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Original Research Article

COMPARISON OF VEGETATION VITALITY DATA AND SOIL MOISTURE MEASUREMENTS AT THE PROSPER-HANIEL CLOSED MINE SITE

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Abstract

Effective management of flood-prone areas, particularly polders, is critical for ecological balance and human safety. This study focuses on mining-induced polders in the Ruhr region, emphasizing the need for sustainable flood protection strategies amidst changing climatic conditions. By analyzing data from the Copernicus Sentinel 2 satellite mission and ground-based measurements, the study investigates vegetation response to variable soil moisture. Especially for polder management in the Ruhr area climate change causes high pressure for adaption. Key findings reveal correlations between soil moisture, soil temperature, and vegetation vitality, emphasizing the importance of continuous monitoring for optimizing post-mining water management. Results suggest that high soil moisture levels, particularly in autumn to spring, significantly influence vegetation health. The study underscores the necessity for long-term, comprehensive research to validate findings across varied and changing climatic conditions.

Keywords: polder areas, vegetation condition, NDVI, soil moisture, soil temperature

1. INTRODUCTION

The observation of flood-prone areas plays an important role in both ecological and human safety perspectives. Polders, in particular, play a crucial role as they act as both natural and artificial retention basins. These are areas that can be flooded to absorb excess runoff during flood threats caused by heavy rains, snowmelt, or other extreme weather events, thus serving as important tools for flood protection.

Special cases include polders in mining regions, anthropogenically initiated during underground coal mining, thus artificial subsidence areas. In the Ruhr area, these subsidence areas are widespread. Ideally, these polders should not be flooded as they encompass residential, agricultural, forestry, or other land uses. Polder management, especially in the Ruhr region, involves pumping approximately

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1,000,000,000 cubic meters of surface water per year from rainfall out of the polders into the drainage systems [1]. Since 2018 the classical polder management in the Ruhr area is facing limits. The classical procedure is currently designed to pump excess surface water out of the area with the help of float controlled pumping stations to prevent damages. It seems to be not appropriate to deal with a wide range of weather induced situations. First investigations are shown in Bernsdorf et al. [2].

It should be emphasized that environmental transformations are increasingly driven by rapidly changing climatic conditions, which are at least partly accelerated by human activity. These developments are giving rise to new weather extremes across Germany and Central Europe, including prolonged droughts, more frequent and intense flood events caused by heavy rainfall, and substantially wetter winters [3-6]. Continuous monitoring of mining polders is therefore essential for sustainable land and water management, enabling early detection of flood risks and supporting effective crisis response. As climate trends continue to shift, Central Europe may be transitioning from a moderate to a more extreme climatic regime, which could ultimately require a revised regional climate classification [7]. Geomonitoring of post-mining polders plays a key role in assessing long-term environmental impacts even after mining activities have ceased. Such monitoring supports the gradual recovery of soil functions and promotes the protection and enhancement of biodiversity. Wetlands, in particular, represent vital ecosystems for biodiversity conservation and natural resource maintenance, as they are strongly dependent on healthy and balanced soil microbial communities [8].

The article summarizes the part of research results on vegetation response to in-creased soil moisture, utilizing data from the Copernicus Sentinel 2 satellite mission and ground station measurements from the "MUSE - Multisensor-Geomonitoring for optimizing post-mining water management" project, funded by the RAG Foundation under the reference number 2021-0002 at the Prosper-Haniel mine in the western Ruhr area.

2. MATERIALS AND METHODS

2.1. Study Area

The research area (red frame in Figure 1) is defined by the aboveground catchment area of the Boye River and the former Prosper Haniel mine.

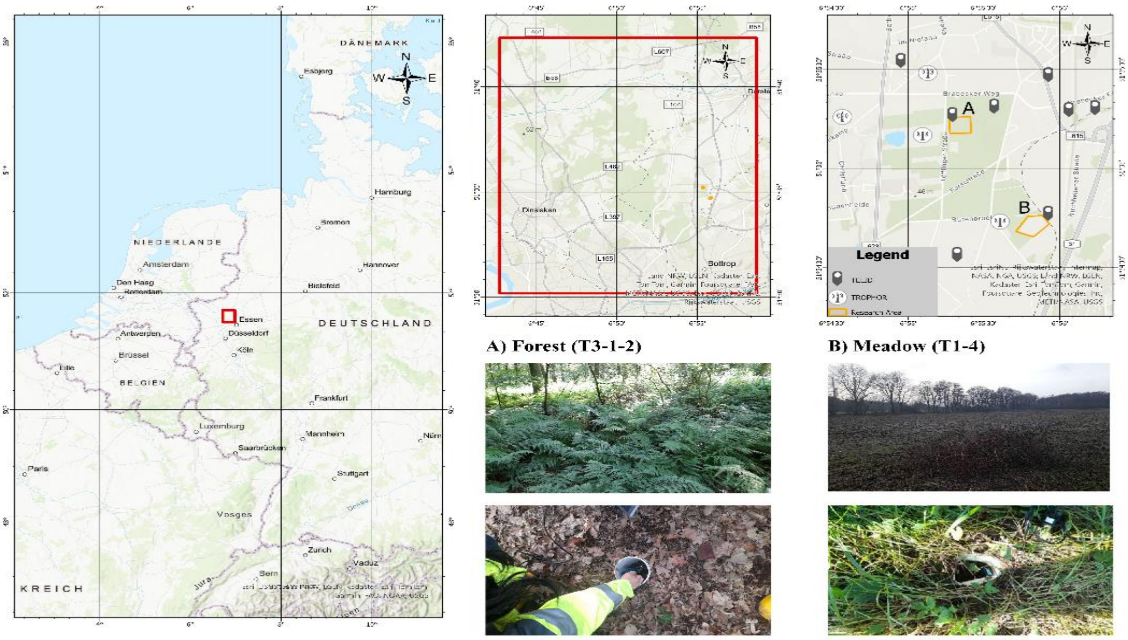


Fig. 1. Location of the research area. Source of basemaps: ESRI

The Boye River is one of the larger tributaries of the Emscher River, currently undergoing reconstruction close to nature, and represents a typical catchment area of a low-gradient lowland river. The study area covers approximately 385 km², with dimensions of about 22 km by 18 km. This includes the cities of Bottrop and Gladbeck in the southeast, as well as Dorsten in the north. The study area is predominantly characterized by urban areas, agricultural, and forestry areas. The region is intricately structured and stands out for its noticeable diversity in landscape over short distances, a small-chambered landscape.

To the north, the Lippe River flows through the study area, while to the south, the Emscher River borders the region. The tributary Boye originates in the middle of the study area, specifically southwest of Kirchhellen, and flows southwards into the Emscher. Due to mining-induced subsidence in this area, the flow of the Boye needs to be maintained using pumping stations at two positions, which is representative for the operation of a polder area. The high-performance pump station Bottrop-Boye can pump 42 m^3 of water into the Emscher every second during extreme rainfall events.

Prosper-Haniel Mine, founded in 1856 in Bottrop, was a key center for coal mining in the Ruhr region [9]. Over the years, it became one of the main suppliers of coal for the developing German economy during the industrialization period. The mine underwent numerous modernizations, introducing advanced technologies to increase mining efficiency and improve working conditions for miners. The mine played a crucial role in supplying coal to power plants and the steel industry, powering the growing energy infrastructure. However, over time, coal mining began facing challenges such as rising extraction costs due to the increasing mine depth, competition from cheaper energy sources like oil and gas, and environmental protection issues e. g. in land restoration. In response to these challenges, many mines, including Prosper-Haniel, underwent restructuring. Ultimately, in December 2018, concluded its extraction activities as a last hard coal mine in Germany. The closure resulted from a decision to gradually phase out coal mining in Germany for environmental reasons due to climate change. The closure of Prosper-Haniel was a symbolic moment, marking the end of the era of coal mining in the Ruhr region. This event not only reflected changes in the industrial landscape but also the necessity to adapt to new economic and environmental realities [9].

2.2. Vegetations Condition

Following the mine's closure has remained is an artificial landscape that requires special attention. In the observation of polders, an important aspect is the early detection of the effects of water stress on vegetation, as described, which can manifest in a change in the vitality of plants. This possibly can be an early indicator for adapting polder pumps. Continuous monitoring allows for timely notification of deteriorating conditions for vegetation, which can be reflected in a decline in atmospheric precipitation and, consequently, a reduction in soil moisture [10,11]. An oversupply of precipitation has a comparable effect. Especially herbaceous plants in particular cover their CO_2 requirements via root respiration [12] which is prevented if the root zone is filled with precipitation. Both situations can be described using soil physical characterizations and have the effect of chloroplast deterioration, which again can be observed using remote sensing methods. According to Bresinsky et al. [12] trees are not as susceptible to excessive moisture in the soil, as they cover their CO_2 requirements more from the canopy. In addition, some trees are rooting much deeper than herbaceous plants.

To examine the state of vegetation at the local level, satellite-based images were used, from which spectral indices were calculated. One of these indices was the NDVI (Normalized Difference Vegetation Index), originally proposed by Rouse et al. [13], which is based on the relationship between the near-infrared and red wavelengths (Formula 1) [14-18]. Chlorophyll in the leaves absorbsed some of the red light while strongly reflected NIR light [19].

$$NDVI = \frac{\rho^{NIR} - \rho^{RED}}{\rho^{NIR} + \rho^{RED}} \tag{2.1}$$

This property is closely related to the previously described photosynthetic process. The plant needs to absorb light to carry out photosynthesis while simultaneously regulating its energy balance to avoid overheating. Therefore, certain bands of the electromagnetic spectrum are absorbed (such as blue around 450 nm and red around 650 nm), while others are reflected (such as green around 500 nm and near-infrared from about 750 nm) [20]. This can be utilized in indices like NDVI. Due to its formula composition, NDVI values range from -1 to +1 [19]. Tucker and Sellers [16] and Wang et al. [21] have found that various factors influence the NDVI value, including plant height and composition, plant health and condition, plant stress, topography, soil type, and the geomorphology of a specific area.

The mentioned studies were based on satellite images. However, Pawlik et al. [22] show that due to similar spectral sensors of the Sentinel-2 satellite mission and the multispectral camera of the DJI multispectral drones (Phantom 4 Multispectral, Mavic 3 M drones), the NDVI index can also be calculated from drone data. This has been utilized in studies on observing the vitality of plants for several times [23-27], correlating soil moisture data and spectral indicators [28-30], certain plant communities and indicator plants [31], and identifying water surfaces [32-34].

2.3. Soil Moisture

The Figure 1 shows the location of the measuring stations for the study area. Prior to the installation of the weather stations, test boreholes were drilled and soil pits were digged for the profile view (soil type) and the soil moisture sensor installation of soil sensors. By that and soil samples were taken for laboratory analysis (grain size analysis, soil humus analysis and soil moisture analysis). The weather stations enable data transmission using the SigFox protocol. The TELID and TEROS sensor network (data logger), on the other hand, requires data acquisition through monthly readings using NFC communication. These sites were distributed in three transects to cover different situations of the subsidence area. There are four locations within each transect. The transects differ in terms of the impact of disturbance. Transect 2 looks at the impact of subsidence on watercourses. Transect 3 focuses on the impact of subsidence in or near the forest. Table 1 shows an overview on the in-situ sensors.

Table 1. Overview of used Sensors

Name	**Type**	**Measurement priciple soil moisture**	**Data capturing**
TROPHOR	Weather station including broad set of sensors	capacitive, relative values in total volume; ± 5%	SigFOX WAN
TELID	Single sensors	capacitive, volumetric water content in total volume; ± 5 Vol-%	Battery operated data logger, NFC read head
TEROS	Combined sensors soil moisture, soil temperature	Time Domain Reflectory TDR; volumetric water content in pore volume m^3/m^3; ± 1 Vol-%	Solar operated logger station, USB

Bernsdorf et al. [2] tested the correlation of the TELID and TEROS indicators. The values obtained with these sensors represent a volume measurement of soil moisture expressed as volumetric water content (VWC) in % of volume. As the authors point out: "The TEROS sensors, however, take into account the ratio of soil volume to pore volume using the Time Domain Reflectance methods. On the other hand, the simpler TELID sensors record the simple capacitive conductivity without taking into account other derived information. The measured values are therefore scaled in different ways. While the TEROS sensors report their maximum values (depending on soil conditions) in the range of 55 to 65 vol-% VWC, the TELID sensors regularly report values of up to100 vol-% VWC."

Knowing about the obstacles of measuring an open system like soil and the varacity on short distances [28], on two locations TEROS and TELID-Sensors was installed in a short distance to compare the measurement results from December 2020 to March 2022. The results obtained from this research have made it possible to determine the coincidence index between the TEROS and TELID 354.2 sensor pair. The value of this index based on the measurements is 0.39 and has been implemented in this project.

Soil moisture and soil temperature data were regularly collected through in-situ readings and then the measurements were implemented in the database schema shown in Figure 2. It is worth noting that the station type was differentiated into TEROS, TELID and TROPHOR and the station identifier was linked to other tables. The measurements stored in the database are characterised by a unique identifier (measurement_id), measurement time (measuerement_timestamp), measurement value (value) depending on the type of measurement: soil moisture or soil temperature (sensor_type) and location (station_id).

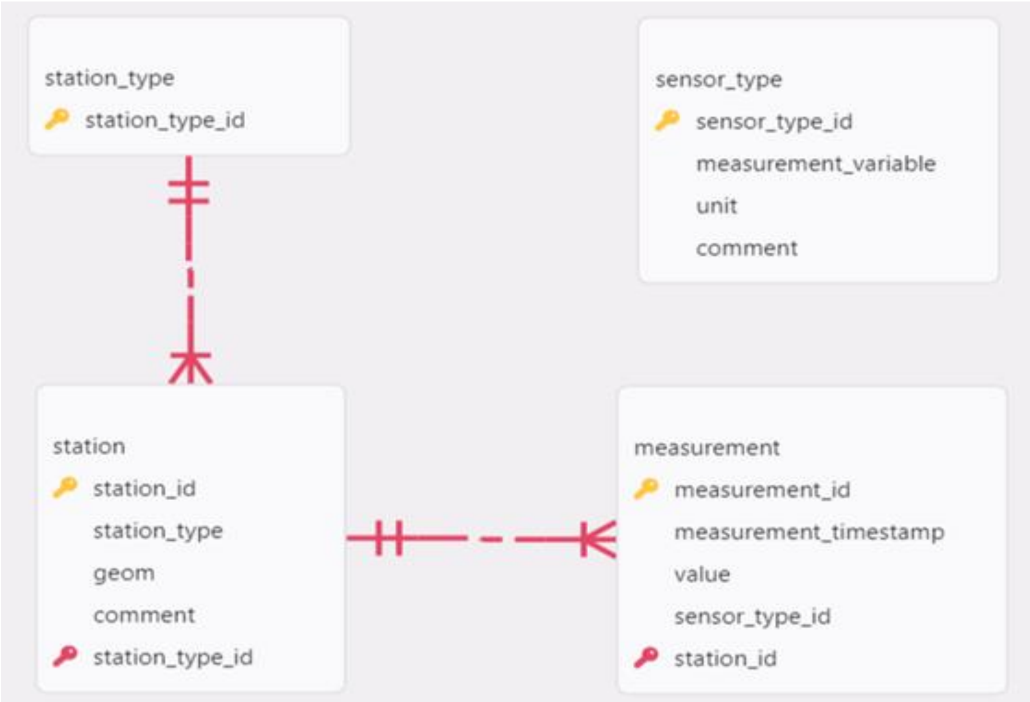


Fig. 2. Schema the database

3. RESULTS

This chapter will present the results of the surveys for the base station T3-1-2 (forest) and T1-4 (meadow) for the period November 2021 to March 2024. The data were collected using TELID soil sensors and weather station measurements, and supplemented with vegetation indices derived from Sentinel-2 imagery. The integration of ground and satellite observations enabled a detailed assessment of soil-vegetation interactions and their seasonal dynamics in different land-use types typical of the post-mining landscape of the Prosper-Haniel mine. Figure 3 presents the temporal variations in soil moisture and soil temperature derived from the TELID sensors, alongside air temperature and precipitation measured at the corresponding metereological station. In the graph, soil moisture is represented in blue, soil temperature in orange, air tempereature in red and precipitation in light blue. The background of the graph shows the seasons: winter (blue), spring (green), summer (orange), and autumn (red), allowing for a correlation of soil moisture changes with seasonal weather conditions.

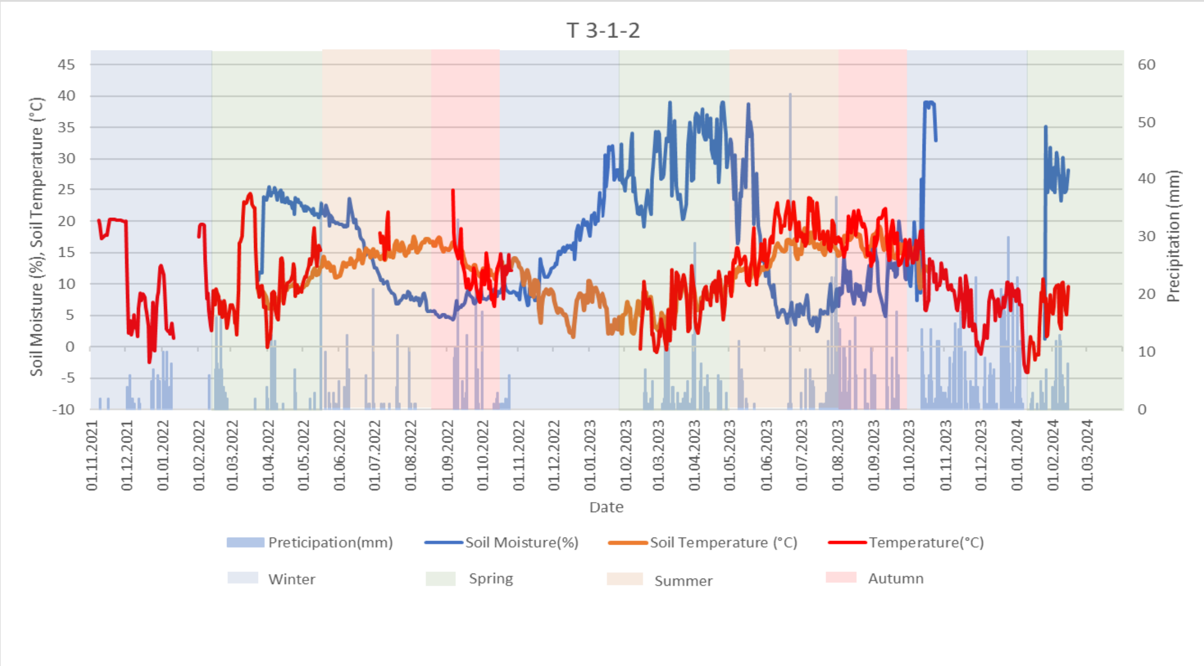


Fig. 3. Soil moisture & Soil Temperature (Telid Station) and Temperature & Precipitation (Weather Station) in the period from November 2021 to March 2024 for test area T3-1-2 [35]

In the forest location (T3-1-2), soil moisture showed distinct seasonal fluctuations closely aligned with the precipitation pattern and air temperature. The lowest values of about 5% to 15% can be observed in the period from June to November, while the highest values of about 25% to 40% can be observed in the period from January to May. In the period from May to June and November to January, the values fluctuate around 20%. Soil Moisture displays variations between 0% and 45%, with higher moisture during the cooler months, and lower levels in the summer months (June-October). Soil temperature is reaching around 25-30°C in the summer and dropping below 0°C in winter.

The results presented in Figure 4 show changes in soil moisture and soil temperature from the TELID Station and temperature and precipitation from weather stations in the location of the meadow (T1-4) from November 2021 to June 2024. The data are all marked accordingly to the data from the above station T 3-1-2. The background of the graph represents different seasons, allowing for the analysis of soil temperature changes in the context of seasonal climate conditions.

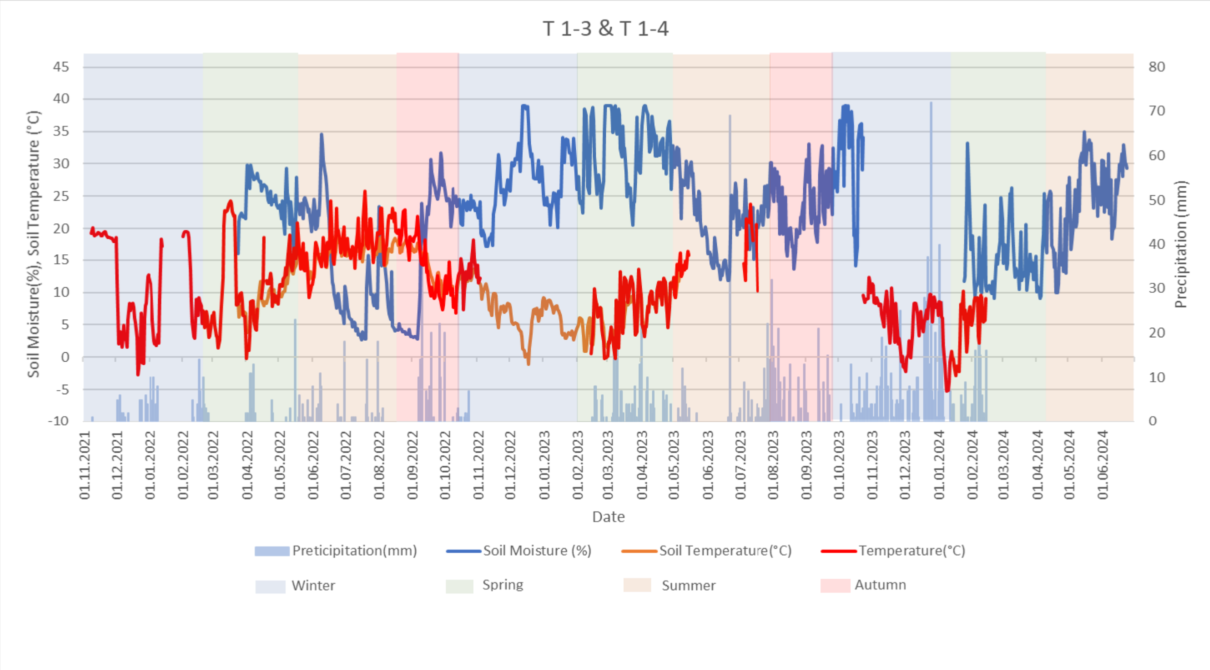


Fig. 4. Soil moisture & Soil Temperature (Telid Station) and Temperature & Precipitation (Weather Station) in the period from November 2021 to June 2024 for test area T1-4 [35]

In the meadow (T1-4), the pattern of soil moisture changes is similar, although there may be greater variability due to differences in water retention and the exposed nature of the terrain, which causes the soil to lose moisture more quickly during dry periods and absorb it more quickly during rainfall. The lowest values of about 5% to 15% can be observed from June to October, but there is a significant change in soil moisture values around July and August, where values reach up to 25%. The highest values from about 25% to 40% can be observed in the period from October to May. Soil moisture fluctuates between 0% and 40%, with significant spikes, especially during the cooler months (October-May). Soil temperature peaks around 25-30°C in summer (May-November) and drops significantly to near 0°C in winter. Precipitation peaks coincide with increased soil moisture, especially during the wetter winter-spring months.

In a forest (T3-1-2), soil temperature is slightly more stable compared to a meadow (T1-4, balanced forest climate). The forest, due to canopy cover and the presence of leaf litter, can better insulate the soil from rapid temperature changes, resulting in smaller fluctuations compared to the open space of the meadow, which is more susceptible to radiation (inward and outward). In the meadow, the soil is more exposed to direct sunlight and wind, leading to larger temperature fluctuations throughout the year. In summer, soil in a meadow heats up faster and reaches higher maximum temperatures than soil in a forest. In winter, the soil in the meadow can lose heat more quickly, leading to lower minimum temperatures compared to the forest. In both locations, the highest soil temperature values can be observed from May to November, while the lowest values can be observed from December to May. The temperature begins to rise from March, peaks in the summer months, and then gradually decreases in autumn. In summary, the seasonal fluctuations in soil temperature in both locations, which align with the phenological annual cycle. The forest demonstrates a greater ability to stabilize soil temperature compared to the meadow, which is related to its natural ecosystem properties. The highest levels of precipitation are usually observed in spring and autumn. In summer, although precipitation occurs, the amount is generally lower, where values are more scattered. In winter, precipitation can take the form of snow, which can also affect the recorded values. It can be obviously seen that precipitation drops to a minimum in summer. With less precipitation, air temperatures are higher, which is typical of warm, dry periods occurring more frequently. In winter, although precipitation may rise much higher than in the reference period, low temperatures are caused by longer nights and reduced solar energy reaching the Earth's surface, leading to extremely wet winters. The increasingly frequent alternation between dry summers and wetted winters in the dataset reflects a broader climatic trend already documented in Central Europe, where climate variability is intensifying due to global change. The data from the studied sites confirm this regional pattern, with both soil and vegetation parameters responding sensitively to hydrological extremes.

To assess vegetation vitality, the NDVI (Normalized Difference Vegetation Index) was calculated using Sentinel-2 imagery processed through the Google Earth Engine (GEE) platform for a given research area. It is a cloud-based computational platform that enables the presentation, analysis, and interpretation of spatial data derived from satellite imagery. Data processing is based on the implementation of source code in languages such as JavaScript. The application is widely accessible and free for research and educational purposes. The NDVI values for the forest (T3-1-2) and the meadow (T1-4) were analyzed for the period from March 2022 to September 2023 and supplemented with historical records from 2016 to early 2024. Figure 5 presents these results, illustrating clear seasonal cycles and multi-annual tendencies.

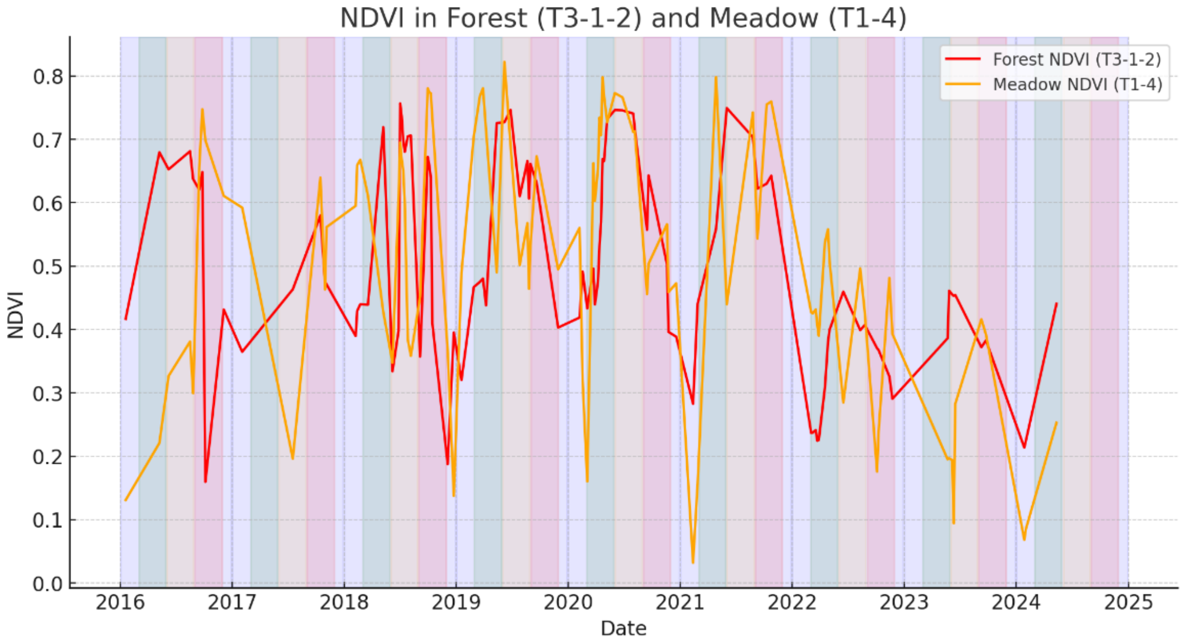


Fig.5. NDVI in the period 2016 to 26 February 2024 for test area T3-1-2 and T1-4

Seasonal patterns on the chart are clearly visible in both locations. The increases in NDVI during spring and summer and decreases in autumn and winter are typical of a temperate climate, where vegetation undergoes cycles of growth and dormancy. In the forest, these changes are more gradual due to the presence of perennial vegetation that maintains some level of activity even during the cooler months. In the working area this are typically pines (majority due to sandy soils), spruces and fires or holly trees. On the meadow, the changes are more pronounced, reflecting the faster life cycle of grassy vegetation and the agricultural processing. The analysis of NDVI values for both locations from 2016 to 2024 allows for a better understanding of how types of ecosystems respond to seasonal and annual climatic changes and how to interpreted the short in situ measurement periods of scientific projects. The forest shows the greater stability, indicating its ability to maintain lush vegetation over a longer period. The meadow, though more variable, also exhibits cyclical patterns related to the seasonal growth and dormancy of vegetation. Both locations have seen a decrease in the value of the NDVI indicator over the period 2022-2024.

Figure 6 presents a comparison of vegetation vitality and soil moisture values for the two different land-use areas in this study: forest and meadow. Soil profiles were collected for both measurement points during the conducted research. The soil structure shown in Figure 6 is presented in a generalized form, while detailed soil profiles are displayed on the left side of each land use class.

On the left side, the forest area is shown with various soil layers labeled as:

- Of – an organic layer consisting of fallen leaves and other plant residues,
- Ah – a humus-rich topsoil layer in which soil organism mixing mineral and humic content,
- Sw – a sandy, water-permeable layer in which precipitation backwater causes hydromorphic reactions,
- SwSd – a layer of sandy sediments from past water activities which shows the transition of the landscape,
- Sd – a dense layer of loamy, detrital sand deposits which causes backwater in the upper level.

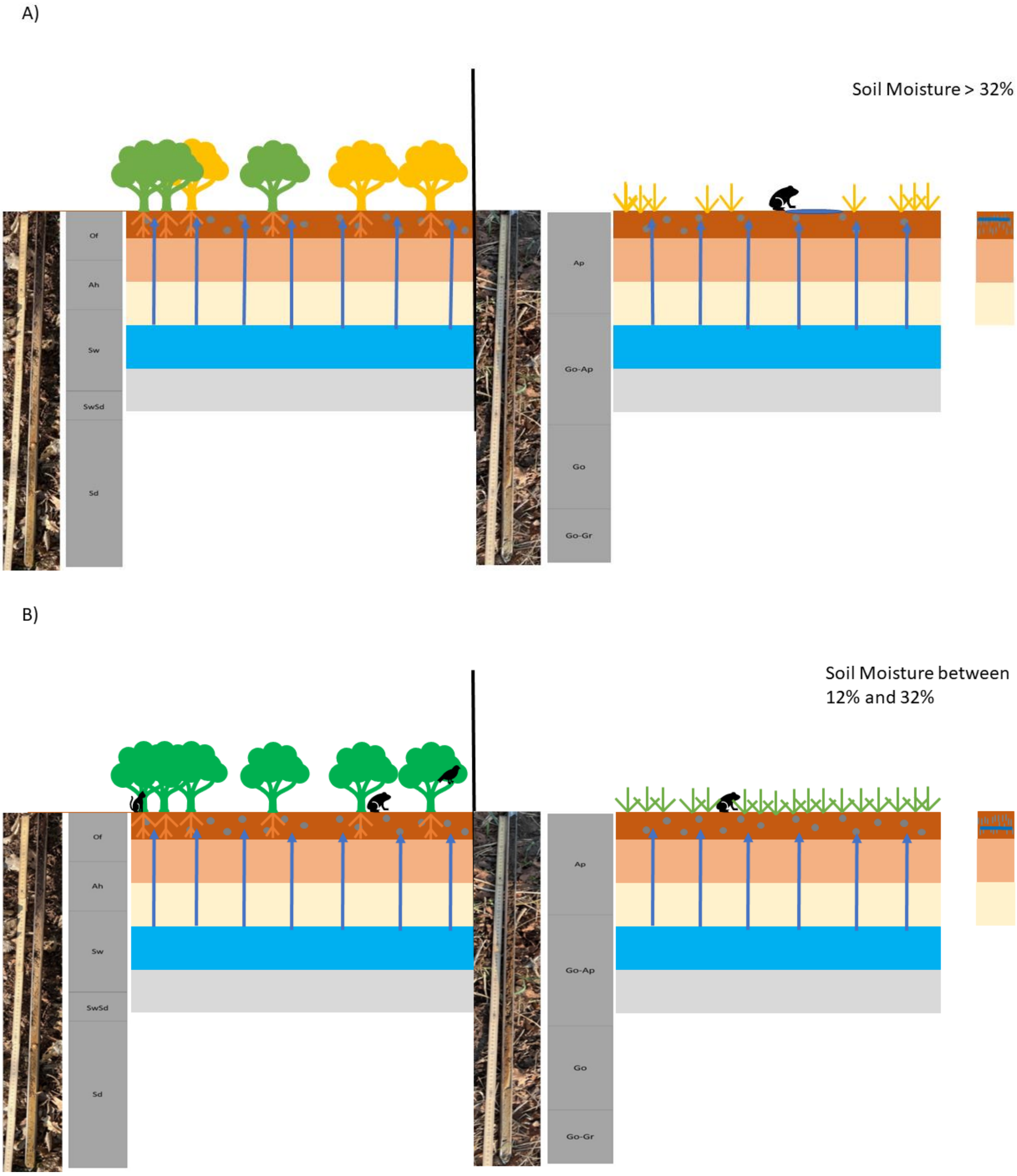
This so called Pseudogley illustrates the soil structure in a forest environment.

On the right side is an agriculturally managed or cultivated area in or close to the flood plain with soil layers labeled as:

- Ap – the plough layer, regularly cultivated and mixed,
- Go-Ap – a transition layer between the plough and deeper layers,
- Go – a layer showing hydromorphic signs of ever-changing groundwater saturation,
- Go-Gr – a transition layer of soil and gravel, indicating effects of drainage conditions.

Below that usually resides the Go-Layer which continuously is water saturated and shows ashen grey tones to washed-out minerals. This soil typically is addressed as Gley while the findings showing this soil type in transition due to agricultural and drainage superimposition.

The retention curves (pF) provided by Jaeckel et al. [36, 37] define critical thresholds for soil water availability. The field capacity (AC/FC) corresponds to approximately 32% VWC (pF 1.8), while the permanent wilting point (PWP) corresponds to 12% VWC (pF 4.2). Based on these values, three possible scenarios were identified: wet period (Figure 6A) – soil moisture values are above 32% VWC, normal period (Figure 6B) – soil moisture values range from 12% VWC to 32% VWC, and dry period (Figure 6C) – soil moisture values are below 12% VWC. Figure 6 illustrates these scenarios in relation to vegetation vitality. Under prolonged wet conditions, vegetation stress symptoms were observed—such as leaf discoloration in deciduous forest species and puddling in meadow areas—resulting from reduced oxygen availability in the root zone (Figure 6A). Under normal conditions, both ecosystems exhibited optimal vegetation health, with balanced soil aeration and water content (Figure 6B). During dry periods, soil moisture below 12% VWC caused a drop in groundwater levels beneath the root zone, leading to visible drought stress in both forest and meadow vegetation (Figure 6C). Figure 7 compares representative field observations using UAV flights from a dry period (summer 2022) (Figure 7A) and a wet period (winter 2023) (Figure 7B), illustrating contrasting vegetation conditions.



C)

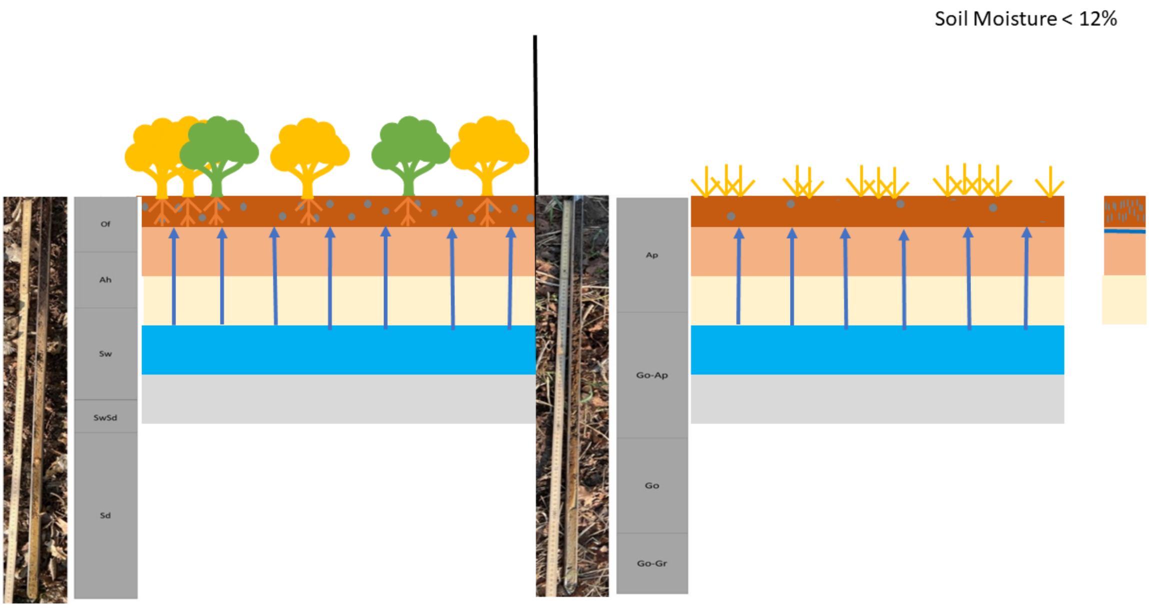


Fig.6 Comparison the vegetation and soil moisture: A) wet period, B) normal period and C) dry period

Fig.7 Comparison the vegetation on the meadow in another study areas in: A) dry period – Summer 2022, B) wet period – Winter 2023

Overall, the results demonstrate a strong relationship between soil moisture, temperature, and vegetation vitality in both land-use types. The forest environment, through its canopy and organic layer, exhibits greater resilience and buffering capacity, while the meadow responds rapidly to climatic variability and serves as a sensitive indicator of hydrological imbalance. These findings confirm that combined monitoring using in-situ sensors and remote sensing indices provides valuable insights into ecosystem functioning in post-mining landscapes, supporting adaptive management of polder systems under changing climatic conditions.

4. DISCUSSION

The integrated research approach, combining Sentinel-2 remote sensing data and in situ measurements of soil moisture and temperature, enabled a comprehensive assessment of hydro-ecological processes in a polder landscape formed after mining exploitation in the Prosper-Haniel region. Such polders represent a specific category of anthropogenic aquatic systems in which geomorphological transformations lead to areas with limited drainage, variable groundwater levels, and diverse biological activity [1, 2, 8, 22]. Understanding the functioning of these systems is crucial for the reclamation of post-mining areas and for maintaining their retention capacity under increasing climatic pressure.

The results confirm a strong seasonality of soil moisture typical of the temperate climate, which is increasingly disrupted by climate change. The highest values (25–40% VWC) were recorded during the autumn–winter period, corresponding to increased precipitation and reduced evaporation during cooler months. Conversely, in summer, soil moisture decreased to 5–15% VWC, indicating rapid drying under high evapotranspiration and low rainfall [35–37]. This relationship is consistent with the findings of Conradt et al. [6] and Alobid et al. [5], who demonstrated that in Central Europe, the amplitude of seasonal soil moisture variations has increased due to prolonged dry periods. From a retention perspective, polder soils are characterized by limited water-holding capacity and low buffering ability against hydrological fluctuations [28]. Unlike natural wetlands, whose peat structure promotes water retention, anthropogenic soils (gleys and pseudogleys) in post-mining areas undergo cyclic wetting and drying [36]. Such variability leads to fluctuations in soil microbial activity, affecting mineralization processes and organic carbon balance [8].

A comparative analysis of forest and grassland sites revealed that differences in vegetation cover and soil type determine the rate and range of soil-moisture changes. In forests (T3-1-2), the litter layer and deep-rooted trees contributed to a more stable microclimate and slower moisture loss during dry periods. In grasslands (T1-4), characterized by shallow roots and greater exposure to atmospheric conditions, soil-moisture variability was much higher, promoting rapid temperature fluctuations [12, 19]. These results confirm the observations of Bresinsky et al. [12] and Wang et al. [21], who showed that vertical differentiation of root systems plays a key role in ecosystem resilience to hydrological extremes. The relationship between soil moisture, temperature, and vegetation condition was also evident in NDVI dynamics. During periods of moderate moisture (20–30 % VWC), NDVI values reached their maximum, reflecting optimal photosynthetic activity. Both water deficit (below 12 % VWC) and excess (above 32 % VWC) caused NDVI decline, indicating vegetation stress. These results align with findings by Joiner et al. [11], who described a linear relationship between surface soil moisture and photosynthetic activity on a weekly scale.

The soil profile structure directly influences its capacity for water retention and drainage. Pseudogley soils, typical of forest areas, retain water in the upper horizons, allowing for gradual release, thus reducing extreme moisture fluctuations but potentially causing short-term oxygen deficits in the root zone during heavy rainfall. In contrast, gley soils in grassland zones exhibit high permeability and variable groundwater depth, leading to alternatling saturation and desiccation [35,36].

The observation period (2021–2024) encompassed both a drought in 2022 and an exceptionally wet winter in 2023. In both cases, NDVI values declined, indicating that both water deficit and excess induce comparable physiological stress in plants. This result is consistent with the observations of Conradt et al. [6] and reports by German Weather Service [4], which highlight the increasing frequency of extreme weather events in Germany. Data from Prosper-Haniel corroborate these tendencies, indicating an increase in the amplitude of seasonal soil-moisture fluctuations and a decline in vegetation stability. In particular, NDVI reductions following extreme events (summer 2022, winter 2023) may be interpreted as signs of reduced biological resilience and disturbances in the balance between transpiration and photosynthesis [15].

The integrated geomonitoring approach — combining satellite, ground, and UAV data — represents a new standard in assessing ecohydrological processes [30-32]. The correlation between NDVI and soil moisture confirms that vegetation condition can serve as an indicator of hydrological status at the landscape scale. Remote-sensing methods, particularly through platforms such as Google Earth Engine, enable the analysis of long-term vegetation trends and evaluation of reclamation effectiveness. The synergy between optical (Sentinel-2) and radar (Sentinel-1) observations provides a robust and transferable methodological framework, extensively applied in soil moisture retrieval and hydrological investigations [39,40], and applicable to the study of post-mining areas. In the context of research on post-mining polders, this methodology is indispensable as it allows for the precise distinction of hydrological effects in a diversified landscape (forests vs. grasslands) and for monitoring the impact of climate extremes. This integrated approach enables the isolation of the soil-moisture signal from vegetation-induced interference, such as canopy effects in forests or biomass variability in grasslands. By enhancing the interpretability of radar-derived moisture estimates, it strengthens the reliability of hydrological assessments in post-mining polders and supports evidence-based conclusions regarding the maintenance of retention capacity and the need for diversified management strategies. Moreover, this methodological framework facilitates the transition from empirical monitoring to process-based modelling, enabling the examination of long-term hydrological and ecological feedbacks — including drought legacies [40] — and their implications for future ecosystem productivity.

The pronounced functional differentiation between forested and grassland ecosystems underscores the necessity of adopting diversified management strategies for reclaimed polder landscapes. Forest ecosystems function as hydrological stabilizers: their deep and extensive root systems promote vertical water infiltration, while canopy structures mitigate evaporative losses by reducing solar radiation and wind exposure. Additionally, the accumulation of surface litter in forest soils serves as an insulating layer that moderates soil temperature fluctuations and buffers moisture losses, thereby maintaining a more stable microclimate compared to open habitats [41]. As De Frenne et al. [42] emphasize, forest microclimates can substantially decouple near-ground thermal and hydrological conditions from regional climate variability, providing refugia and enhancing overall ecosystem stability. This stability is fundamental to strengthening the resilience of reclaimed ecosystems to increasing climatic variability, including the long-term impacts of drought legacies. Conversely, grasslands, characterized by their rapid physiological and structural responses to hydrological fluctuations, can serve as sensitive bioindicators of ecosystem water dynamics. Maintaining a balanced mosaic of these habitat types—while strategically leveraging the hydrological buffering capacity of forests—is therefore essential for advancing sustainable water-resource management in post-mining polder environments.

5. CONCLUSIONS

In conclusion, this paper aims to present the results of a study on the response of vegetation to increased soil moisture, using data from the Copernicus satellite mission Sentinel-2 and in-situ measurements from the 'MUSE – Multisensor Geomonitoring for optimizing post-mining water management' project. The results highlight the interdependence between climatic and soil parameters and demonstrate the importance of continuous environmental monitoring for sustainable post-mining water management.

- Seasonal variability in soil moisture and temperature was clearly expressed, reflecting the climatic cycle of the study region. Maximum soil moisture values (25–40% VWC) occurred during autumn and winter, while minima (5–15% VWC) were observed in summer. Soil temperature followed an inverse pattern, with the highest values in summer and the lowest in winter. Forest soils exhibited more stable hydrological and thermal conditions than meadows, due to the buffering effects of canopy cover, litter accumulation, and reduced evaporative losses.

- The analysis of NDVI values demonstrated a strong correspondence with soil moisture variation. Optimal vegetation vitality was recorded under moderate soil moisture conditions (12–32% VWC), whereas both excessive wetness (>32% VWC) and dryness (<12% VWC) were associated with declining NDVI, indicating physiological stress. These findings confirm that deviations from the field-capacity range impair plant function through either oxygen deficiency or water limitation.

- The differentiation between pseudogleyic forest soils and gleyic meadow soils exerted a major control on moisture retention and drainage dynamics. The pseudogleyic profile retained water in upper horizons, enhancing moisture stability but promoting waterlogging under prolonged saturation. The gleyic soils in the meadow zone showed rapid alternation between saturation and desiccation, consistent with the observed variability in NDVI. These results underline the importance of soil physical properties in shaping vegetation response to climatic forcing.

- The monitoring period included both dry and wet extremes (e.g., drought in summer 2022 and wet winter 2023), which significantly influenced soil moisture and NDVI. Vegetation stress occurred during both extremes, demonstrating the sensitivity of these ecosystems to climatic variability and the need for adaptive management strategies.

- The integration of remote sensing and in-situ data proved to be an effective framework for the continuous observation of soil–vegetation interactions. NDVI dynamics provided a reliable proxy for soil moisture variation and vegetation health, offering potential for operational monitoring at the landscape scale. The approach enhances early warning capabilities for hydrological imbalance and supports data-driven decision-making in post-mining land reclamation and polder management.

In conclusion, precipitation has a direct impact on soil moisture, yet its effectiveness in sustaining vegetation depends strongly on air and soil temperature. Forest ecosystems contribute to greater hydrological stability, while meadows serve as sensitive indicators of environmental change. Continuous, long-term monitoring of soil and vegetation parameters is therefore essential for effective and sustainable management of mining-induced polders in the context of ongoing climate change.

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REFERENCES

1. RAG Aktiengesellschaft, Poldermaßnahmen – Bäche im Fluss halten [Polder measures – Keeping streams in the river]. https://www.rag.de/loesungen/poldermassnahmen (last accessed 16 October 2024).
2. Bernsdorf, B et al. 2022. Climate Change | Management and Monitoring – Boden- und In situ-Sensordaten als Schlüssel zum Prozessverständnis halten [Climate Change | Management and Monitoring – Soil and in-situ sensor data as key to process understanding]. *Mining Report Glückauf* **158 (1)**, 32-52.
3. Fekete, A 2024. *Risiko, Katastrophen und Resilienz – Eine Einführung in Methoden, Konzepte und Themen [Risk, Disasters, and Resilience – An Introduction to Methods, Concepts, and Topics]*. Berlin: Springer Spektrum.
4. Deutscher Wetterdienst 2024. Deutschland erlebte den nassesten zwölfmonatigen Zeitraum seit Messbeginn 1881- Aktuelle Auswertung des Deutschen Wetterdienstes [Germany experienced the wettest twelve-month period since records began in 1881 - Current analysis by the German Weather Service] https://www.dwd.de/DE/presse/pressemitteilungen/DE/2024/20240703_die-zwoelf-nassesten-monaten-seit-messbegin_news.html (last accessed 16 October 2024).
5. Alobid, M et al. 2024. Trends and Drivers of Flood Occurrence in Germany: A Time Series Analysis of Temperature, Precipitation, and River Discharge. *Water* **16(18), 2589**, 1-15.
6. Conradt, T et al. 2023. Cross-sectoral impacts of the 2018–2019 Central European drought and climate resilience in the German part of the Elbe River basin. *Reg Environ Change* **23, 32**, 1-18.
7. Young, H 2024. Are extreme floods the new normal for Germany? Deutsche Welle. https://www.dw.com/en/are-extreme-floods-the-new-normal-for-germany (last accessed 20 October 2025)
8. Neumann, N 2022. Peatlands clean acid mine drainage: Wetland restoration and microbial ecosystem services in post-mining areas. Leibniz Institute of Freshwater Ecology and Inland Fisheries. https://www.igb-berlin.de/en/news/peatlands-clean-acid-mine-drainage (last accessed 20 October 2025)
9. Böse, C, Farrenkopf, M and Weindl, A 2018. *Kohle-Koks-Öl, Die Geschichte des Bergwerks Prosper-Haniel [Coal-Coke-Oil, The History of the Prosper-Haniel Mine]*. Münster: Aschendorff Publisher.
10. Otkin, JA et al. 2015. Facilitating the use of drought early warning information through interactions with agricultural stakeholders. *Bulletin of the American Meteorological Society*, 1073-1078.
11. Joiner, J et al. 2018. Global relationships among traditional reflectance vegetation indices (NDVI and NDII), evapotranspiration (ET), and soil moisture variability on weekly timescales. *Remote Sensing of Environment* **219 (15),** 339-352.
12. Bresinsky, A, Körner, C, Kadereit, JW, Neuhaus, G and Sonnewald, U 2008. *Strasburger – Lehrbuch der Botanik 36 [Strasburger – Textbook of Botany 36]*. Heidelberg: Spektrum Akademischer Publisher.
13. Rouse, JW, Haas, RH, Deering, DW and Schell, JA 1973. *Monitoring the Vernal Advancement and Retrogradation (Green Wave Effect) of Natural Vegetation*. Remote Sensing Center. Texas University, 1-87.
14. Tucker, CJ 1979. Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment* **8(2)**, 127-150.

15. Sellers, PJ 1985. Canopy reflectance, photosynthesis and transpiration. *International Journal of Remote Sensing* **6 (8)**, 1335–1372.
16. Tucker, CJ and Sellers, PJ 1986. Satellite remote sensing of primary production. *International Journal of Remote Sensing* **7 (11)**, 1395–1416.
17. Crippen, RE 1990. Calculating the vegetation index faster. *Remote Sensing of Environment* **34 (1)**, 71-73.
18. Sellers, PJ et al. 1992. Canopy reflectance, photosynthesis and transpiration. III. A reanalysis using improved leaf models and a new canopy integration scheme. *Remote Sensing of Environment* **42 (3)**, 187-216.
19. Kuechly, H, Cozacu, A, Kodl, G, Nicolai, C and Vallentin, C 2020. *Grundlagen der Fernerkundung, (Inforeihe SAPIENS: Satellitendaten für Planung, Industrie, Energiewirtschaft und Naturschutz) [Fundamentals of remote sensing, (SAPIENS series: Satellite data for planning, industry, energy management and nature conservation)]*. Potsdam: Deutsches GeoForschungsZentrum GFZ.
20. Kadereit, JW, Körner, C, Nick, P and Sonnewald, U 2003. *Strasburger – Lehrbuch der Pflanzenwissenschaften 38 [Strasburger - Textbook of Plant Sciences 38]*. Heidelberg: Spektrum Akademischer Publisher.
21. Wang, J et al. 2003. Temporal responses of NDVI to precipitation and temperature in the central Great Plains, USA. *International Journal of Remote Sensing* **24**, 2345–2364.
22. Pawlik, M et al. 2022. Analyse des Zustands der Vegetation auf dem Gelände des stillgelegten Bergwerks Prosper Haniel anhand von multispektralen Satellitenbildern der Sentinel-2 Mission und Drohnenflüge [Analysis of the vegetation condition on the site of the closed Prosper Haniel mine using multispectral satellite images from the Sentinel-2 mission and drone flights]. *Markscheidewesen* **129**, 37–44.
23. Candiago, S et al. 2015. Evaluating Multispectral Images and Vegetation Indices for Precision Farming Applications from UAV Images. *Remote Sensing* **7(4),** 4026-4047.
24. Maresma, Á et al. 2016. Analysis of Vegetation Indices to Determine Nitrogen Application and Yield Prediction in Maize (Zea mays L.) from a Standard UAV Service. *Remote Sensing* **8 (12) 973**, 1-15.
25. Marino, S and Alvino, A 2020. Agronomic Traits Analysis of Ten Winter Wheat Cultivars Clustered by UAV-Derived Vegetation Indices. *Remote Sensing* **12 (2) 249**, 1-16.
26. Marino, S and Alvino, A 2021. Vegetation Indices Data Clustering for Dynamic Monitoring and Classification of Wheat Yield Crop Traits. *Remote Sensing* **13 (4) 541,** 1-21.
27. Doughty, CL et al. 2021. Characterizing spatial variability in coastal wetland biomass across multiple scales using UAV and satellite imagery. *Remote Sensing 7in Ecology and Conservation* **7 (3),**1-19.
28. Bernsdorf, B and Khaing Zin Phyu 2023. Zur Bewertung von In-situ-Sensoren bei der Einschätzung von Prozessabläufen im Geomonitoring [For the evaluation of in-situ sensors in the assessment of process sequences in geomonitoring]. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften* **173 (4)**, 581-598.
29. Bernsdorf, B, Pawlik, M, Rudolph, T, Jaeckel, J and Haske, B. 2023. *Die Integration von In-Situ- und multispektraler UAV Daten, Ein Ansatz zur Beurteilung des Vegetationszustands in nachbergbaulichen Poldern [The integration of in-situ and multispectral UAV data, an approach to assess vegetation condition in post-mining polders]*. 21. Altbergbaukoloquim, Essen, Germany, November 09-10, 218-228.
30. Bernsdorf, B et al. 2023. Multisensorales Geomonitoring – Ein Beitrag zur Datenfusion im Nachbergbau [Multisensor Geomonitoring - A contribution to data fusion in post-mining]. *gis-Science*, **1**, 1-16.

31. Seidel, D 2023. *Nutzung von Vegetationsindikatoren zur Einschätzung der hydraulischen Lieferfähigkeit des Boye-Einzugsgebietes in Bottrop und Gladbeck*. [*Use of vegetation indicators to assess the hydraulic supply capacity of the Boye catchment area in Bottrop and Gladbeck*]. Masterthesis Technische Hochschule Georg Agricola University (unpublished).
32. Pawlik, M, Haske, B, Flores, H, Jaeckel, J, Bernsdorf, B and Rudolph, T 2023. *The use of UAV data to observe post-mining processes and the formation of subsidence lakes in the former mining area of Prosper-Haniel mine.* Proceedings of XXIII Conference of PhD Students and Young Scientists, Wroclaw, Poland, Juni 15, p. 41.
33. Pawlik, M, Rudolph, T, Bernsdorf, B and Benndorf, J. 2023. *Green Red Water Indices – vegetation indices for environmental Geomonitoring.* Proceedings of XXIII Conference of PhD Students and Young Scientists, Wrocław, Poland, Juni 16, p. 39.
34. Pawlik, M et al. 2024. Proposal for a new Green Red Water Index for geo-environmental surface water monitoring. *IOP Conference Series: Earth and Environmental Science* **1295 012013**, 1-24.
35. Than Thar Lwin, N, Pawlik, M, Bernsdorf, B, Rudolph, T and Jaeckel, J 2024. *The use of in-situ sensor to observe the soil moisture in mining-influenced polder areas.* XXIV Conference of PhD Students and Young Scientists, Wrocław, Poland, October 23-25.
36. Jaeckel, J, Pawlik, M, Bernsdorf, B and Rudolph. T 2024. *Comparison of soil moisture data from in-situ measure with geological data,* XXIV Conference of PhD Students and Young Scientists, Wrocław, Poland, October 23-25.
37. Jaeckel, J et al. 2025. Comparison of Soil Moisture Data From In-situ Measurements with Geological Data. *Civil and Environmental Engineering Reports,* **35(1),** 272–284.
38. Attarzadeh, R et al. 2018. Synergetic Use of Sentinel-1 and Sentinel-2 Data for Soil Moisture Mapping at Plot Scale. *Remote Sensing*, **10(8), 1285**, 1-18.
39. Gao, Q et al. 2017. Synergetic Use of Sentinel-1 and Sentinel-2 Data for Soil Moisture Mapping at 100 m Resolution. *Sensors*, **17(9), 1966**, 1-21.
40. Müller, LM and Bahn, M 2022. Drought legacies and ecosystem responses to subsequent drought. *Global Change Biology*, **28**, 5086–5103.
41. Wilson, TB et al. 2012. The effect of soil surface litter residue on energy and carbon fluxes in a deciduous forest. *Agricultural and Forest Meteorology* **161**, 134-147
42. De Frenne, P et al. 2021. Forest microclimates and climate change: importance, drivers and future research agenda. *Global Change Biology,* **27(18)**, 2279–2297.