine (Pinus sylvestris) and European larch (Larix decidua). The deciduous forests are dominated by European beech (Fagus sylvatica) and pedunculate oak (Quercus robur).

Soil types in the forests of Central Germany are highly variable depending on the topography, underlying geology and forest type. In general, in the mountainous regions of TN and SN podzols and brown soils are common for the forests and in lowlands gleys (or pseudogleys) appear along with abovementioned types as well (Krug, 2000). Typically, forest soils are characterised by rich humus horizons resulting from decades of accumulation of deciduous and coniferous litter. In deciduous forests, especially those dominated by beech and oak, the soils are often loamy with high humus content that promotes fertility. Coniferous forests, especially those dominated by spruce, often have pale podsolic loamy (or sandy loam) soils. These are typically more acidic and much less fertile than in deciduous forests. Mixed forests could combine the soil properties of deciduous and coniferous forests, although the specific properties are highly variable depending on the dominant tree species and site conditions.

2.2 Data from the German National Federal Forest Inventory

The National Federal Forest Inventory ('Bundeswaldinventur' in German, in short - 'BWI') is a long-term national German project aiming to collect and store information about forested areas in the country. It not only provides a comprehensive overview on the condition of Germany's forests, but also integrates important soil information. Every ten years, field observations are conducted to record tree species changes, growth data, update soil profile data and other relevant forest and soil information. To allow intercomparison between inventories, observations are made on the same plots (Fig.1) and using standardised procedure. Due to the secrecy of real plot coordinates, BWI rounds coordinates of the plots for the publishing, thus forming square/triangle-formed shapes with a side of 1 km within which the inventory sites lie. The third round of the BWI, which data is open sourced and was used in this study, took place in 2012 (https://www.bundeswaldinventur.de, Bundesministerium für Ernährung und Landwirtschaft, 2014). The fourth round started in 2021 and was completed by the end of 2022, however data processing is not finished yet (publication is planned for the end of 2024). The data provides insights into forest management, tree species composition, timber use and soil conditions. In particular, the soil data collection and update are essential for determining nutrient availability and water holding capacity, which directly affect forest health and growth. They also help to assess carbon sequestration and are key indicators of forest health and resilience to environmental stress. By linking forest and soil data with climate and site information, profound analyses of the effects of different environmental factors on forests can be carried out.

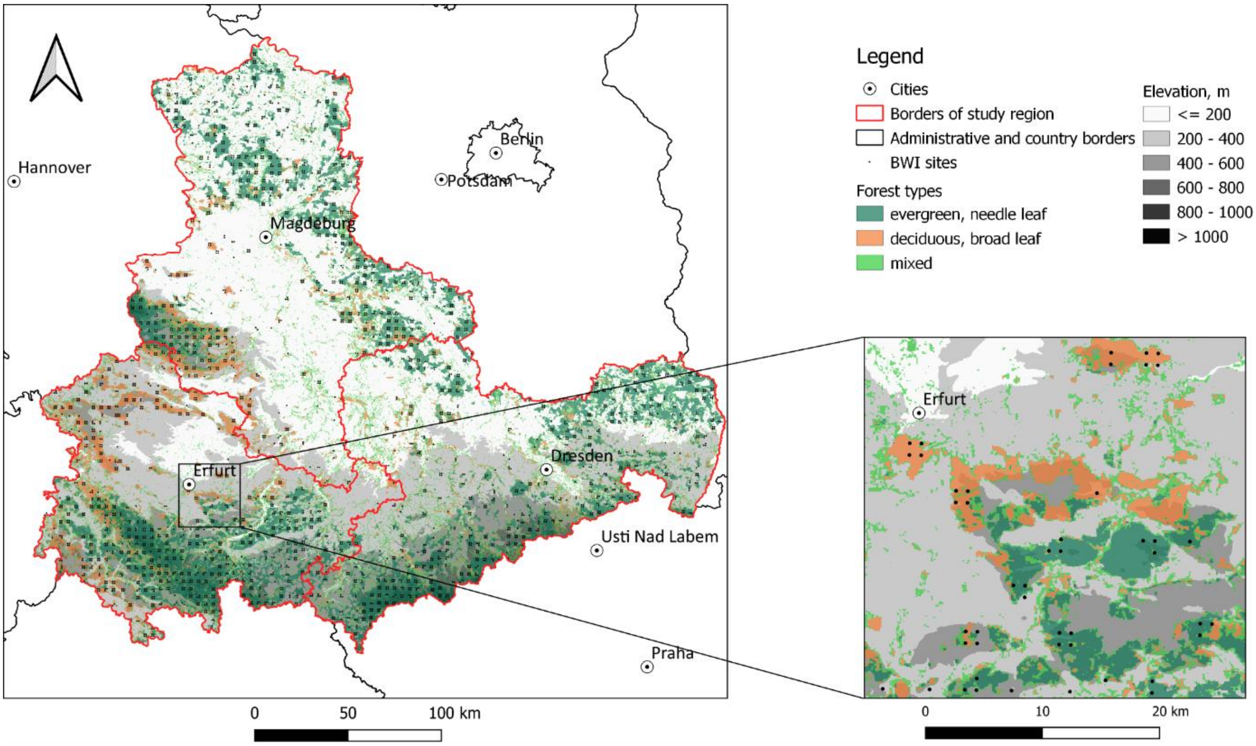


Figure 1. Overview of the study region and 3206 BWI monitoring sites.

2.3 Forest Climate stations and Local Soil Types

Another source of the monitoring data are the local forest authorities. Forestry of Saxony (‘Sachsenforst’) provides operational information from 21 forest climate stations (‘Waldklimastationen’) located in Saxony, which includes not only standard meteorological parameters, but also soil wetness measurements. The REST-API access to the data is provided via ‘OpenSensorHub’ (https://sh-rekis.hydro.tu-dresden.de/) under cooperation with Pykobytes GmbH.

Additionally, Forestry of Saxony provides the local soil types (Lokalbodenformen) dataset (Petzold et al., 2016). The local soil type is a subdivision of the (main) soil type that takes into account finer differences in the substrate, the deposition features, and the horizon arrangement. Additional criteria for their identification can include nutrient and humus ratios, which have significance for tree species selection and soil treatment. To distinguish these soil types, local place names are typically added in front of the main soil type, for example, for the main soil type ‘Gneiss Brown Soil’, local soil type ‘Ölsengrunder Gneiss Brown Soil’ could be identified. This dataset has around 50000 nodes in Saxony and is based on the soil profile excavation data as well as BWI; however, it does not belong to the monitoring forest system. Additionally, for each node, the dominant forest type data is available.

3 Framework description

3.1 LWF-BROOK90 water balance model and its parameterisation

The LWF-BROOK90 water balance model (Hammel and Kennel, 2001) is a branch of the BROOK90 model originally developed by Federer et al., 2003 and recently adopted in R-package ‘LWFBrook90R’ (Schmidt-Walter et al., 2020). As its ancestor, LWF-BROOK90 focuses on detailed atmosphere-plant-soil water exchange on a 1D scale and is well known for its accurate representation of evaporation and vertical soil water movement processes. The model applies modification of the Penman-Monteith approach by Shuttleworth and Wallace (Shuttleworth and Wallace, 1985) which allows separate evaporation process into its components: interception, transpiration, and bare soil (or snow) evaporation. This approach uses a ‘single big leaf’ concept and two layers, separating canopy and soil. The soil profile could be represented with multiple layers. The water movement within the soil column could be divided into matrix and macropore bypass flow. It is controlled by matrix potential as well as potential evaporation and is described with the Darcy-Richards equations using the Mualem-van Genuchten hydraulic parameterisation (van Genuchten, 1980), instead of Clapp and Hornberger (Clapp and Hornberger, 1978) used in BROOK90. Additionally, LWF-BROOK90 is capable of including dynamic temperature-based vegetation characteristics (i.e. bud-burst and leaffall timings, leaf-area-index variations) using ‘vegperiod’ package (Orlowsky et al., 2008).

For the study, a set of land cover parameters was created to represent beech, oak, spruce and pine mature forests commonly widespread in the region. Additionally, grassland land cover was considered as a reference. This parameter set represents site topographical conditions, plant stand with its stem, leaf coverage and roots parameters. The set is based on the standards for temperate deciduous broadleaf and evergreen coniferous forests and grasslands proposed by Federer et al., 1996 with adaptation to the site-specific conditions of Middle Germany. Site aspect and slope were calculated from SRTM30 (NASA JPL, 2019) digital elevation model. Forest height was set according to the GEDI dataset (Potapov et al., 2021). Main plant parameters like reflectivity, conductivity and stomatal behaviour, roughness, interception, root parameters were assigned based on existing extensive reports on the model application for the forests in Germany (Weis et al., 2023; Wellbrock et al., 2016), Level II data from forest monitoring plots (https://bwi.info/Download/) and measured and calibrated BROOK90 parameters for FLUXNET towers in Saxony (Vorobevskii et al., 2022). The vegetation phases are determined dynamically. Budburst timing is based on the chill-day-number method of Menzel, 1997, applicable for various tree species. For the leaffall phase von Wilpert, 1990 method was used, which takes into account temperature moving average or short day criteria. Seasonal course of Leaf Area Index (LAI) is then determined from maximum annual LAI, budburst and leaffall dates and duration using integrated ‘b90’ model. Root distribution over the soil profile is controlled by an integrated ‘betamodel’ (Gale and Grigal, 1987) with maximum length, depth of roots and curve shape parameters, which were assigned after Weis et al., 2023. It should be pointed out that long-term vegetation changes (i.e. tree ageing) are not considered in the presented operational-mode framework.

Soil parameters for the model were taken from the NFIWADS database, specifically created for BWI plots (Schmidt-Walter et al., 2019). Physical soil properties (layers, depth, texture, bulk density and coarse fragments) were obtained from the BWI soil profile database (Petzold and Benning, 2017). This database contains the predominant soil types for the inventory plots, based on the area within a 20 m radius of the centre of a plot. These soil types are linked to detailed soil profiles compiled by federal soil experts and based on the best available data in federal soil information systems for the BWI plots. Typically, all soil profiles contain information to a depth of at least 2m, unless the subsoil (bedrock) appears before. Based on this data, the hydraulic properties for the mineral soils, which are needed for Mualem-van Genuchten water retention curve and conductivity functions were determined using pedotransfer function (van Genuchten, 1980; Wessolek et al., 2009). These include the residual and saturated water content, 'n' parameter as a measure of pore-size distribution, 'alpha' parameter related to inverse of the air-entry, saturation conductivity and tortuosity parameter related to pore connectivity. Due to absence of data about forest floor horizons, a uniform root-free floor horizon (6 cm) was added to profiles to provide uniform soil evaporation conditions. For the organic soil horizons, retention and conductivity parameters were taken from Wösten et al., 1999. The depth of the soil profile was organised by dividing it into layers of increasing thickness.

3.2 Meteorological data

Meteorological data needed to force the LFW-BROOK90 model is collected from open-access database – German Weather Service (Deutscher Wetterdienst - DWD) File Transfer Protocol (FTP) server (https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/daily/). The following variables are used on a daily scale: minimum, maximum and mean air temperature, precipitation, wind speed, relative humidity and sunshine duration. At first, the summary table on all available meteorological stations in Germany provided and regularly updated by DWD ('Stationlsexikon') was filtered to meet the spatio-temporal and variable requirements of the study. Type of meteorological stations was limited to climatological and precipitation stations ('KL' and 'RR' types) with data availability starting from the year 2010. In total 147 climate and 619 precipitation stations matched the criteria (Fig. 2). According to FTP metadata meteorological data for the last day is added to the files between 9 and 10 a.m. of the current day. However, many test-trials revealed that usually real updates inside the files happen one or two hours later. Furthermore, station data is splitted in parts: 'historical' and 'recent' (data from the current year).

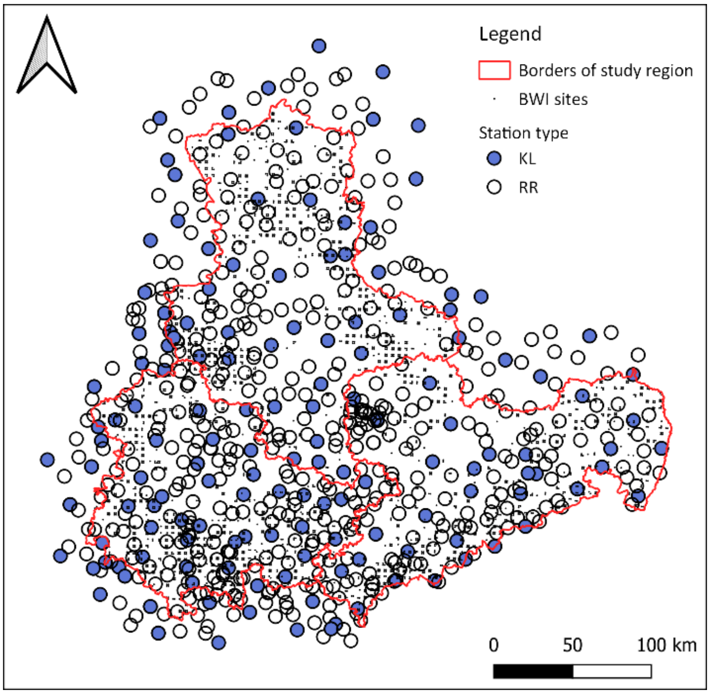


Figure 2. Potentially available meteorological stations within the study area.

In reality, available meteorological data which could be found and retrieved from the DWD FTP server significantly vary from the selected station short-list (Fig. 3). Up-to-date (1-day lag) air temperature and relative humidity data is available from around 115 stations, sunshine duration and wind data could be retrieved from 31 and 54 stations respectively. Finally, precipitation measurements are represented with 330 up-to-date stations. Still, the spatial coverage of meteorological data for all the variables in the study area can be considered good and homogeneous. Although the exact number of available stations with up-to-date data vary from day to day, test runs during the framework build up (June-October 2023) reveal, that these deviations are minor (< 5% of total station number).

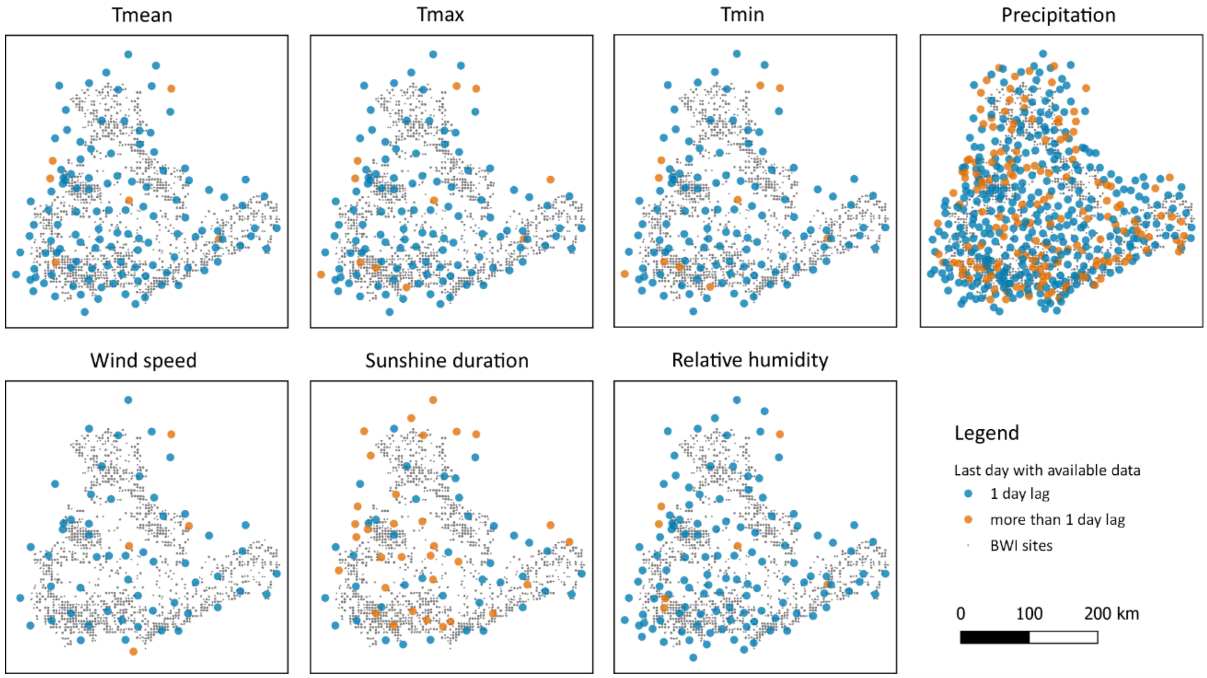


Figure 3. Real meteorological data availability for different variables for the study area: last date with not missing data (retrieved from DWD FTP server at 12:00 20.09.2023).

Figure 4 summarises the availability of actual (1-day-lag) meteorological data with regard to the distances to the BWI plots. Median distance to the nearest station with temperature and relative humidity is about 11 km, while for the less dense wind and radiation measurements the closest station is on average 15 km away. Precipitation stations due to higher density are typically found in much shorter distances of approximately 5 km.

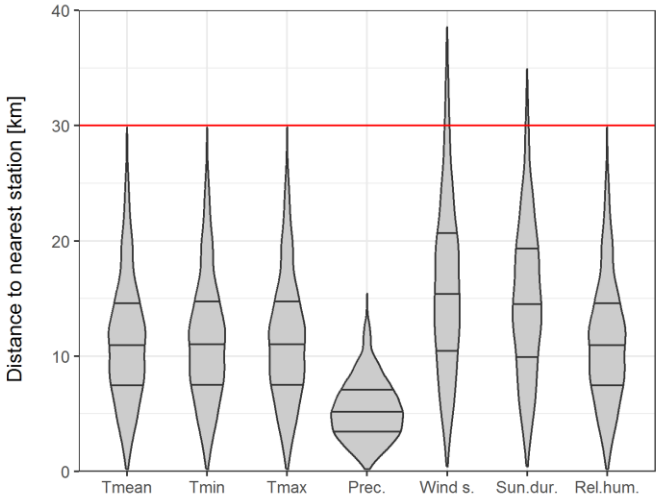


Figure 4. Violin plots with distance to the nearest meteorological station with available 1-day-lag data for BWI plots. Red line represents the chosen 30 km buffer zone. Horizontal lines inside violins represent the 25th, 50th and 75th quartiles.

For each BWI site, the meteorological input data to force the model is prepared in the following way. For all the necessary variables separately, framework scans for the nearest stations with available data within the 30 km buffer zone (Fig. 5). Filtered stations are thereafter checked for a real data availability. Stations with more than 5% of missing data (within simulation time period) are not further considered. Afterwards, inverse distance weighted mean is applied to create one time-series from filtered stations' data. In case there was no station found within the default buffer zone (e.g. some wind speed and sun duration data for some of the plots) or, 1-day-lag data is not presented in any of the filtered stations, the framework expands its buffer to take the next nearest station, which matches data criteria. To avoid too much smoothing of local weather patterns in case of too many stations available around the point, which is especially important for precipitation, the maximum number of stations, which are considered, is limited to seven nearest ones. Temperature and wind speed data are thereafter used directly as model input. Sunshine duration is converted to global radiation using site latitude and day of year according to Angstrom equation (Angstrom, 1924). Vapour pressure deficit is calculated from relative humidity and mean air temperature using Magnus equation (Alduchov and Eskridge, 1996). Precipitation values are corrected for the systematic measurement error (i.e. drifting, wetting, evaporation) using mean air temperature, day of the year and 'well-protected' station-shielding type using Richter equation (Richter, 1995). Finally, if any NA values appear in the prepared time-series, they are filled with monthly-mean values, which however never happens for the 1-day-lag data.

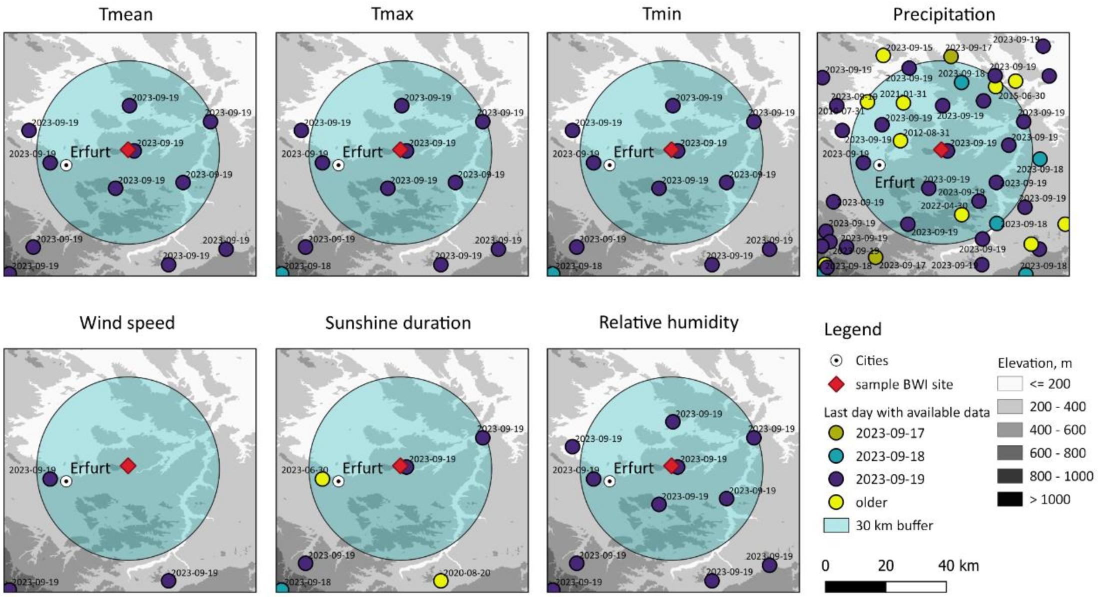


Figure 5. Subset of available meteorological data for selected BWI site (retrieved from DWD FTP server at 12:00 20.09.2023).

LWF-BROOK90 uses precipitation input on a daily scale as default and disaggregates the data into hourly resolution internally using the 'pdur' parameter (average duration of daily precipitation by month, 4h for each by default). Therefore, to improve correct separation between canopy interception, overland flow and infiltration, it was decided to estimate this parameter more accurately based on real data from meteorological stations in the area. For that, three climate stations with hourly time series

1995-2022 were taken: Erfurt-Weimar (ID#1270), Magdeburg (ID#3126) and Dresden-Klotzsche (ID#1048). Resulting monthly duration values averaged over three stations were found to be 3h in all months except for November (4h).

3.3 Operational mode and website

The first pilot version of 'Soil Moisture Traffic Light' was first released in 2022 (Kronenberg et al., 2022). The setup was successfully validated using soil moisture measurements from eight grassland and three forest sites for the 2006-2019 time-period (Luong et al., 2023). The novel framework, initially developed and tested for Saxony, has now upgraded its architecture, improved meteorological input and model parameterization and been expanded spatially in this paper.

The presented upgraded framework for three German regions is functioning in an operational automatic mode with 24h update time (Fig.6). It starts each day at 11 a.m. with the download and pre-processing of 1-day lag meteorological data, which lasts about 3 min. Afterwards, the simulations for each BWI site (with four dominant tree types and grassland, resulting in 3206 plots * 5 vegetation types model runs) and forest climate stations (with grassland for 21 stations) are run for a 10-year period using parallel processing, which takes approximately 40 min with 48 cores and could be potentially reduced by applying more cores. Despite the fact that the tree-species composition at each BWI site is known, in some of the cases it is a mixed forest with no predominant tree type, moreover, forest managers requested that the results should be presented for each of the selected tree species at each plot. For the local soil types, the results were assigned from the neighbouring BWI plots based on dominating forest and soil type. Raw model runs are post-processed and stored in 'csv' and 'geojson' files, which can be downloaded from the website. Soil moisture conditions are represented with the Root Extractable Water (REW) coefficient (Eq. 1), which indicates the amount of water left in the soil profile accessible to the plant before it starts to wilt:

$$REW = \frac{THETA_{c} - THETA_{wp}}{THETA_{fc} - THETA_{wp}} \qquad (1)$$

where $THETA$ is volumetric soil moisture and different indexes state for different conditions: C is current value, WP is wilting point, and FC is field capacity. Here, the soil moisture at the field capacity is directly taken from the hydraulic properties of the soil based on soil type and pedotransfer function. Soil moisture at the wilting point however is not only dependent on soil type, but also on a plant, while for different tree species the wilting point typically varies between -1.5 and -2.5 mPa, which was taken into account. Values of REW greater than 1 indicate oversaturation (soil moisture is higher than field capacity) and values lower than 0 represent situation, when soil water content is below the plant-extractable threshold (i.e. water remains only in smallest pores and as films or is chemically-bonded to soil particles).

The final product of the framework is the 'Soil Moisture Traffic Light' website, which is accessible online via https://life.hydro.tu-dresden.de/BoFeAm/dist_bfa_kk/index.html. It was developed using the Node Package Manager in conjunction with the Javascript runtime environment Node.js using OpenLayers and ApexCharts Java libraries. These enable the web display of geodata and various data visualisations. As the main stakeholders are German authorities, the website was initially made only in German. The framework uses two virtual machines provided and managed by the Center for information services and high performance computing (ZIH) of TU Dresden.

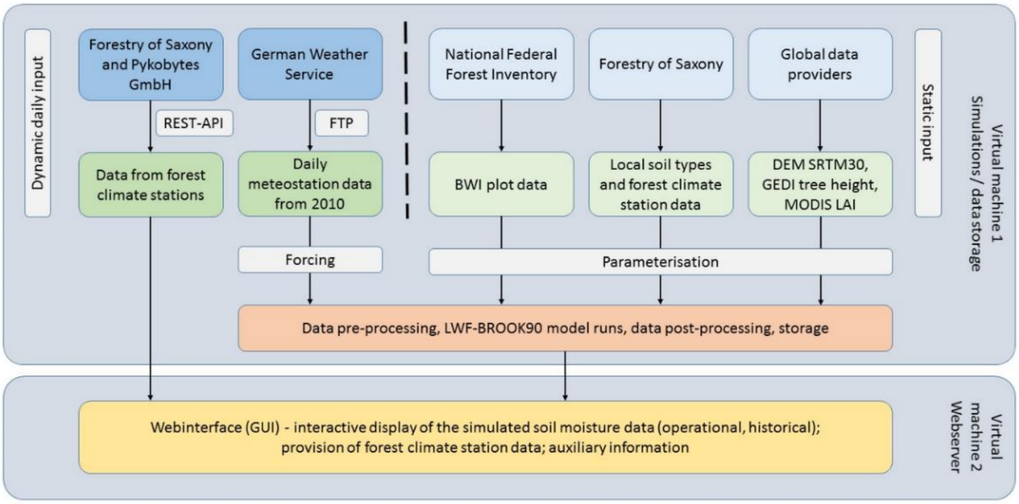


Figure 6. Framework architecture.

4 Results

4.1 Advantages of point simulations

Main difference between raster and point simulations is accounting for local conditions. Raster-based setups are capable of covering the whole area of interest without gaps, however, due to high computational costs, local scale (first hundreds of meters) could not be reached so far (Vorobevskii, 2023). Thus, point-based setups are still superior when it comes to local scale, since here local differences is geographical conditions could be easily taken into account. To illustrate the advantages of the point-based framework two examples were chosen. Local effects of precipitation front which occurred after a dry week (no recorded precipitation for almost all used stations) over the study region on the soil moisture is shown on Figure 7. It could be seen (Fig. 7a), that the daily precipitation sums on the autumn day of 12.09.2023 decrease from 20-30 mm on the north-west (some stations recorded up to 48 mm) to 0.1-1 mm on the south-east (about 60 stations mostly located in Ore mountains did not record any precipitation on that day). The soil moisture situation under spruce forests for the major parts of the region before the rain event could be expressed as a drought condition, as the precipitation sums for the August and beginning of September were below the climate means while the potential evaporation was still high. REW values (Fig. 7a) in the lowlands were mostly below 0.1, while in the mountainous regions enough plant-available water (REW>0.6) was simulated, which correlates well with the topography and soil textures distribution. This soil moisture situation is also confirmed by absolute values of volumetric water content (Fig. 7b). Thus, low REW values correspond to 4-15% of water content, while normal and wet conditions (REW>0.4) showed volumetric soil moisture content in general between 15% and 30%. As expected, under the conditions of severely depleted water storage in the soils in lowlands, even a considerable amount of precipitation did not result in significant improvement of drought conditions for the plants or soil water storage recharge. BWI sites located near the meteorological stations, which registered more than 10 mm showed on average 0.1-0.15 REW (or 4-6% for volumetric moisture) increase, while for the rest, the change was on average less than 0.05. Overall, all the local changes for 12.09.2023 followed the precipitation patterns. Comparing two selected depths, it could be concluded that the upper soil layers (up to 40 cm) showed more distinct reaction to the rain event. The lower horizons (up to 100 cm), which on 11.09.2023 had lower mean soil moisture content (especially for sites with REW>0.3), were almost not affected by the event. Here volumetric soil moisture increased on average only by 1-2 % even in north-western parts. This could be explained by the fact, that under general drought conditions, infiltration of even a substantial rainfall amounts into deeper horizons was prevented in the topsoil by root uptake and thereafter transpiration process.

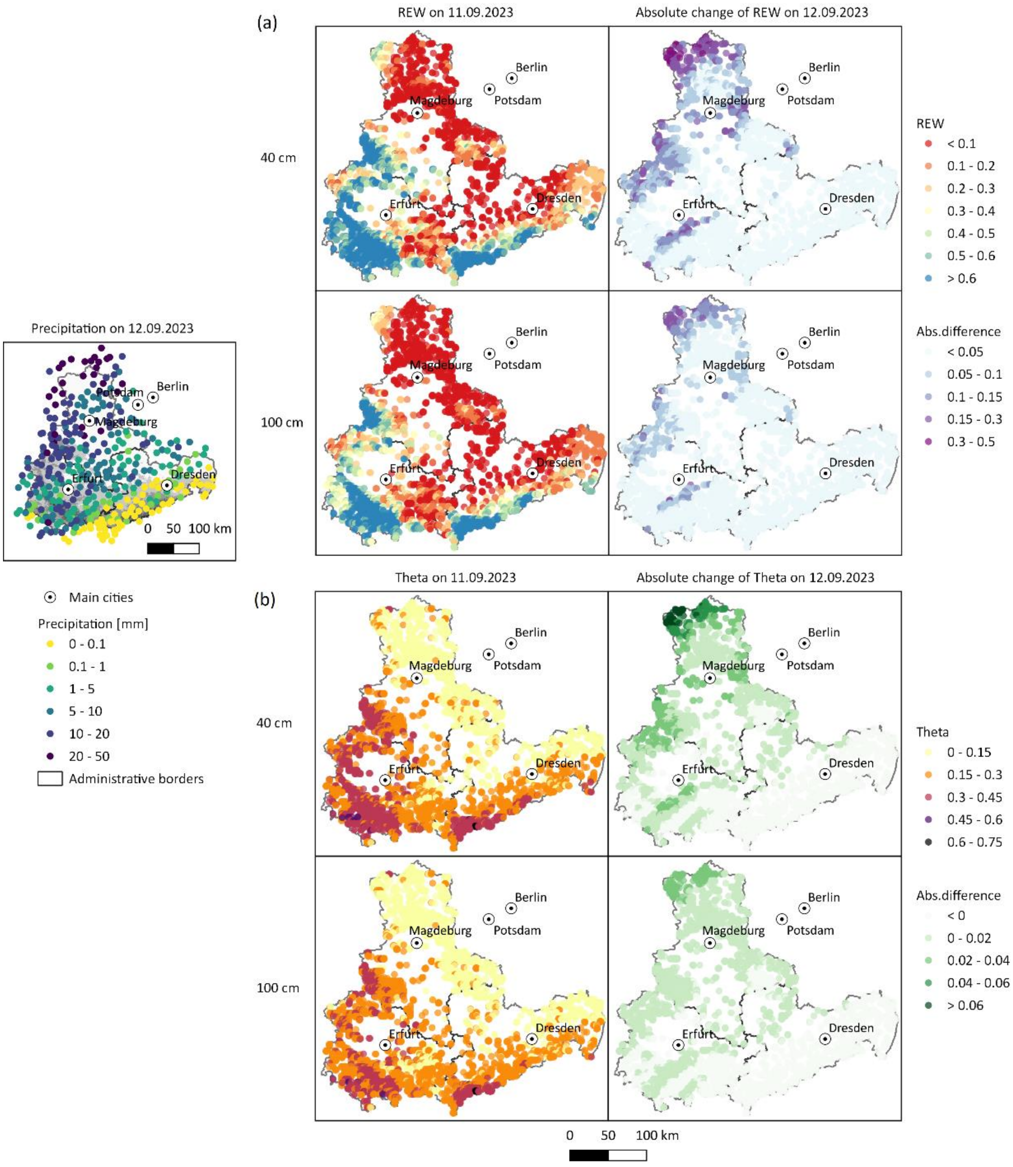


Figure 7. Spatial effect of one-day rainfall after a dry week (a) on REW (b) and volumetric soil moisture content (c) in spruce forests for 40 and 100 cm profile depth

The effect of the local-scale topography on the depletion of the soil moisture storage in the beginning of the 2018-2019 drought period is shown on Figure 8. Here both slope and aspect influence the net radiation and downslope flow, thus affecting the potential evaporation and soil column outflow rate respectively. Thus, south-orientated site (#56712_3) with an almost 25-degree slope showed up to 20% lower REW values than north or west sites with flat slopes, especially in the drought propagation phase. Moreover, different tree species exhibited varying reactions and sensitivities to changes in soil moisture based on the topographical features. During the growing season (spring 2018), this impact was notably pronounced in deciduous forests owing to the higher available soil water resulting from reduced transpiration and interception rates. However, during summer period, the influence of slope and aspect became more significant in spruce forests due to elevated total evaporation rates (which are indicated by larger LAI and SAI values compared to beech forests).

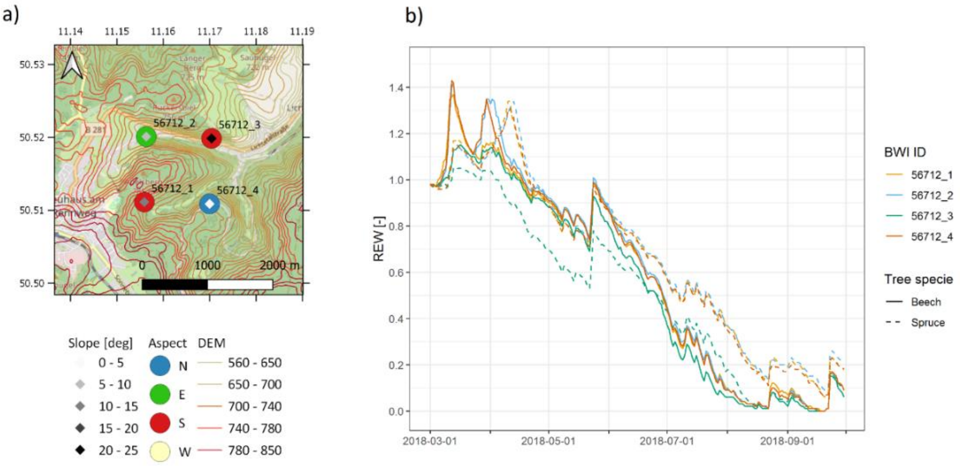


Figure 8. Effect of slope and aspect (a) of BWI plot (#56712, near Apelsberg, Thuringia) on the simulated REW values (up to 100 cm depth) in spruce and beech forests for the drought propagation phase in 2018 (b).

4.2 Accounting for seasonality in soil moisture changes during vegetation period

As the study region has heterogeneous topographical, climatological and landscape features, they all have a strong influence on the seasonal course of soil moisture. As an example, fortnight changes of REW up to 1 m depth under beech forests for a 'normal' (climatologically, meaning not abnormally dry or wet) year of 2020 are presented (Fig. 9). In January, soil moisture in the central and northern parts is still not recovered from the dry season of 2019, especially in the eastern parts of Saxony, where the REW values were around 0.2. Starting from February until the end of March, precipitation amounts and snowmelt combined with low evaporation rates (deciduous forest, thus mainly only stem interception and soil/snow evaporation occur) refill soil with moisture until its maximum annual values. High-elevated areas in the south of Thuringia and Saxony, as well as western and northern parts of Saxony-Anhalt received therefore oversaturated soils (REW>1.2) for more than a month, while middle part of the area still remained unsaturated (REW<0.6). Thereafter in the beginning of the vegetation period (growing phase in April-May) soil moisture mostly remained in normal stable conditions (0.6<REW<1), while constantly, but slowly increasing evaporation values were still compensated by relatively high precipitation input. Starting from June and till the end of September transpiration clearly dominated among evaporation processes and coupled with typically lower rainfall sums, let the soil water storage quickly deplete and remain almost in an empty state (REW<0.2). Thus in this time period, almost all the precipitation input was immediately consumed by the forest and did not contribute to refill of the soil profile. Situation started to straighten out in the middle of October with the leaffall and thus a reduction of total evaporation, so that the fallen rainfall could finally recharge depleted soil water storage. Due to typically higher precipitation amounts in the mountainous regions, this process started and was more clearly visible exactly in the southern parts of the study area, while in the middle and northern typically flat and dryer parts, the moisture refill was much slower and less effective. Thus, by the end December, the spatial distribution of the soil moisture under the beech forests looked similar to what it has started with in the January of 2020.

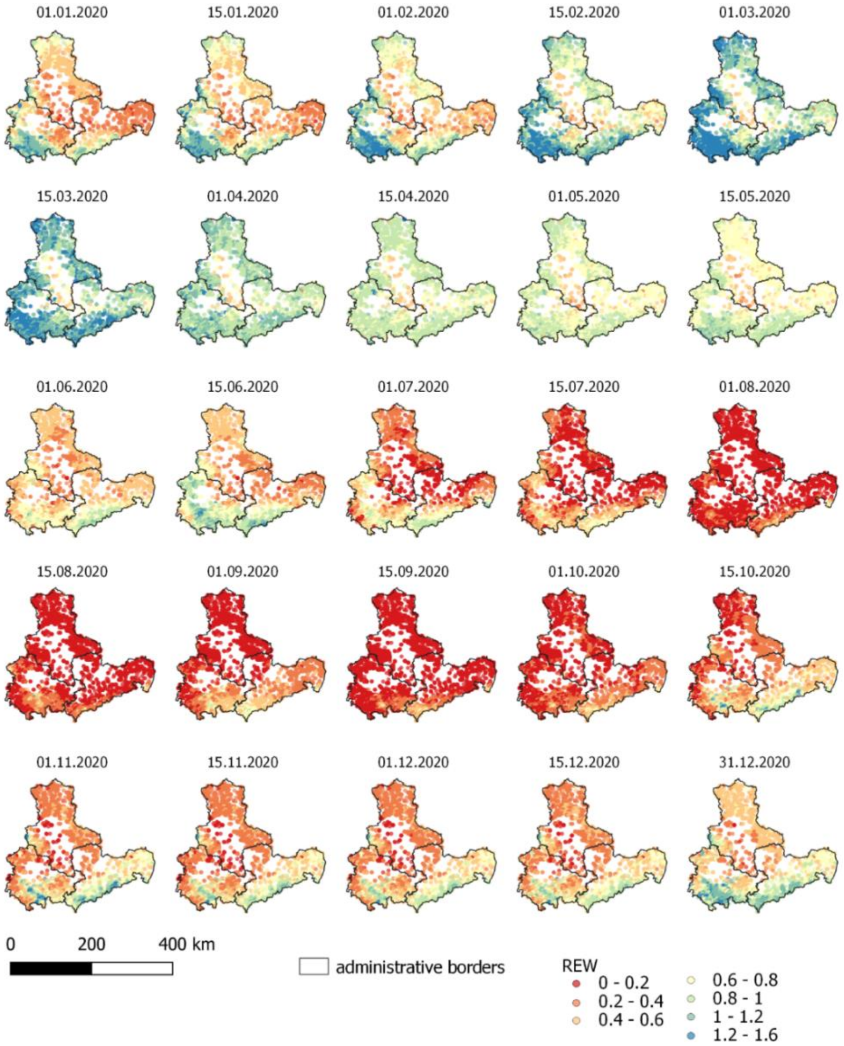


Figure 9. Seasonal changes of REW (up to 100 cm depth) under beech forests in 2020.

4.3 Influence of forest composition on the evaporation and its components

Redistribution of precipitation input into evaporation and runoff components as well as in their sub-components is crucial for correct representation of in-situ soil moisture. Long-term simulations (30 years) for the BWI plots revealed that the evaporation-precipitation ratio (Fig. 10) in deciduous forests is lower (85% median) than in coniferous forests (95% median) and has higher range (almost 50%). Highest values were found in central and northern dry flatland areas. Evaporation of intercepted rain and snow is a substantial part of mature forests and possesses large spatial heterogeneity. It is estimated higher for spruce (350 mm/year median) and pine (330 mm/year median) forests, thereby deciduous showed much lower interception amounts (220 mm/year median). Transpiration, on the other hand, was found higher for oak (350 mm/year median) and beech (320 mm/year median) forests, while coniferous forests transpire about 270 mm/year. Soil evaporation is the smallest part of total evaporation (about 20%) and remains almost stable with regard to spatial scale and vegetation cover (80-90 mm/year median).

Although bandwidth of obtained E/P ratios for forests does cover a very wide range (0.5-1), high median E/P ratios (above 0.8) do not correspond well with other studies. For example, in the study of Renner et al., 2014, it was found, that according to watershed-based evaporation estimations (discharge subtracted from precipitation), the E/P ratio for small forest-dominated catchments in Saxony laid typically in a range of 0.3-0.7 for the 1950-2009 time-period. It was however mentioned, that actual evaporation tends to consistently increase in the last two decades. In another study by Vorobevskii et al., 2022 different BROOK90 frameworks were applied to simulate FLUXNET sites within Saxony. It was found, that the E/P ratios in forest stands based on measurements (0.50 for Tharandt, 0.41 for Oberbärenburg and 0.65 for Hetzdorf) could not be reached with standard model parameterisation without calibration, especially for coniferous forests, where modelled E/P ratios were found up to 0.8. These facts reveal the importance and sensibility of the model parameterisation, especially regarding the interception component, which should be addressed more in-depth in further studies.

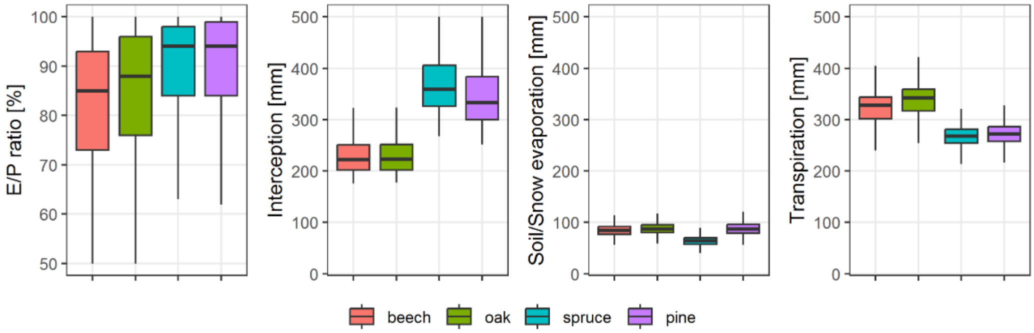
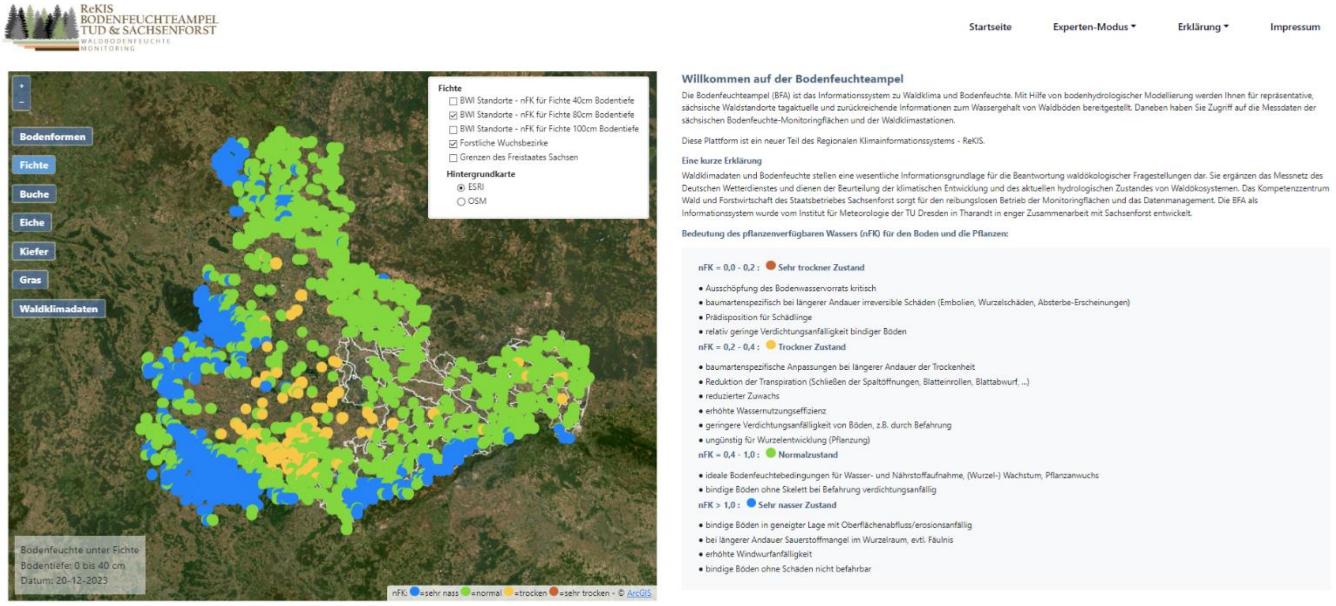


Figure 10. Mean annual evaporation components in different forest types for 1990-2020 period.

4.4 Soil Moisture Traffic Light - informative web-platform for forest managers

The website homepage (Fig. 11) shows the soil moisture conditions for 3206 BWI tract corners located in Thuringia, Saxony and Saxony-Anhalt. For easier communication of the results to non-expert stakeholders, current moisture states are divided into four colour categories: very wet (‘sehr nass’), normal (‘normal’), dry (‘trocken’) and very dry (‘sehr trocken’). Intuitive buttons allow the user to switch between different vegetation types (‘Fichte’ for spruce, ‘Eiche’ for oak, ‘Buche’ for beech, ‘Kiefer’ for pine, ‘Grass’ for grass) and different soil profile depths (0-40 cm, 0-80 cm and 0-100 cm). There is also an option to customise the background maps with Google Maps or OpenStreetMap. On the right side, the user finds supportive information of what each colour means in terms of vegetation feedback.

The expert mode offers deeper insights into the soil moisture condition of each BWI plot. By clicking on a specific point on a map (or menu bar), the user gets detailed information (Fig. 12c) on the selected plot (name and ID, soil profile data, forest type, climate overview). Furthermore, on the right side two interactive graph panels appear. Upper graph (Fig. 12a) shows a temporal REW (‘nFK’) course up to a depth of 40 cm for the current year with different quantiles and median values as a background, calculated from 30-year period historical simulations. Lower panel (Fig. 12b) gives an overview on the annual REW developments for different soil depths up to 100 cm. In addition, expert mode provides the possibility to download raw data from each of the shown panels. Additionally, the simulations for forest climate stations (Fig. 13) and the local soil types with dominant forest type (Fig. 14) are presented, which are currently available only for Saxony. Besides presentation of the up-to-date main climate elements, the soil moisture measurements data from the climate stations could be used as an indirect validation of the framework (with grassland as a chosen land cover). Further, the website has FAQ and Glossary (under the ‘Erklärung’ button), which explains the main methods and terms behind the framework. Finally, a citizen-science approach was implemented via Feedback-survey button (‘Umfrage’) on the start page to continuously optimise the application.



Fichte
☐ BWI Standorte - nFK für Fichte 40cm Bodentiefe
☑ BWI Standorte - nFK für Fichte 80cm Bodentiefe
☐ BWI Standorte - nFK für Fichte 100cm Bodentiefe
☑ Forstliche Wuchsbezirke
☐ Grenzen des Freistaates Sachsen

Hintergrundkarte
● ESRI
○ OSM

Bodenfeuchte unter Fichte
Bodentiefe: 0 bis 40 cm
Datum: 20-12-2023

Willkommen auf der Bodenfeuchteampel

Die Bodenfeuchteampel (BFA) ist das Informationssystem zu Waldklima und Bodenfeuchte. Mit Hilfe von bodenhydrologischer Modellierung werden Ihnen für repräsentative, sächsische Waldstandorte tagaktuelle und zurückreichende Informationen zum Wassergehalt von Waldböden bereitgestellt. Daneben haben Sie Zugriff auf die Messdaten der sächsischen Bodenfeuchte-Monitoringflächen und der Waldklimastationen.

Diese Plattform ist ein neuer Teil des Regionalen Klimainformationssystems - ReKIS.

Eine kurze Erklärung

Waldklimadaten und Bodenfeuchte stellen eine wesentliche Informationsgrundlage für die Beantwortung waldökologischer Fragestellungen dar. Sie ergänzen das Messnetz des Deutschen Wetterdienstes und dienen der Beurteilung der klimatischen Entwicklung und des aktuellen hydrologischen Zustandes von Waldökosystemen. Das Kompetenzzentrum Wald und Forstwirtschaft des Staatsbetriebes Sachsenforst sorgt für den reibungslosen Betrieb der Monitoringflächen und das Datenmanagement. Die BFA als Informationssystem wurde vom Institut für Meteorologie der TU Dresden in Tharandt in enger Zusammenarbeit mit Sachsenforst entwickelt.

Bedeutung des pflanzenverfügbaren Wassers (nFK) für den Boden und die Pflanzen:

nFK = 0,0 - 0,2 : ● Sehr trockner Zustand

- Ausschöpfung des Bodenwasservorrats kritisch
- baumartenspezifisch bei längerer Andauer irreversible Schäden (Embolien, Wurzelschäden, Absterbe-Erscheinungen)
- Prädisposition für Schädlinge
- relativ geringe Verdichtungsanfälligkeit bindiger Böden

nFK = 0,2 - 0,4 : ● Trockner Zustand

- baumartenspezifische Anpassungen bei längerer Andauer der Trockenheit
- Reduktion der Transpiration (Schließen der Spaltöffnungen, Blatteinrollen, Blattabwurf, ...)
- reduzierter Zuwachs
- erhöhte Wassernutzungseffizienz
- geringere Verdichtungsanfälligkeit von Böden, z.B. durch Befahrung
- ungünstig für Wurzelentwicklung (Pflanzung)

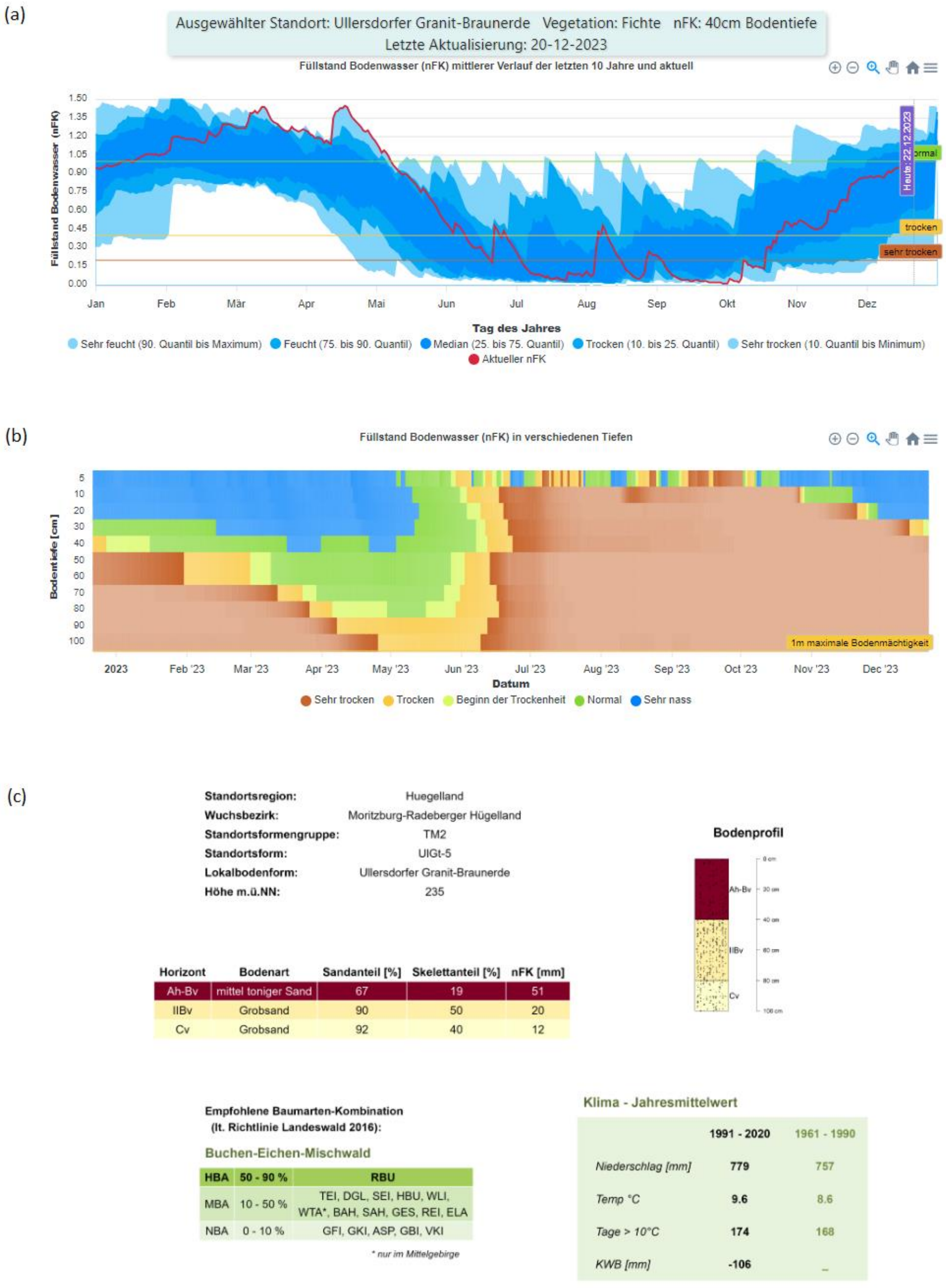
nFK = 0,4 - 1,0 : ● Normalzustand

- ideale Bodenfeuchtebedingungen für Wasser- und Nährstoffaufnahme, (Wurzel-) Wachstum, Pflanzanwuchs
- bindige Böden ohne Skelett bei Befahrung verdichtungsanfällig

nFK > 1,0 : ● Sehr nasser Zustand

- bindige Böden in geneigter Lage mit Oberflächenabfluss/erosionsanfällig
- bei längerer Andauer Sauerstoffmangel im Wurzelraum, evtl. Fäulnis
- erhöhte Windwurfanfälligkeit
- bindige Böden ohne Schäden nicht befahrbar

Figure 11. Overview Soil Moisture Traffic Light platform – REW map for spruce stand for 20.12.2023 (80 cm depth)



Standortsregion:	Huegelland
Wuchsbezirk:	Moritzburg-Radeberger Hügelland
Standortsformengruppe:	TM2
Standortsform:	UIGt-5
Lokalbodenform:	Ullersdorfer Granit-Braunerde
Höhe m.ü.NN:	235

Horizont	Bodenart	Sandanteil [%]	Skelettanteil [%]	nFK [mm]
Ah-Bv	mittel toniger Sand	67	19	51
IIBv	Grobsand	90	50	20
Cv	Grobsand	92	40	12

Empfohlene Baumarten-Kombination
(lt. Richtlinie Landeswald 2016):

Buchen-Eichen-Mischwald

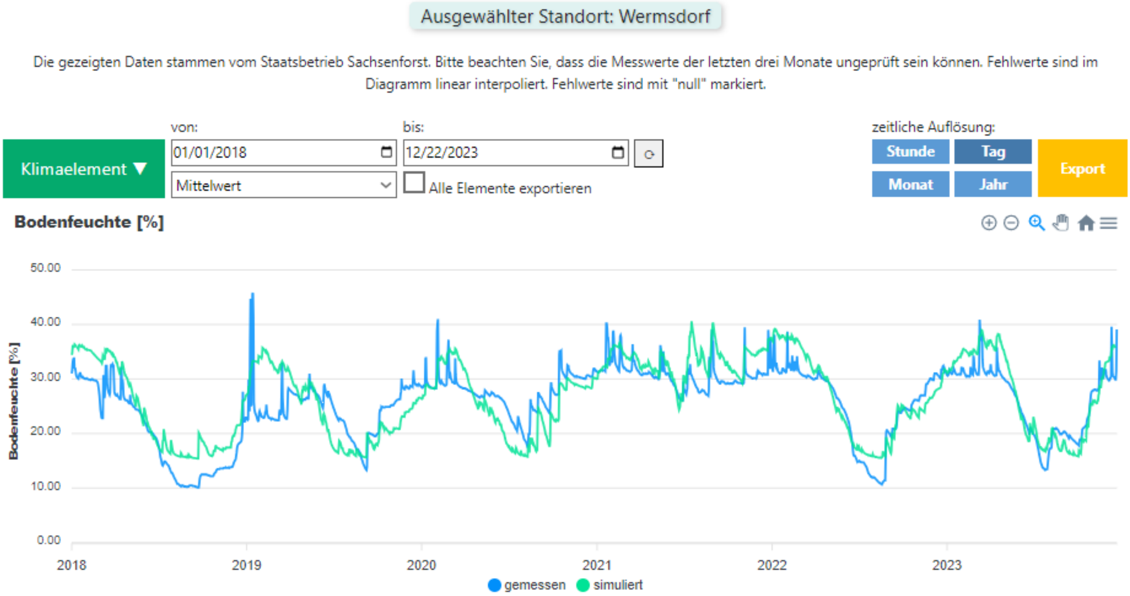
HBA	50 - 90 %	RBU
MBA	10 - 50 %	TEI, DGL, SEI, HBU, WLI, WTA*, BAH, SAH, GES, REI, ELA
NBA	0 - 10 %	GFI, GKI, ASP, GBI, VKI

** nur im Mittelgebirge*

Klima - Jahresmittelwert

	1991 - 2020	1961 - 1990
Niederschlag [mm]	**779**	757
Temp °C	**9.6**	8.6
Tage > 10°C	**174**	168
KWB [mm]	**-106**	–

380 **Figure 12. Overview on the expert-mode of the Soil Moisture Traffic Light for one selected BWI site (#52174_2, Dresdner Heide, Saxony) and spruce forest: simulated REW until 40 cm depth for the current year in comparison to quantiles derived from the 30-year historical runs (a); simulated REW for the different layers of the whole soil profile for the current year (b); detailed information on the soil profile, tree composition and standard climate elements (c)**

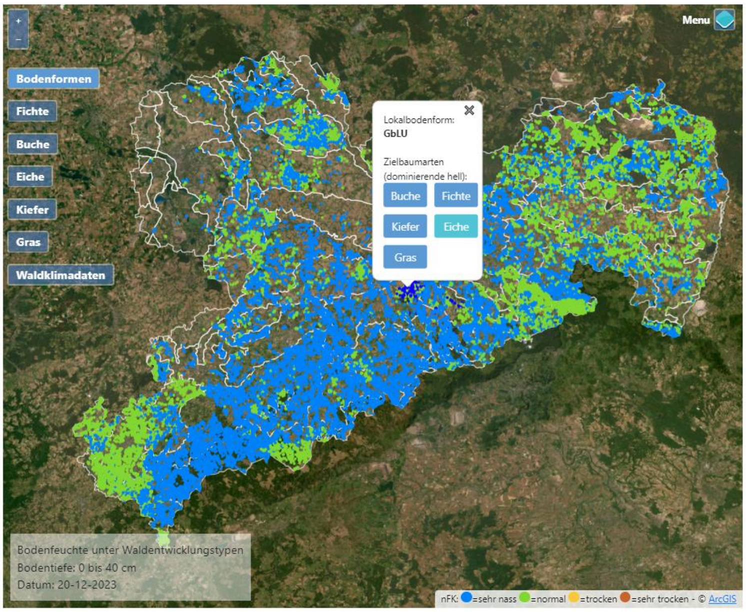


Ausgewählter Standort: Wermsdorf

Die gezeigten Daten stammen vom Staatsbetrieb Sachsenforst. Bitte beachten Sie, dass die Messwerte der letzten drei Monate ungeprüft sein können. Fehlwerte sind im Diagramm linear interpoliert. Fehlwerte sind mit "null" markiert.

von: 01/01/2018
bis: 12/22/2023
Mittelwert
☐ Alle Elemente exportieren

385 **Figure 13. Example of the integrated forest climate stations soil moisture data for grassland (Wermsdorf, 2018-2023) in the Soil Moisture Traffic Light (simulated values in green, measured values in blue colour)**



Lokalbodenform: GbLU

Zielbaumarten (dominierende hell):

Bodenfeuchte unter Waldentwicklungstypen
Bodentiefe: 0 bis 40 cm
Datum: 20-12-2023

Figure 14. Representation of the local soil types with dominant trees in the Soil Moisture Traffic Light

5 Conclusion

The article highlights the need for high-resolution operational soil moisture monitoring in the forests of Central Germany.
390 Existing soil moisture monitoring products possess various practice-oriented limitations, including spatial coverage and

resolution issues. The presented operational point-based framework addresses major shortcomings of the existing systems taking into account local information, including meteorological (station) and geographical (i.e. aspect, slope, forest type and specific soil profile data) point data. This system allow forest managers to take targeted, local-scale measures for sustainable forest management.

The framework's technical details and its architecture are described in detail, including its all core elements such as the LWF-BROOK90 water balance model, meteorological data and its processing techniques, land cover and soil parameterization based on the National Federal Forest Inventory datasets. The operational mode and website as the end-product through which the results are presented to end-users are outlined. We highlighted the advantages of high-resolution point simulations in understanding soil moisture dynamics, illustrating the impacts of a single precipitation event and local geographical conditions on soil moisture conditions. Further, the seasonal dynamics of soil water storage in different regions was demonstrated. Thereafter we showed influence of different tree species on the redistribution of the main water balance components. Finally, the Soil Moisture Traffic Light web information platform was introduced and showcased, representing a significant advance in the dissemination of information about soil moisture for three German regions to forest managers and stakeholders, providing an intuitive and informative tool for more effective monitoring and management of forest ecosystems.

7 Outlook

Since the pilot release in 2022, we continue development of the Soil Moisture Traffic Light and the framework constantly receives new upgrades. In the future, these updates could include the following features.

- Model parameterisation itself could be improved, especially the representation of LAI as one of the most sensitive model parameters. Incorporation of dynamic annual values using Coupmodel (Jansson and Karlberg, 2004) method (in-build in the LWF-BROOK90 R-package) based on MODIS satellite data will improve the evaporation estimations.
- Operational mode of the framework could be expanded to a seasonal forecast time-scale, by getting access to German Weather Service long-term meteorological forecast data.
- Local soil types and up-to-date information from forest monitoring stations from another two states could be included in the product based on the data availability and cooperation with forestry authorities.
- Other tree species could be included, based on the availability of appropriate parametrization sets. Moreover, with the emerge of new high-resolution (10 m) ‘Dominant tree species for Germany’ dataset (Blickensdörfer et al., 2022) it is possible to provide higher spatial coverage and more detailed soil moisture information in the end-product.
- The framework in general could be set up for other vegetation types. This could be especially of high interest in the case of simulations for various crops and thus advancing agricultural management.
- Extension of the framework to the whole of Germany is possible, as the BWI database and climate data are available. For that, the computational costs will be much higher and need to be advanced.

- As a 1D-model, LWF-BROOK90 is not suited to simulate stagnant and groundwater-influenced sites in a satisfying manner. Therefore, other model (i.e. SWAP-model (Kroes et al., 2017)) or model coupling is needed in these cases.

Data and Code availability

Soil Moisture Traffic Light web-platform is assessable via https://life.hydro.tu-dresden.de/BoFeAm/dist_bfa_kk/index.html. Simulation results and R-scripts to reproduce figures and tables for the manuscript could be provided upon a request due to a relatively large size (20 GB).

Author contribution

Conceptualization VI, LTT and KR; data curation VI, LTT and PR, formal analysis VI, methodology VI, LTT; visualization VI; writing: original draft preparation VI and LTT, writing: review KR, PR.

Competing interests

The authors declare that they have no conflict of interest.

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References

Albrich, K., Rammer, W., and Seidl, R.: Climate change causes critical transitions and irreversible alterations of mountain forests, Global Change Biology, 26, 4013–4027, https://doi.org/10.1111/gcb.15118, 2020.

Alduchov, O. A. and Eskridge, R. E.: Improved Magnus Form Approximation of Saturation Vapor Pressure, Journal of Applied Meteorology and Climatology, 35, 601–609, https://doi.org/10.1175/1520-0450(1996)035<0601:IMFAOS>2.0.CO;2, 1996.

Angstrom, A.: Solar and terrestrial radiation. Report to the international commission for solar research on actinometric investigations of solar and atmospheric radiation, Quarterly Journal of the Royal Meteorological Society, 50, 121–126, https://doi.org/10.1002/qj.49705021008, 1924.

Blickensdörfer, L., Oehmichen, K., Pflugmacher, D., Kleinschmit, B., and Hostert, P.: Dominant Tree Species for Germany (2017/2018), 2022.

Buchhorn, M., Smets, B., Bertels, L., Lesiv, M., and Tsendbazar, N.-E.: Product user manual. Moderate dynamic land cover 100 m. Version 2., Copernicus Global Land Operations “Vegetation and Energy,” 2019.

Bundesministerium für Ernährung und Landwirtschaft: Der Wald in Deutschland - ausgewählte Ergebnisse der dritten Bundeswaldinventur, 2014.

Bundesministerium für Ernährung und Landwirtschaft: Massive Schäden - Einsatz für die Wälder, Bundesministerium für Ernährung und Landwirtschaft, 2023.

Buras, A., Rammig, A., and Zang, C. S.: Quantifying impacts of the 2018 drought on European ecosystems in comparison to 2003, Biogeosciences, 17, 1655–1672, https://doi.org/10.5194/bg-17-1655-2020, 2020.

Clapp, R. B. and Hornberger, G. M.: Empirical equations for some soil hydraulic properties, Water Resources Research, 14, 601–604, https://doi.org/10.1029/WR014i004p00601, 1978.

Dorigo, W., Himmelbauer, I., Aberer, D., Schremmer, L., Petrakovic, I., Zappa, L., Preimesberger, W., Xaver, A., Annor, F., Ardö, J., Baldocchi, D., Bitelli, M., Blöschl, G., Bogena, H., Brocca, L., Calvet, J.-C., Camarero, J. J., Capello, G., Choi, M., Cosh, M. C., van de Giesen, N., Hajdu, I., Ikonen, J., Jensen, K. H., Kanniah, K. D., de Kat, I., Kirchengast, G., Kumar Rai, P., Kyrouac, J., Larson, K., Liu, S., Loew, A., Moghaddam, M., Martínez Fernández, J., Mattar Bader, C., Morbidelli, R., Musial, J. P., Osenga, E., Palecki, M. A., Pellarin, T., Petropoulos, G. P., Pfeil, I., Powers, J., Robock, A., Rüdiger, C., Rummel, U., Strobel, M., Su, Z., Sullivan, R., Tagesson, T., Varlagin, A., Vreugdenhil, M., Walker, J., Wen, J., Wenger, F., Wigneron, J. P., Woods, M., Yang, K., Zeng, Y., Zhang, X., Zreda, M., Dietrich, S., Gruber, A., van Oevelen, P., Wagner, W., Scipal, K., Drusch, M., and Sabia, R.: The International Soil Moisture Network: serving Earth system science for over a decade, Hydrology and Earth System Sciences, 25, 5749–5804, https://doi.org/10.5194/hess-25-5749-2021, 2021.

Federer, C. A., Vörösmarty, C., and Fekete, B.: Intercomparison of Methods for Calculating Potential Evaporation in Regional and Global Water Balance Models, Water Resources Research, 32, 2315–2321, https://doi.org/10.1029/96WR00801, 1996.

Federer, C. A., Vörösmarty, C., and Fekete, B.: Sensitivity of Annual Evaporation to Soil and Root Properties in Two Models of Contrasting Complexity, Journal of Hydrometeorology, 4, 1276–1290, https://doi.org/10.1175/1525-7541(2003)004<1276:SOAETS>2.0.CO;2, 2003.

Gale, M. R. and Grigal, D. F.: Vertical root distributions of northern tree species in relation to successional status, Canadian Journal of Forest Research, 17, 829–834, https://doi.org/10.1139/x87-131, 1987.

van Genuchten, M. Th.: A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils, Soil Science Society of America Journal, 44, 892–898, https://doi.org/10.2136/sssaj1980.03615995004400050002x, 1980.

Hammel, K. and Kennel, M.: Charakterisierung Und Analyse Der Wasserverfügbarkeit Und Des Wasserhaushalts von Waldstandorten in Bayern Mit Dem Simulationsmodell BROOK90, 2001.

Hanel, M., Rakovec, O., Markonis, Y., Máca, P., Samaniego, L., Kyselý, J., and Kumar, R.: Revisiting the recent European droughts from a long-term perspective, Scientific Reports, 8, 94–99, https://doi.org/10.1038/s41598-018-27464-4, 2018.

Hlásny, T., Zimová, S., Merganičová, K., Štěpánek, P., Modlinger, R., and Turčáni, M.: Devastating outbreak of bark beetles in the Czech Republic: Drivers, impacts, and management implications, Forest Ecology and Management, 490, 119075, https://doi.org/10.1016/j.foreco.2021.119075, 2021.

Hoermann, G. and Meesenburg, H.: Calculation and modelling of forest water budgets for Level II plots in Germany - a comparison of soil water models; Die Erfassung und Modellierung des Wasserhaushaltes im Rahmen des Level II-Programms in der Bundesrepublik Deutschland, Forstarchiv, 71, 70–75, 2000.

Jansson, P.-E. and Karlberg, L.: Coupled heat and mass transfer model for soil-plant-atmosphere systems., Royal Institute of Technology, Department of Civil and Environmental Engineering, 2004.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., and Rubel, F.: World Map of the Köppen-Geiger climate classification updated, Meteorologische Zeitschrift, 15, 259–263, https://doi.org/10.1127/0941-2948/2006/0130, 2006.

Kroes, J. G., Van Dam, J. C., Bartholomeus, R. P., Groenendijk, P., Heinen, M., Hendriks, R. F. A., Mulder, H. M., Supit, I., and Van Walsum, P. E. V.: SWAP version 4; Theory Description and User Manual, Wageningen Environmental Research, Wageningen University and Research, Wageningen, The Netherlands, 2017.

Kronenberg, R., Thành, T. L., Müller, M., Andreae, H., and Petzold, R.: Die Bodenfeuchteampel – Ein webbasiertes Informationssystem für die tagaktuelleBewertung der Wasserverfügbarkeit in Wäldern, Waldökologie, Landschaftsforschung undNaturschutz – Forest Ecology, Landscape Research and Nature Conservation, https://www.afsv.de/images/download/literatur/waldoekologie-online/waldoekologie-online_heft-21-2.pdf, 2022.

Krug, D.: Soil Map of Germany at scale 1:200,000 (BÜK200), 2000.

Luong, T. T., Vorobevskii, I., Kronenberg, R., Jacob, F., Peters, A., Petzold, R., and Andreae, H.: Toward reliable model?based soil moisture estimates for forest managers, Meteorologische Zeitschrift, 32, 143–164, https://doi.org/10.1127/metz/2023/1155, 2023.

Menzel, A.: Phänologie von Waldbäumen unter sich ändernden Klimabedingungen - Auswertung der Beobachtungen in den Internationalen Phänologischen Gärten und Möglichkeiten der Modellierung von Phänodaten, München, 1997.

Meusburger, K., Trotsiuk, V., Schmidt-Walter, P., Baltensweiler, A., Brun, P., Bernhard, F., Gharun, M., Habel, R., Hagedorn, F., Köchli, R., Psomas, A., Puhlmann, H., Thimonier, A., Waldner, P., Zimmermann, S., and Walthert, L.: Soil–plant interactions modulated water availability of Swiss forests during the 2015 and 2018 droughts, Global Change Biology, 28, 5928–5944, https://doi.org/10.1111/gcb.16332, 2022.

NASA JPL: NASA Shuttle Radar Topography Mission Global 1 arc second [Data set], NASA EOSDIS Land Processes DAAC, https://doi.org/10.5067/MEaSUREs/SRTM/SRTMGL1.003, 2019.

Obladen, N., Dechering, P., Skiadaresis, G., Tegel, W., Keßler, J., Höllerl, S., Kaps, S., Hertel, M., Dulamsuren, C., Seifert, T., Hirsch, M., and Seim, A.: Tree mortality of European beech and Norway spruce induced by 2018-2019 hot droughts in central Germany, Agricultural and Forest Meteorology, 307, 108482, https://doi.org/10.1016/j.agrformet.2021.108482, 2021.

Orlowsky, B., Gerstengarbe, F.-W., and Werner, P. C.: A resampling scheme for regional climate simulations and its performance compared to a dynamical RCM, Theoretical and Applied Climatology, 92, 209–223, https://doi.org/10.1007/s00704-007-0352-y, 2008.

Orth, R., Vogel, M. M., Luterbacher, J., Pfister, C., and Seneviratne, S. I.: Did European temperatures in 1540 exceed present-day records?, Environmental Research Letters, 11, 114021, https://doi.org/10.1088/1748-9326/11/11/114021, 2016.

Patacca, M., Lindner, M., Lucas-Borja, M. E., Cordonnier, T., Fidej, G., Gardiner, B., Hauf, Y., Jasinevičius, G., Labonne, S., Linkevičius, E., Mahnken, M., Milanovic, S., Nabuurs, G.-J., Nagel, T. A., Nikinmaa, L., Panyatov, M., Bercak, R., Seidl, R., Ostrogović Sever, M. Z., Socha, J., Thom, D., Vuletic, D., Zudin, S., and Schelhaas, M.-J.: Significant increase in natural disturbance impacts on European forests since 1950, Global Change Biology, 29, 1359–1376, https://doi.org/10.1111/gcb.16531, 2023.

Petzold, R. and Benning, R.: Standortskartierung – Wissen von gestern?, AFZ-DerWald, 15, 25–28, 2017.

Petzold, R., Burse, K., Benning, R., and Gemballa, R.: Die Lokalbodenform im System der forstlichen Standortserkundung im Mittelgebirge/Hügelland und deren bodenphysikalischer Informationsgehalt, Waldökologie, Landschaftsforschung und Naturschutz, 29–33, https://doi.org/urn:nbn:de:0041-afsv-01641, 2016.

Potapov, P., Li, X., Hernandez-Serna, A., Tyukavina, A., Hansen, M. C., Kommareddy, A., Pickens, A., Turubanova, S., Tang, H., Silva, C. E., Armston, J., Dubayah, R., Blair, J. B., and Hofton, M.: Mapping global forest canopy height through integration of GEDI and Landsat data, Remote Sensing of Environment, 253, https://doi.org/10.1016/j.rse.2020.112165, 2021.

Renner, M., Brust, K., Schwärzel, K., Volk, M., and Bernhofer, C.: Separating the effects of changes in land cover and climate: a hydro-meteorological analysis of the past 60 yr in Saxony, Germany, Hydrology and Earth System Sciences, 18, 389–405, https://doi.org/10.5194/hess-18-389-2014, 2014.

Richter, D.: Ergebnisse methodischer Untersuchungen zur Korrektur des systematischen Meßfehlers des Hellmann-Niederschlagsmessers von Dieter Richter, Deutscher Wetterdienst:, Offenbach am Main, 1995.

Schmidt-Walter, P., Ahrends, B., Mette, T., Puhlmann, H., and Meesenburg, H.: NFIWADS: the water budget, soil moisture, and drought stress indicator database for the German National Forest Inventory (NFI), Annals of Forest Science, 76, 39, https://doi.org/10.1007/s13595-019-0822-2, 2019.

Schmidt-Walter, P., Trotsiuk, V., Meusburger, K., Zacios, M., and Meesenburg, H.: Advancing simulations of water fluxes, soil moisture and drought stress by using the LWF-Brook90 hydrological model in R, Agricultural and Forest Meteorology, 291, 108023, https://doi.org/10.1016/j.agrformet.2020.108023, 2020.

Scholz, H., Lischeid, G., Ribbe, L., and Grahmann, K.: Differentiating between crop and soil effects on soil moisture dynamics, EGUsphere, 2023, 1–21, https://doi.org/10.5194/egusphere-2023-1115, 2023.

Schuldt, B., Buras, A., Arend, M., Vitasse, Y., Beierkuhnlein, C., Damm, A., Gharun, M., Grams, T. E. E., Hauck, M., Hajek, P., Hartmann, H., Hiltbrunner, E., Hoch, G., Holloway-Phillips, M., Körner, C., Larysch, E., Lübbe, T., Nelson, D. B., Rammig, A., Rigling, A., Rose, L., Ruehr, N. K., Schumann, K., Weiser, F., Werner, C., Wohlgemuth, T., Zang, C. S., and Kahmen, A.: A first assessment of the impact of the extreme 2018 summer drought on Central European forests, Basic and Applied Ecology, 45, 86–103, https://doi.org/10.1016/j.baae.2020.04.003, 2020.

Sharma, M., Rastogi, R., Arya, N., Akram, S. V., Singh, R., Gehlot, A., Buddhi, D., and Joshi, K.: LoED: LoRa and edge computing based system architecture for sustainable forest monitoring, Int. J. Eng. Trends Technol., 70, 88–93, https://doi.org/10.14445/22315381/ijett-v70i5p211, 2022.

Shuttleworth, W. J. and Wallace, J. S.: Evaporation from sparse crops-an energy combination theory, Quarterly Journal of the Royal Meteorological Society, 111, 839–855, https://doi.org/10.1002/qj.49711146910, 1985.

Speich, M.: Quantifying and modeling water availability in temperate forests: a review of drought and aridity indices, iForest - Biogeosciences and Forestry, 12, 1–16, https://doi.org/10.3832/ifor2934-011, 2019.

Spiecker, H. and Kahle, H.-P.: Climate-driven tree growth and mortality in the Black Forest, Germany—Long-term observations, Global Change Biology, 29, 5908–5923, https://doi.org/10.1111/gcb.16897, 2023.

Vindstad, O. P. L., Jepsen, J. U., Ek, M., Pepi, A., and Ims, R. A.: Can novel pest outbreaks drive ecosystem transitions in northern-boreal birch forest?, Journal of Ecology, 107, 1141–1153, https://doi.org/10.1111/1365-2745.13093, 2019.

Vorobevskii, I.: Supplement materials for publication: Seasonal forecasting of local-scale soil moisture droughts with Global BROOK90., 2023.

Vorobevskii, I., Luong, T. T., Kronenberg, R., Grünwald, T., and Bernhofer, C.: Modelling evaporation with local, regional and global BROOK90 frameworks: importance of parameterization and forcing, Hydrology and Earth System Sciences, 26, 3177–3239, https://doi.org/10.5194/hess-26-3177-2022, 2022.

Weis, W., Ahrends, B., Böhner, J., Falk, W., Fleck, S., Habel, R., Klemmt, H.-J., Meesenburg, H., Müller, A.-C., Puhlmann, H., Wehberg, J.-A., Wellpott, A., and Wolf, T.: Standortsfaktor Wasserhaushalt im Klimawandel, Zentrum Wald Forst Holz Weihenstephan, 2023.

Wellbrock, N., Bolte, A., and Flessa, H.: Dynamik und räumliche Muster forstlicher Standorte in Deutschland. Ergebnisse der Bodenzustandserhebung im Wald 2006 bis 2008., Thünen Institut, 550 pp., 2016.

Wessolek, G., Kaupenjohann, M., and Renger, M.: Bodenphysikalische Kennwerte und Berechnungsverfahren für die Praxis, Technische Universität Berlin, Berlin, 2009.

von Wilpert, K.: Die Jahrringstruktur von Fichten in Abhängigkeit vom Bodenwasserhaushalt auf Pseudogley und Parabraunerde: ein Methodenkonzept zur Erfassung standortsspezifischer Wasserstressdisposition, Selbstverlag des Instituts für Bodenkunde und Waldernährungslehre, 1990.

Wösten, J. H. M., Lilly, A., Nemes, A., and Bas, C. L.: Development and use of a database of hydraulic properties of European soils, Geoderma, 90, 169–185, https://doi.org/10.1016/S0016-7061(98)00132-3, 1999.

Zang, C., Hartl-Meier, C., Dittmar, C., Rothe, A., and Menzel, A.: Patterns of drought tolerance in major European temperate forest trees: climatic drivers and levels of variability, Global Change Biology, 20, 3767–3779, https://doi.org/10.1111/gcb.12637, 2014.

Zhou, S., Zhang, Y., Williams, A. P., and Gentine, P.: Projected increases in intensity, frequency, and terrestrial carbon costs of compound drought and aridity events, Science Advances, 5, eaau5740, https://doi.org/10.1126/sciadv.aau5740, 2019.

Zink, M., Samaniego, L., Kumar, R., Thober, S., Mai, J., Schäfer, D., and Marx, A.: The German drought monitor, Environmental Research Letters, 11, https://doi.org/10.1088/1748-9326/11/7/074002, 2016.

Zweifel, R., Pappas, C., Peters, R. L., Babst, F., Balanzategui, D., Basler, D., Bastos, A., Beloiu, M., Buchmann, N., Bose, A. K., Braun, S., Damm, A., D'Odorico, P., Eitel, J. U. H., Etzold, S., Fonti, P., Freund, E. R., Gessler, A., Haeni, M., Hoch, G., Kahmen, A., Körner, C., Krejza, J., Krumm, F., Leuchner, M., Leuschner, C., Lukovic, M., Martínez-Vilalta, J., Matula, R., Meesenburg, H., Meir, P., Plichta, R., Poyatos, R., Rohner, B., Ruehr, N., Salomón, R. L., Scharnweber, T., Schaub, M., Steger, D. N., Steppe, K., Still, C., Stojanović, M., Trotsiuk, V., Vitasse, Y., Arx, G. von, Wilmking, M., Zahnd, C., and Sterck, F.: Networking the forest infrastructure towards near real-time monitoring – A white paper, Science of The Total Environment, 872, 162167, https://doi.org/10.1016/j.scitotenv.2023.162167, 2023.