Soil characteristics of flood control dikes along the Morava-Thaya River in eastern Austria

Effects of environmental factors and dike management

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Abstract

This study investigates the interactions between soil physical, chemical and biological parameters as well as the influence of climatic, environmental and spatial components on them in the context of dike stability along the Morava-Thaya river system in Central Europe. Climatic variability with more frequent droughts and extreme precipitation events in the future, induced through climate change, might affect flood protection systems through changes in soil structure, hydrology and biogeochemical processes. This study aims to identify dominant environmental gradients, site-specific variability and assess the potential implications for dike stability in the mentioned region.

In total, 20 dike sites, including 4 measurement points on the landside and waterside were taken into consideration together with management practices, exposition, distance to agriculture and to forest as well as location along the dam. Soil texture, bulk density, aggregate stability, organic matter fractions, nutrient availability, microbial biomass, enzyme activities, soil moisture, and temperature were analyzed together with climatic variables.

The results revealed a pronounced spatial heterogeneity along the dam. Coarse-textured sandy sites with lower moisture, reduced microbial biomass, weaker macroaggregate stability and lower organic carbon content could favor piping, seepage and internal erosion. On the other hand, finer-textured sites exhibited stronger aggregation, greater nutrient availability and increased microbial biomass. There, an increase in water retention capacities could occur, but also an increase in vulnerability to shrink-swell dynamics, desiccation cracking and preferential flow formation during drought periods.

Organic carbon, microbial biomass, nutrient availability and macroaggregate stability are indicators of biologically mediated aggregation processes, which can contribute to structural cohesion of dike soils. Additionally, climatic gradients could exert an influence on microbial functioning and aggregation processes along the dike system, where warmer conditions can lead to the promotion of nutrient turnover and enhanced biological activity, while wetter and colder conditions were associated with increased microaggregation and phosphatase activity.

In the PCA analysis, a distinct hydro-biogeochemical gradient structured the dataset where coarse-textured, enzyme-active soils were separated from nutrient-rich and microbially enriched soils. The hydrological position and management practices considered revealed an increase in compaction and structural variability, especially on the waterside and grazed sections.

Overall, dike stability appears to be controlled by interacting with hydro-biogeochemical processes, not isolated geotechnical parameters alone. The importance of integrated physicochemical, biological, climatic and soil structural indicators and hydrological monitoring has been highlighted for the assessment of flood dike stability and establishing an effective flood protection management system (J.-M. Zhang et al., 2021). Spatial heterogeneity may lead to different vulnerability pathways for the dike system under climate change scenarios. Therefore, an emphasis on site-specific and process-based approaches to long-term dike resilience assessment is advised.

Keywords: Flood dike stability, soil characteristics, climate change, aggregate stability, Morava–Thaya region

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Abbreviations

Abbreviation	Description
SLU	Swedish University of Agricultural Sciences
DistanceAgri	Distance from Agriculture [km]
DistanceForest	Distance from Forest [km]
Precipitation2024	Average mean precipitation in 2024 [mm]
Precipitation2025	Average mean precipitation in 2025 [mm]
MacroAg	Macroaggregates
MicroAg	Microaggregates
BD	Bulk density of the soil
EC	Electrical conductivity
K	Potassium
P	Phosphorus
Nt	Total Nitrogen
C_{org}	Organic Carbon
C/N	Carbon to Nitrogen Ratio
DOC	Dissolved organic Carbon
Diss. N	Dissolved Nitrogen
C_{mic}	Microbial Carbon
N_{mic}	Microbial Nitrogen
C_{mic}/C_{org}	Microbial Carbon per organic Carbon
N_{mic}/C_{org}	Microbial Nitrogen per organic Carbon
N_{min}	Mineral Nitrogen
GDD	Growing Degree Days
VPD	Water Pressure Deficit
PET	Potential Evapotranspiration
GSL	Growing Season Length
CWD	Climatic Water Balance

Units

Sand	[%]
Silt	[%]
Clay	[%]
Fract 63-20µm	[%]
Fract 20-2µm	[%]
Soil Thickness (cm)	[cm]
MakroAg	[%]
MikroAg	[%]
SD	[g/cm3]
EC (1:10)	[µS/cm]
pH (in CaCl2)	
K (in CAL)	[mg/kg]
P (in CAL)	[mg/kg]
CaCO3	[%]
Nt	[%]
C_{org}	[%]
C/N	
DOC	[mg/kg]
Diss. N	[mg/kg]
C_{mic}	[mg/kg]
N_{mic}	[mg/kg]
C_{mic}	[mg/gC_{org}]
N_{mic}	[mg/gC_{org}]
Ammonium	[mg/kg]
Nitrate	[mg/kg]
N_{min}	[mg/kg]
Exoglucanase	[nmol/mgC_{org}/h]
Phosphatase	[nmol/mgC_{org}/h]
Protease	[nmol/mgC_{org}/h]
Phenoloxidase	[µmol/mgC_{org}/h]
Average temperature	[°C]
Average temperature (mean in the warmest month)	[°C]
Average temperature (mean in the coldest month)	[°C]
Average temperature (minimum in the coldest month)	[°C]
Average temperature (maximum in the warmest month)	[°C]
Average number of frost days per year	[days/year]
Average length of the growing season	[days]
Average Growing Degree Days per year (>5°C)	[°C x year]
Average number of extremely hot days (<35°C)	

Average number of days with hard frost (<-10°C) per year	[days/year]
Average relative humidity	[%]
Average vapor pressure deficit	[kPa]
Average precipitation sum	[mm/year]
Average annual potential evapotranspiration	[mm/year]
Average climatic water balance	[mm/year]
Average climatic water balance in the growing season	[mm]
Temperature	[°C]
Soil moisture	[m^3/m^2]

1. Introduction

Flood protection dikes play a crucial role in protecting settlements, agricultural land, infrastructure, and ecosystems from floods. These structures, sometimes also called levees or embankments, are earthen structures constructed parallel to rivers in order to prevent floodwater from inundating adjacent land. Such soil flood protection dikes are typically composed of compacted natural materials (sand, silt, clay, gravel). Their stability depends on the behavior of the soil body, the hydraulic loading imposed by floodwaters, as well as the interaction between seepage processes and soil strength (Simm et al., 2013).

Flood dikes consist of a relatively impermeable core, often made of clay-rich materials, surrounded by compacted earth fill. The landside and waterside slopes are designed to maintain stability under varying hydraulic conditions, while protective vegetation helps to reduce erosion. Although these structures appear simple, their behavior during flood events is governed by complex geotechnical and hydraulic processes. Even minor deficiencies in construction quality, material properties, or maintenance can significantly increase the probability of failure during extreme flood events (Simm et al., 2013).

Along the Morava-Thaya river system, flooding is expected to intensify together with extreme precipitation events, prolonged drought periods and fluctuating hydrological conditions, which might increase pressure on the existing flood protection infrastructure (Masson-Delmotte et al., 2021). Soil physical, chemical and biological properties can influence long-term structural resilience. Soil texture, aggregate stability, bulk density, organic matter dynamics, nutrient availability and microbial activity conditions regulate processes such as seepage, erosion, piping, cracking, and slope instability. Furthermore, environmental gradients, hydrological position, vegetation management, and spatial variability may create locally different conditions within the dike system, resulting in varying susceptibility to structural weakening or failure. Common failure mechanisms include slope instability, internal erosion (piping), excessive seepage, overtopping, and foundation failure. Even minor deficiencies in construction quality, material properties, or maintenance can significantly increase the probability of failure during extreme flood events (Blöschl et al., 2019).

The Austrian section of the Morava and Thaya river system provides an important example of the vulnerability of flood protection infrastructure to extreme hydrological events. In spring 2006, a combination of heavy rainfall and rapid snowmelt throughout the catchment area generated a flood event with an estimated return period of approximately 100 years.

Peak discharges in the Morava River exceeded 1,400 m^3/s, placing extraordinary stress on the flood protection system along the Austrian–Slovak border. During the event, several breaches occurred in the March flood protection dike system, particularly near Dürnkrut, Grub, and Stillfried. On 3 April 2006, the dike near Jedenspeigen failed, allowing floodwater to rapidly inundate the surrounding lowlands. Within hours, large parts of Dürnkrut were flooded, approximately 350 houses had to be evacuated, and hundreds of residents were displaced. Additional breaches followed near Stillfried, while emergency services, the Austrian Armed Forces, and thousands of volunteers worked continuously to stabilize the damaged structures using sandbags, helicopters, and temporary reinforcement measures (viaDonau, n.d.).

The consequences of the flood extended far beyond the immediate inundation. Residential buildings, agricultural land, industrial facilities, railway infrastructure, roads, and public utilities suffered extensive damage. Contamination from heating oil released from flooded buildings complicated cleanup efforts and increased environmental impacts. Across the affected region, damages exceeded €72 million, while some assessments estimated total losses approaching €100 million in the most heavily affected communities. The flood also highlighted long-standing concerns regarding the condition of parts of the dike system, as reports had previously identified sections requiring rehabilitation. The 2006 Morava–Thaya flood therefore represents a significant case study for evaluating the performance of earthen flood protection dikes. Understanding the mechanisms that contributed to these failures is essential for improving flood risk management strategies and ensuring the resilience of flood protection systems under future climate conditions (viaDonau, n.d.)

The importance of understanding dike stability has increased considerably in recent decades due to climate change. Rising global temperatures are intensifying the hydrological cycle, leading to more frequent and severe precipitation events, accelerated snowmelt, and greater variability in river discharge. As a consequence, flood magnitudes and durations are expected to increase in many European river basins. These changing conditions expose flood protection systems to hydraulic loads that often exceed those considered during their original design. Furthermore, repeated wetting and drying cycles, prolonged saturation, and increasing erosion pressures can reduce soil strength and increase the susceptibility of earthen dikes to failure. Climate change therefore presents a significant challenge for the long-term reliability of existing flood defense infrastructure (Tambah Emmanuel Saah et al., 2025).

The Morava-Thaya floodplain exhibits heterogeneous soils and a dynamic hydrological environment, which is why the investigation on climatic and environmental factors is crucial for the assessment of present-day dike stability and long-term flood risk management strategies under future climate scenarios, especially after the flooding in 2006 followed by restoration measures (viaDonau, n.d.).

This study combines soil physical, chemical and biological analysis with environmental, climatic and spatial variables to understand processes influencing dike resilience within the flood protection system.

The major questions arising were:

How heterogeneous are the physical, chemical, and biological soil properties within the flood protection dike system along the Morava–Thaya river region, and how are these properties interrelated?

How are soil characteristics influenced by environmental gradients, hydrological position, climatic conditions, land management, and spatial factors within the investigated dike system?

How do soil properties, environmental conditions, and spatial variability collectively relate to potential dike stability, structural resilience, and vulnerability within the Morava–Thaya flood protection system?

In the following chapter, dike resilience and dike failure mechanisms are described.

2. Literature review

2.1 Flood Protection Dikes

2.1.1 Dike stability

When it comes to flood protection, dikes are essential to reduce flooding risk, protecting human settlements, agricultural land as well as ecosystems. In the future, climate change will most likely increase the frequency as well as the intensity of flooding events, therefore, resilient and adaptive flood protection systems need to be implemented in order to combat those changes (Gul et al., 2024). Flood dikes are not only static structures, but they are also dynamic systems, whose stability depends on geotechnical, hydrological and ecological processes. The internal structure of soils strongly defines the connectivity and availability of pores, which has an effect on water retention, infiltration and particle transport (Six et al., 2002).

Dike stability is closely linked to soil structure and aggregate stability, since those factors influence the risk for erosion. Aggregate stability can increase infiltration, reducing runoff, which lowers the formation of preferential flow paths. Furthermore, water storage, aeration and biological activity are additionally influenced by those factors. From a hydrological perspective, fluctuating water levels and intense precipitation events can lead to soil degradation and dike failure due to piping and slope instability (Li et al., 2026).

2.1.2 Vegetation

Another factor, which is crucial for dike stability, is vegetation. It can protect the soil surface and enhance soil structure, shielding the soil from the impact of rainfall as well as runoff, limiting erosion. Root systems can enhance soil aggregation and improve dike stability by reinforcing the soil matrix and increasing shear strength. However, roots may also create preferential flow paths and macropores that facilitate water infiltration and seepage, potentially reducing structural stability. Consequently, the overall influence of vegetation on dike stability depends on vegetation type, root characteristics, site conditions, and management practices (Vannoppen et al., 2016).

2.1.3 Climate change

Climate change might also lead to more extreme hydrological conditions, which will have an effect on periods of droughts, soil moisture dynamics as well as the vegetation cover. Droughts might lead to the cracking of soil layers, they can also reduce vegetation resilience. That's why a holistic approach needs to be taken when investigating dike stability now and in the future (Li et al., 2026).

2.1.4 Dike failure mechanisms

Flood protection dikes are systems whose stability is strongly influenced by soil physical structure, hydrological processes and biogeochemical dynamics. Soil structure can be an indicator for aggregation of particles, the movement of water, aeration and biological activity, while vegetation contributes through the input of organic matter and root systems, influencing aggregation and soil cohesion. Multiple interacting factors must be considered when assessing dike failure mechanisms because of spatially and temporally varying soil processes (Hamza et al., 2025).

In the following chapters, different causes for dike failure will be described.

2.1.5 Slope failure resistance

Shear strength is a key factor controlling slope stability and is influenced by aggregation, clay content, organic matter and moisture conditions. Soil cohesion is strengthened by soil aggregation between mineral particles, organic matter and microbial activity (Bronick & Lal, 2005). Soil can further be stabilized by vegetation roots by reinforcing aggregates and providing organic binding agents (Kumar et al., 2013). Aggregate breakdown, organic matter decomposition and moisture fluctuations may further weaken soil structure over time, reducing slope resistance (Szabo & Brandl, n.d.).

2.1.6 Internal erosion and piping

Soil particle detachment and transport through pore spaces under the hydraulic gradient can lead to internal erosion. Soil texture combined with aggregate stability are key factors, which influence particle mobility and dispersibility. Aggregate breakdown leads to fine particle mobilization, reducing cohesion and increasing the susceptibility to piping and subsurface erosion. Soil chemical conditions, particularly ionic composition, additionally affect dispersion processes and erosion risk. (Bronick & Lal, 2005).

2.1.7 Flood-induced weakening

Flooding can also alter aggregate cohesion due to changes in soil hydrology and chemical conditions, influencing organic matter stability. Mobilized dissolved organic carbon (DOC) due to repeated wetting-drying cycles weakens organic bonds and reduces aggregate stability after prolonged saturation. These processes enhance soil erodibility and structural instability (Tisdall & Oades, 1982).

2.1.8 Slip planes and delayed failure

Differences in texture, aggregation and compaction, which suggest a heterogeneous soil property, create slip planed and preferential flow paths. Pore water pressure might be raised with increased soil saturation, which reduces shear strength, especially in soils with contrasting permeability (Fredlund & Rahardjo, 1993). Furthermore, delayed failure might occur in soils with high water retention and low hydraulic conductivity because of elevated and prolonged pore water pressure, weakening effective stress and soil strength over time (Terzaghi et al., 1996).

2.1.9 Biogeochemical effects

Soil aggregation and structural stability is influenced by biogeochemical processes through interactions between organic matter and microbial activity. Aggregate stabilization is enhanced by soil organic matter, while microbial processes produce binding agents such as polysaccharides that enhance cohesion (Six et al., 2004). The decomposition of organic matter, conversely, weakens soil structure and reduces stability (Bronick & Lal, 2005).

2.1.10 Cracking and seepage

Changes in soil moisture and temperature might induce shrink-swell processes, which might lead to cracking, particularly in clay-rich soils (Tang et al., 2023). Preferential flow paths, created by cracks, increase seepage and permeability even in previously stable soils. Carbonates can also help to improve aggregation through cementation processes, although excessive brittleness can also increase structural vulnerability (Beven & Germann, 1982).

2.1.11 Local vulnerability and spatial heterogeneity of soils

Across dike systems, soil properties often vary considerably. This results in local differences in texture, aggregation, moisture and organic matter content (Vereecken et al., 2014). Due to this heterogeneity, weak zones can be created associated with root channels, soil layering or structural discontinuities, which can lead to an increase in local susceptibility to dike failure. Therefore, dike stability must be understood as a function of spatially heterogeneous soil systems requiring site-specific analysis (Beven & Germann, 1982).

2.2 Soil factors

Geotechnical and hydrological investigations of dikes revealed that the condition of the embankment soils, not just their height or slope, plays a critical role in the integrity and resilience of the flood defenses (Szabo & Brandl, n.d.)

Specifically, soil characteristics such as texture, density, and aggregate structure determine how water seeps, how internal erosion develops, and how stable the slope remains under hydraulic stress (Szabo & Brandl, n.d.). Therefore, a detailed understanding of soil physical and chemical properties is not merely academic but foundational for improving flood protection (Ali & Tanaka, 2023).

In order to understand how dike stability is affected by the changes in climate, first, the inherent soil characteristics at site need to be described. Soil characteristics can have a significant influence on dike stability when it comes to shear strength, hydraulic behaviour as well as erodibility (Szabo & Brandl, n.d.). Therefore, in the following chapters, those characteristics will be put into context.

In table 1, an overview of the measured soil factors is given together with their context in terms of dike stability. They are structured in physical, chemical and biological controls and are linked to processes within the dikes as well as to the implications for dike stability.

Table 1: Link between soil factors and dike stability

Category	Factors	Processes	Implication for dike stability	Reference
General	Heterogeneous soil systems	Spatial variability in soil properties and layering	Requires site-specific assessment of failure mechanisms	Metwally et al., 2019
Physical controls	Soil texture (sand, silt, clay)	Fine particles (especially clay) get mobilized under seepage, leading to internal erosion	Increased risk of piping and structural failure	Zwanenburg et al., 2018a
	Soil structure (Macroaggregates, Microaggregates)	Aggregate abundance, size and cohesion increase resistance to particle detachment and reduce hydraulic conductivity	Improved erosion resistance and structural stability	Zwanenburg et al., 2018a
	Soil thickness	Controls stratification and hydraulic gradient	Influences of seepage pathways and failure depth. Rooting depth has positive and negative influences on dike stability, plant water availability is influenced	J.-M. Zhang et al., 2021, Osman & Barakbah, 2006
	Bulk density	Increased density enhances shear strength and reduces seepage, excessive compaction may increase pore pressure and impair drainage	Context dependent, can both stabilize and destabilize	Zwanenburg et al., 2018a
	Soil temperature	Soil drying/desiccation, shrinking/swelling behaviour, freeze/thaw cycles	Structural weakening, soil cohesion, cracking, influencing vegetation and root water uptake	Guo et al., 2014, Duan et al., 2025

	Soil moisture	Influences pore water pressure, saturation, hydraulic conductivity, infiltration dynamics, capillary forces, water retention capacity	Can reduce effective stress and make shear strength decline, can cause preferential flow paths, internal erosion, piping, seepage	Jotisankasa et al., 2015
Chemical controls	Electrical conductivity (EC)	Proxy for soluble ions (Na^+, Ca^{2+}, Mg^{2+}), ionic strength affects clay dispersion and aggregation	High EC may indicate stable aggregates, low EC linked to dispersity and erosion, may also indicate seepage zones	Tucker-Kulesza et al., 2019
	pH	Controls surface charge, cation availability (Ca^{2+}, Mg^{2+}, Al^{3+}), plasticity, and aggregation	Stability highest near neutral pH, extreme pH increases dispersity and erosion risk	Gan et al., 2024
	Potassium (K^+)	Enhances clay flocculation, reduces dispersion, supports plant growth and root reinforcement	Improves aggregate stability and resistance to internal erosion	Xu et al., 2022, Six et al., 2004
	Phosphorus (P)	Promotes microbial activity and organic binding agents, enhances aggregate formation	Improves structural stability and vegetation cover	Liu, Wang, et al., 2024
	Carbon (SOC, DOC, $CaCO_3$)	SOC enhances aggregation via organic binding agents, DOC affects colloidal transport, Ca^{2+} promotes flocculation and cementation	Generally, improves cohesion and reduces erodibility, DOC may increase particle transport	Zhou et al., 2020
	Nitrogen (N)	Influences vegetation, microbial activity and DOC dynamics, effects depend on form (NH_4^+ vs NO_3^-) and duration	Short-term inputs may enhance aggregation; long-term inputs may reduce stability via acidification and SOC loss	Su et al., 2024

Biological controls	Enzyme activity (general)	Reflects microbially driven biogeochemical processes affecting soil structure and hydraulic properties	Indicators of long-term stability and soil functioning	Wang et al., 2023
	Exoglycanase	Decomposition of cellulose and carbon turnover affecting aggregate dynamics	Balances short-term destabilization with long-term aggregation	Burns et al., 2013
	Phosphatase	Mineralization of organic P, supports vegetation and aggregation processes	Enhance root stabilization and soil cohesion	Turner et al., 2013
	Protease	Controls nitrogen mineralization and organic matter turnover	Can increase or decrease aggregation depending on conditions	Burns et al., 2013
	Phenoloxidase	Degrades lignin and influences hydrophobicity and redox conditions	Affects long term structural integrity and erosion resistance	Sinsabaugh, 2010

3. Study area

3.1 Morava-Thaya Region

3.1.1 Location

The Morava/Thaya river system is a major transboundary fluvial network in Central Europe. It forms borders between Austria, the Czech Republic, and the Slovak Republic. The river, known as March in Austria and Morava in the Czech Republic and Slovakia, originates in the Králický Sněžník mountains in the Czech Republic and flows in general to the south for approximately 350 km before joining the Danube River near Devínska Nová Ves / Hainburg an der Donau. Its basin covers roughly 26 600 km², with the majority in the Czech Republic, and smaller portions in Slovakia and Austria; the river acts as a significant left bank tributary to the Danube. (Flood Action Plan for Drava and Mura | ICPDR - International Commission for the Protection of the Danube River, n.d.).

Figure 1: The Morava River Basin (Flood Action Plan for Drava and Mura | ICPDR - International Commission for the Protection of the Danube River, n.d.)

Geographically, the lower courses of the river and its floodplains, especially around the Morava-Thaya floodplain area, are characterized by low-gradient alluvial plains formed by Quaternary fluvial deposits.

This region includes extensive wetlands, floodplain forests, and alluvial meadows, among the largest in Central Europe, that historically experienced regular inundation by overbank flows.

The floodplain landscape, which spans across the Austrian–Slovak–Czech border, exhibits complex hydromorphology and a mosaic of side arms and channels, although river regulation and artificial embankments constructed since the early 20th century have significantly altered its natural dynamics (Seffer & Stanova, n.d.).

The Morava basin lies within the temperate central European climate zone. Seasonal variability influences precipitation and runoff patterns strongly. Spring snowmelt as well as summer precipitation from the upstream highlands can commonly be associated with flood peaks. In winter, rain-on-snow episodes can cause flooding events. The frequency and magnitude of flooding events varied historically, especially in the spring and summer months (‘(Floods and Floodplain Changes of the River Morava, the Strážnické Pomoraví Region (Czech Republic) over the Past 130 Years’, n.d.).

The flood protection dikes along the Morava run along the downstream reaches as well as adjacent to the tributaries such as the Thaya. Especially affected is the region of Marchfeld, where the river flows through low-lying plains in Lower Austria. These dikes were constructed in the 20^{th} century as part of a broader river regulation and flood defense program, during which the embankments have been constrained to ensure protection of agricultural land, infrastructure as well as settlements. The region shows a significant hydro-climatic variability, which must be considered, together with future ecological and geomorphological changes when it comes to structural flood risk management (*LIFE+ Restoration of the Lower Morava Floodplains*, n.d.).

In Figure 2, a map of the area is shown with the sites marked, that have been considered during this study. They represent the flood protection dike system constructed along the river. On 20 sites, measurements on soil, climate and mowing methods have been collected.

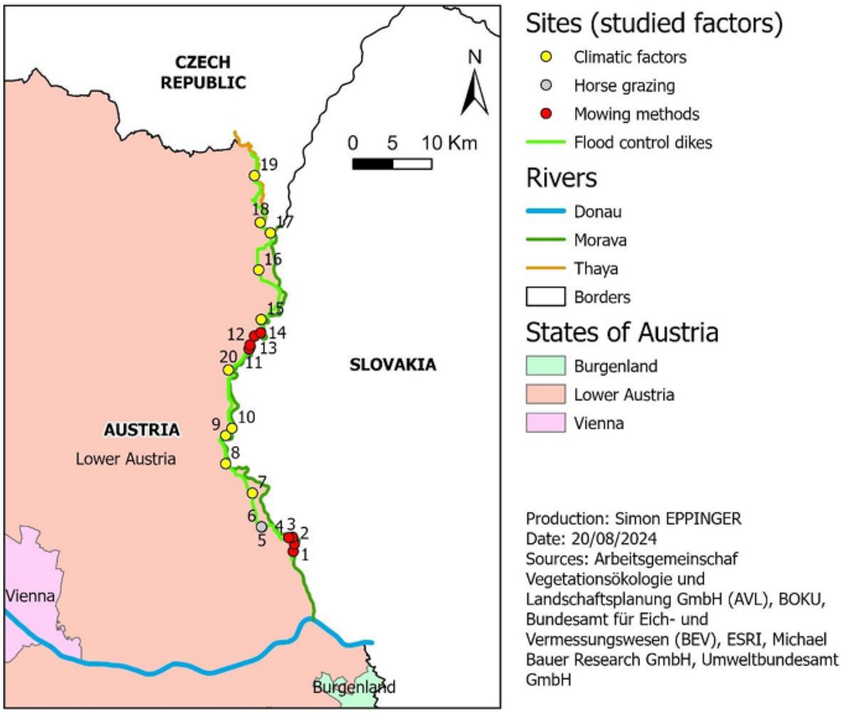


Figure 2: Studied sites along the Morava river (Eppinger, 2024)

3.1.2 Climate

In Figure 3, the average climate of the region is described:

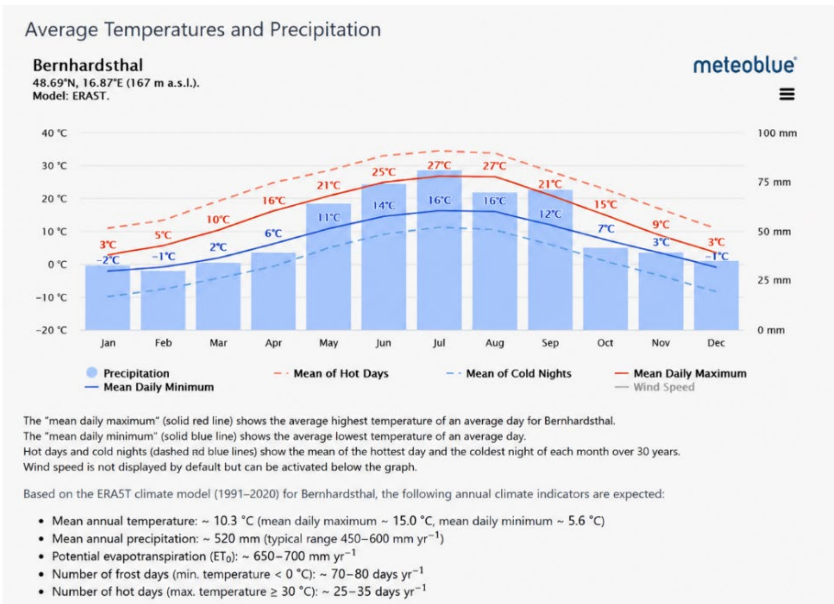


Figure 3: Climate in the Morava-Thaya Region (Bernhardsthal) (Simulierte historische Klima- und Wetterdaten für Bernhardsthal, n.d.)

The climatic conditions indicate a moderately warm and relatively dry environment, with a higher ET than precipitation during the growing season, leading to seasonal water deficit that influences soil moisture dynamics and drought risk (*Simulierte historische Klima- und Wetterdaten für Bernhardsthal*, n.d.).

Europe has experienced increasingly intense and unpredictable precipitation events in the recent decades, which will lead to more frequent flooding in the future (Nissen & Ulbrich, 2017a).

The Morava River basin is particularly sensitive to climatic changes affecting flood regimes and hydrological processes (Blöschl et al., 2019). Snow accumulation will change in the future and temperatures rise, shifting flood dynamics from snowmelt-driven spring floods towards rainfall-driven winter floods. Parallel to this, heavy rainfall events will increase in intensity and change patterns, generating more runoff and therefore increasing flood hazards in the region (Haslinger et al., 2025)

Historical river regulation, floodplain disconnection, wetland drainage and intensified land use also altered the flood behavior in the Morava-Thaya region, because they altered the natural runoff and retention processes (Brázdil et al., 2011).

With increased atmospheric moisture and urbanization, higher flood risks and greater damage potential is at given. Therefore, an adaptive and resilient flood protection system is becoming increasingly important (Blöschl et al., 2019).

Processes like soil moisture dynamics, infiltration, vegetation stress and drought development are strongly influenced by climatic conditions, which are directly linked to dike stability and resilience. Temperature variability, frost conditions, and atmospheric moisture influence soil physical, chemical, and biological processes that may contribute to cracking, seepage, erosion, and changes in soil cohesion. Therefore, understanding the interaction between climate and soil processes is essential for assessing long-term dike stability under future climate change scenarios (Li et al., 2026).

3.2 History

The Morava-Thaya region has historically always been prone to flooding, since the dynamic river system meanders through the landscape, the levels of groundwater are high and natural floodplains tend to form because of these conditions. Flood attenuation and ecological diversity were key elements of this area (Rivers of Europe, n.d.).

Before 2006, flood management has mainly been implemented in form of structural measures such as channel straightening, deepening, drainage of wetlands, bank stabilization as well as flood dike implementation. The goal was to reduce local flooding and to improve land use in the area. The consequences of these measures were increased flow velocities, reduced floodplain connectivity and higher hydraulic loads, especially on the later constructed dikes. Especially erosion risk and peak flow have been increased (Hohensinner et al., 2023).

Another aspect, that has been affected is the natural flood protection like retention areas, inundation as well as groundwater recharge. Due to the introduced measures, the natural intervention capacity has been lowered, the peak discharge increased and prolonged high-water levels were normalized. This might have led to additional stress to the dike systems, increasing the risk of leakage and internal erosion (*Rivers of Europe*, n.d.).

For a long time, the structural integrity of the dike systems has been crucial for the safety of agricultural land and settlements. However, under extreme conditions, dike failures based on overtopping, piping, slope instability and an increased hydraulic load were increasingly at risk of happening (*The Analysis of the Danube Floods 2006 FINAL.Pdf*, n.d.).

Locally, weirs, pumping stations and sluices were used to regulate the water levels. All in all, the goal has been to confine the water, resulting in reduced system resilience, increased downstream flood risk and an increased pressure on the dike system (Preliminary Flood Risk Assessment in the Danube River Basin, 2012).

Ecological degradation and the alteration of natural floodplain vegetation may reduce soil stability and increase susceptibility to erosion, potentially affecting the long-term stability of adjacent flood protection structures (Stokes et al., 2014a)

Overall, before 2006, flood protection relied heavily on flood protection dikes along the Morava-Thaya region. While they are in some cases effective as short-term solutions, their implementation also reduced natural retention and increased stress on the dikes themselves, making them more prone to failure under extreme conditions (The Analysis of the Danube Floods 2006, 2008).

3.3 Flooding in 2006

In the Morava - Thaya region, flood protection is of utmost importance. This especially has been a concern after severe high-water events. One example for it would be the April 2006 flood, when portions of the dike system failed. Since then, dike stability has been brought more into focus. During the event, three dikes broke and major transport infrastructure between Vienna and Prague was damaged as well as further roads, with losses of about 40 million €. Furthermore, 460 homes were affected, and private losses were estimated to be about 28 Mio. €. The dike reconstruction alone has been estimated to be 3.5 Mio. €. After this incident, loss prevention and mitigation for future scenarios has been a concern of the affected stakeholders (The Analysis of the Danube Floods 2006, 2008).

To cope with the challenges emerging after the flooding in 2006, a large dike restoration project has been started, which will be discussed in the following chapter.

3.4 Local environment at the dikes

3.4.1 Location within the dikes

The position of the measured site on the dike, whether it is situated towards the flooded area or away from it, plays a crucial role in order to understand the spatial controls, soil properties and dike stability. Differences that might be significant per side, include hydrological, chemical, and mechanical boundary conditions, resulting in altered soil structure and dike behavior. On the water side, the soil is directly influenced by fluctuating water levels as well as with periodic saturation. This can increase the pore water pressure inside the dike, reducing the shear strength during high water events. Especially during repeated wetting/drying periods, soil aggregation might be influenced, decreasing soil structural stability, leading to a wash-out of fine particles and enhancing seepage. From a chemical view, on the water side, redox conditions, affecting soil cementation processes, can be altered (Terzaghi et al., 1996).

The land side of the dike is mainly influenced by precipitation, evapotranspiration as well as drainage. Due to the lower saturation frequency, more aerobic conditions are expected, which is enhancing aggregate stability as well as shear resistance. Nevertheless, in clay-rich soils shrinkage and cracking can lead to flow paths that reduce internal stability during rewetting significantly (Fredlund & Rahardjo, 1993).

The contrast between waterside and landside soil conditions therefore represents a critical spatial control on dike stability. Their differences lie in soil moisture regimes, pore pressure development, and soil chemical processes (Terzaghi et al., 1996).

3.4.2 Distance to Agricultural Land

The most relevant factors tied to the distance of flood dikes to agricultural land are the anthropogenic input to the agricultural land as well as the hydrological connectivity. Nutrients, agrochemicals as well as fine sediments can reach the dike via surface runoff, subsurface flow or atmospheric deposition. Furthermore, the clogging of soil pores with fine particles, reducing permeability, can lead to a change in hydraulic properties, increasing runoff and enhancing erosion risk (Lal, 2001).

In terms of nutrients, nitrogen and phosphorus can enhance the growth of vegetation, which can increase soil structure through the input of organic matter as well as a stabilizing root system. Nevertheless, with an increased nutrient load, microbial activity might be increased together with the organic matter turnover, reducing the amount of persistent organic binding agents and therefore aggregate stability (Haygarth & Sharpley, 2000).

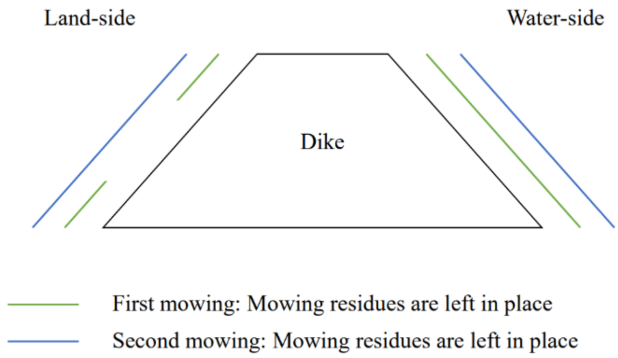
3.4.3 Distance to Forested Areas

Forested areas might have an influence on dike soils in terms of organic matter inputs, hydrological regulation, and root dynamics. Organic matter inputs enhance soil aggregate stability, however, forest soils tend to have higher infiltration capacities, which might result in destabilizing subsurface water fluxes. On the aspect of dike stability, root systems might provide more mechanical reinforcements, however, they can also create macropores, increase the risk of internal erosion (Simon & Collison, 2002).

3.4.4 Management of the Dike Vegetation

On site, there were four different management methods used on the vegetation, which were applied to the land side of the dikes.

Table 2: Vegetation management at the study area (Eppinger, 2024)

Code	Sites	Mowing frequency	Plant residue
C	1, 11	Twice a year	Left on site
1R	2, 12	Twice a year	Removed during first mowing, left on site during second mowing
2R	3, 14	Twice a year	Removed both times
US	4, 13	Twice a year	Unmown strip is left at the flank during the first mowing, residue left on site after the second mowing  *Figure 4: Mowing type US, Eppinger, 2024*

On site 5, with site 6 as reference site, there has additionally been horse-grazing practices. This has been done on both, the land- and the waterside.

3.4.5 Construction Period

The period or year a dike has been constructed can be an indicator for certain soil characteristics as well as construction practices. Historically, dikes have often been created using locally available material with a heterogeneous grain-size distribution and with limited compaction controls (van Baars & van Kempen, 2009). This choice of material might increase the dike's permeability, resulting in weak layers and an increased risk for internal erosion (Duncan, 2014). In recent years, more advanced methods have been used, especially when it comes to the selection of the dike's material, the drainage design as well as the consideration of controlled compaction. A homogeneous soil structure might improve the hydraulic performance of flood protection dams (Fell et al., 2014).

Not only the timing of the implementation of dikes matters when it comes to dike stability but also the soil aging processes, which, over time, are influenced by consolidation, weathering and biogeochemical processes (Fell et al., 2014). While aggregation and densification might improve dike stability, cracking, oxidation and material degradation can result in a weakened structure (Duncan, 2014).

4. Methods

4.1 Available Data

The dataset, which consists of 20 different sites as well as 2 separate measurements, one per land side of the dike and one per rewetted side next to the water, showed a wide range of soil and climate variables and a total of 40 observations. They include physical, chemical, and biological parameters.

4.1.1 Soil sampling and preparation

Soil samples were collected by the University of Life Science in Vienna (BOKU) and were analyzed in the laboratory of the institute of soil science (Figure 2). The samples were taken from flood control dikes at a depth of 0 - 20 cm. At each site, four field replicates were taken to ensure statistical robustness. Samples were stored at 8 °C prior to analysis to limit biological activity. All samples were oven-dried at 40 °C and dry-sieved to retain the 1 000 - 2 000 µm fraction in order to standardize moisture and texture before analysis (Eppinger, 2024).

4.1.2 Soil aggregate stability

Soil aggregate stability was determined using the ultrasonic dispersion method (USAS) with a self-developed ultrasonic device. Samples were subjected to ultrasound for 30 s at a vibration amplitude of 0.50 µm, corresponding to an applied energy of 0.17 ± 0.04 J m L^{-1}. After physical dispersion, samples were wet-sieved to separate macroaggregates (> 250 µm) and microaggregates (63–250 µm). Remaining stable aggregates were fully dispersed using sodium pyrophosphate (DIN 19683-16) to quantify sand content. Ultrasonic macroaggregate and microaggregate stability were expressed as the percentage of aggregates remaining stable at a given applied energy (Eppinger, 2024).

4.1.3 Additional soil parameters

Bulk density was measured using soil samples of known volume. Separate soil samples were collected for microbial activity analyses as part of the broader ClimD project (Eppinger, 2024).

4.1.4 Climate parameter measurements

Soil moisture and soil temperature were continuously monitored in situ using TOMST sensors buried at each sampling plot. These data were used to characterize microclimatic conditions at the sites and to support interpretation of soil and vegetation responses (Eppinger, 2024).

The measurements have been taken four times at the land side and four times at the water side of the 20 sites, where the dikes are located.

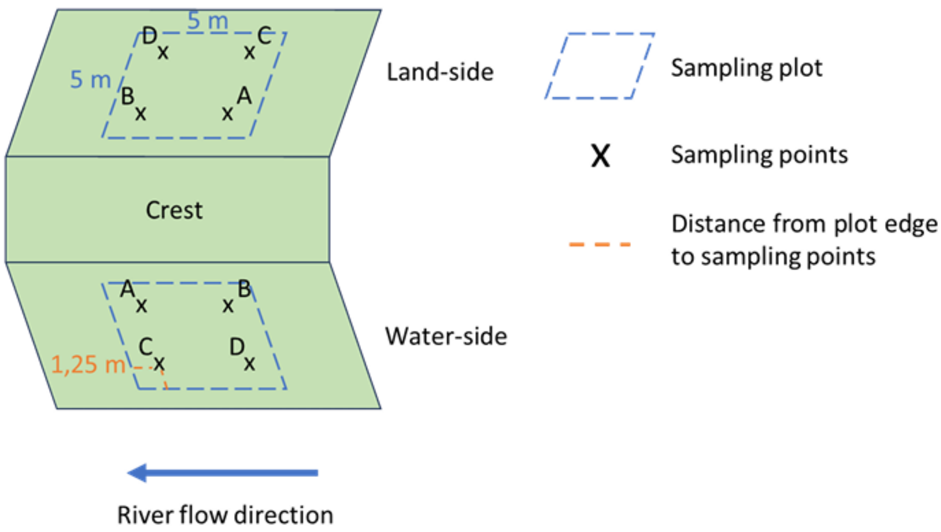


Figure 5: Data sampling on the flood protection dikes at the study area (Eppinger, 2024)

In Table 3, a list of the methods used to determine the soil parameters has been added.

Table 3: Soil parameters and their measurement methods

Soil parameters	**Measuring units**	**Method**	**Citation**
MakroAg	%	Ultrasonic soil aggregate stability	Mentler et al., 2004
MikroAg	%	Ultrasonic soil aggregate stability	Mentler et al., 2004
BD	g/cm3	Core method	*KelloggSSL_MethodsManual_R42V5_2014.Pdf*, n.d.
EC (1:10)	µS/cm	Water extraction at 1:10 (w/v)	*KelloggSSL_MethodsManual_R42V5_2014.Pdf*,
pH (in CaCl2)		Equilibration in 0.01 M $CaCl_2$ at 1:5 (w/v)	*KelloggSSL_MethodsManual_R42V5_2014.Pdf*, n.d.
K (in CAL)	mg/kg	Calcium-acetate-lactate (CAL) extraction	Schüller, 1969
P (in CAL)	mg/kg	Calcium-acetate-lactate (CAL) extraction	Schüller, 1969
CaCO3	%	Gas-volumetrical determination (Scheibler method)	*KelloggSSL_MethodsManual_R42V5_2014.Pdf*, n.d.
Nt	%	Dry combustion	*Tabatabai, M.A. and Bremner, J.M. (1991), n.d.*
C_{org}	%	Difference of total C (by dry combustion) and carbonate C	*Tabatabai, M.A. and Bremner, J.M. (1991), n.d*
C/N		Calculated from C_{org} and Nt	n/a
DOC	mg/kg	Extraction with 1 M KCl at 1:10 (w/v) and NPOC/TN analysis	Vance et al., 1987
Diss. N	mg/kg	Extraction with 1 M KCl at 1:10 (w/v) and NPOC/TN analysis	Vance et al., 1987
C_{mic}	mg/kg	Chloroform fumigation extraction and NPOC/TN analysis	Vance et al., 1987
N_{mic}	mg/kg	Chloroform fumigation extraction and NPOC/TN analysis	Vance et al., 1987
Ammonium-N	mg/kg	Extraction with 1 M KCl at 1:10 (w/v) and colorimetric determination	Shand et al., 2008
Nitrate-N	mg/kg	Extraction with 1 M KCl at 1:10 (w/v) and colorimetric determination	Hood-Nowotny et al., 2010
N_{min}	mg/kg	Calculated as the sum of ammonium and nitrate N	n/a
Exoglucanase	nmol/gSoil/h	Substrate addition to soil–buffer suspension	Ameur et al., 2018
Phosphatase	nmol/gSoil/h	Substrate addition to soil–buffer suspension	Ameur et al., 2018
Protease	nmol/gSoil/h	Substrate addition to soil–buffer suspension	Ameur et al., 2018
Phenoloxidase	µmol/gSoil/h	Substrate addition to soil–buffer suspension	Sinsabaugh, 2010

4.2 Climate parameter

General data about the weather has been obtained by using data gathered during the BioClim Austria Project, where (Lehner et al., 2024) gathered climate indicators for 1961-1990 and 1991-2020 at 250m resolution in Austria.

The following parameters have been available as averages. The values were used twice, once for the water side and once for the landside for each of the 20 sites.

For the period from 1991 to 2020 the following parameters have been used during the statistical analysis:

- Average temperature
- Average temperature mean in the warmest month
- Average temperature mean in the coldest month
- Average temperature minimum in the coldest month
- Average temperature maximum in the warmest month
- Average number of frost days per year
- Average length of the growing season
- Average Growing Degree Days per year above 5°C
- Average number of extremely hot days above 35°C per year
- Average number of days with hard frost below -10°C per year
- Average relative humidity
- Average water vapor pressure deficit
- Average precipitation sum
- Average annual potential evapotranspiration
- Average climatic water balance
- Average climatic water balance in the growing season

The summer half-year has been chosen to be April to September. Soil temperature and soil moisture have been measured from April 2025 to April 2026 at BOKU.

4.3 Construction of the dikes post 2006

The data used to correlate construction years with the different sites based on the project timeline of the restoration of the dikes along the Morava river (Figure 6).

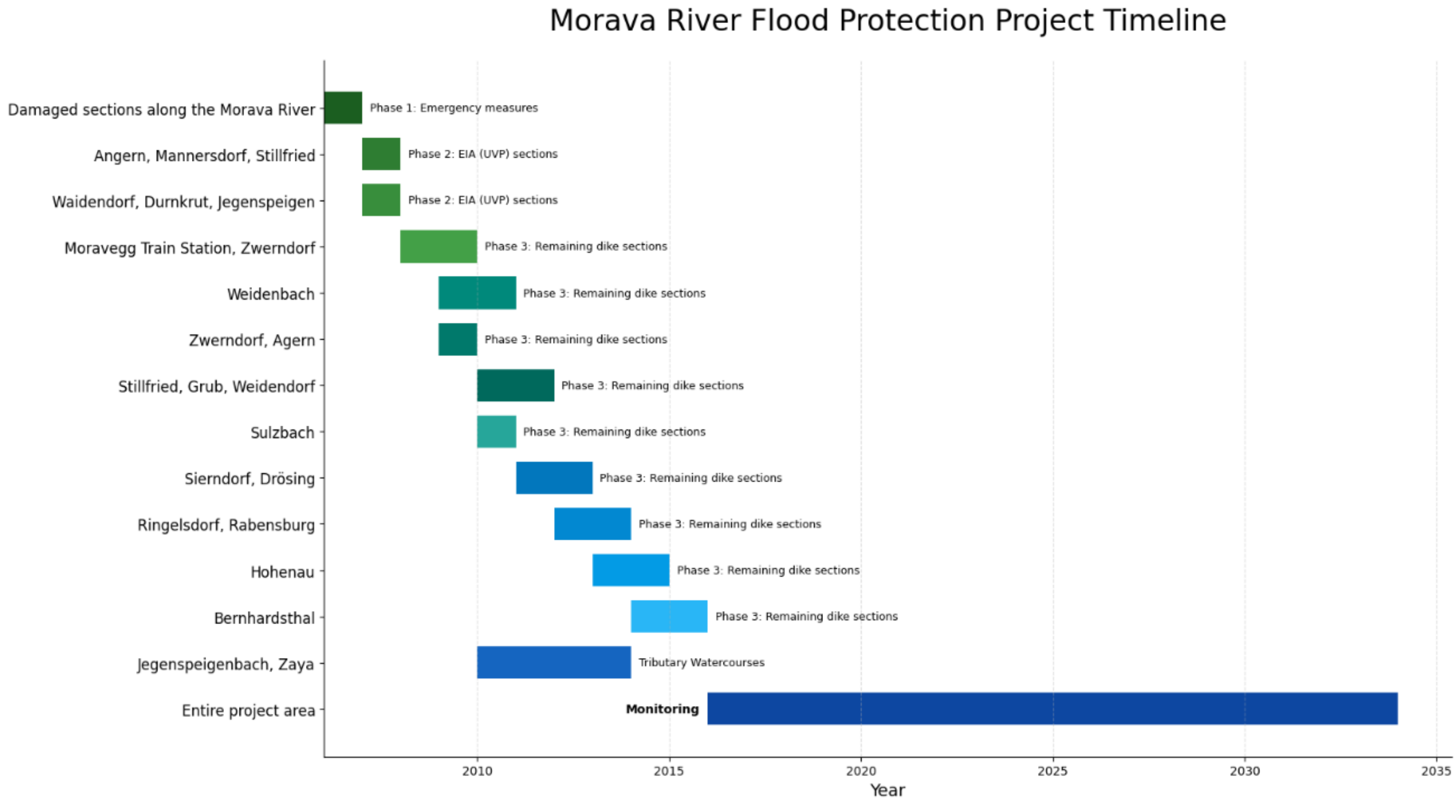


Figure 6: Restoration of the dikes post 2006 (Sanierung des Hochwasserschutzdammes March, n.d.)

All statistical analyses have been conducted using RStudio as well as Microsoft Excel. Statistical analyses and data visualization were performed using R version 4.5.2 (*RStudio IDE User Guide*, 2026) in RStudio. Data processing and manipulation were conducted using the tidyverse (Wickham et al., 2019), particularly dplyr (Wickham et al., 2026) and tidyr (Wickham, 2025), while readxl (Wickham & Bryan, 2023) was used to import Microsoft Excel datasets. Figures were created using ggplot2 (Wickham, 2016). Statistical analyses, including principal component analysis (PCA), Shapiro–Wilk normality tests, analysis of variance (ANOVA), Tukey's post hoc tests, and Welch's t-tests, were performed using functions from R's base stats package (*RStudio IDE User Guide*, 2026).

In the beginning of the analysis, all variables were screened for consistency, and descriptive statistics (mean, standard deviation, minimum, and maximum) were calculated to summarize the distribution and variability of soil, climate, and environmental predictor variables. In order to visualize this, violin plots have been used (Tanious & Manolov, 2022).

Normality of the data was assessed using the Shapiro–Wilk test, which is widely applied for small to moderate sample sizes (Mohd Razali & Wah Yap, n.d.)

Furthermore, heatmaps were used in order to illustrate the strength and direction of the relationships between soil variables as well as the interaction between soil and climate variables (Pleil et al., 2011).

To reduce data dimensionality and identify dominant gradients in the dataset, Principal Component Analysis (PCA) was applied to standardized variables. This method helped to identify the main gradients within the soil and climate variables (*Principal Component Analysis*, 2002).

The relationships between sites with similar vegetation management practices (sites 1-4, sites 11-14 and sites 5 & 6) were evaluated using Analysis of Variance (ANOVA), which evaluates whether group means differ significantly (Quinn & Keough, 2002).

Following significant results from one-way analysis of variance (ANOVA), post-hoc multiple comparison tests were conducted to identify which specific group means differed. Post-hoc tests are required because ANOVA only determines whether at least one group differs but does not specify where these differences occur. To address this, Tukey's Honestly Significant Difference (HSD) test was applied, which performs all pairwise comparisons between group means while controlling the family-wise error rate (FWER) (Frost, 2019).

Pearson correlation coefficients were used to quantify linear associations between principal components and environmental variables. This parametric measure captures the strength and direction of linear relationships between continuous variables and is commonly applied in ecological data analysis. The method assumes approximate normality and linearity and may be sensitive to outliers. Statistical significance was assessed using p-values ($p < 0.05$). Analyses were performed in R using the *Hmisc* package (Field et al., n.d.)

As base component for the statistical analysis, an Excel list with one-time measurements of various soil parameters has been used. They are listed together with all other abbreviations in the beginning of this paper.

5. Results

5.1 Statistical Analysis per Site

5.1.1 Distribution of physical soil variables

Substantial variability has been observed within the soil physical variables, especially when it comes to texture-related variables (Figure 7). Sand, silt and clay showcased a wide distribution, which is an indicator of a heterogeneous soil composition across the study area. Sand and clay especially showed contrasting soil types between sites.

Soil thickness exhibited a skewed distribution towards lower depths, only a few sites showed considerably greater soil depths.

Bulk density has a rather narrow distribution, which indicated a rather uniform and consistent soil compaction level within the sites.

Macroaggregate stability showed a broader distribution, while microaggregate stability displayed a moderate variability.

Overall, soil physical properties demonstrated strong heterogeneity, particularly in texture and spatial variables.

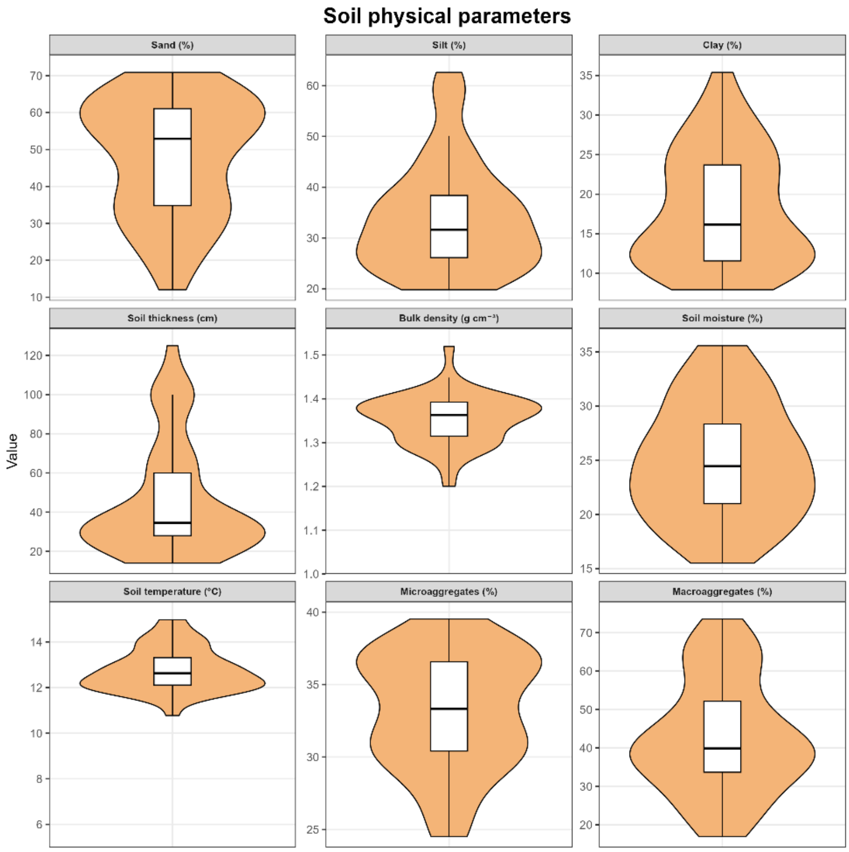


Figure 7: Violin plots for soil physical properties measured for 40 sites (20 sites with landside and water side each), including the percentage of sand, silt and clay, soil thickness, bulk density, soil moisture, soil temperature, microaggregates and macroaggregates

5.1.2 Distribution of chemical soil variables

Soil chemical parameters have been moderately variable; several variables showed a skewed distribution (Figure 8).

Soil pH exhibited a relatively narrow and symmetric distribution, indicating consistent soil acidity across the study area. Similarly, C:N ratio showed moderate variability but remained within a relatively constrained range.

Organic carbon (C_{org}) and dissolved organic carbon (DOC) displayed broader distributions, indicating spatial heterogeneity in carbon availability. DOC in particular showed signs of skewness, suggesting elevated values at specific sites.

Mineral nitrogen (N_{min}), nitrate, and ammonium exhibited variable distributions, with nitrate and ammonium showing noticeable skewness. This reflected heterogeneity in nitrogen dynamics and potential differences in microbial processing or land-use influence. Electrical conductivity (EC) showed a wide distribution, indicating variability in soil salinity or ion content.

Phosphorus (P) and potassium (K) also displayed broad distributions, with potassium showing particularly high variability and potential outliers at higher concentrations.

Calcium carbonate ($CaCO_3$) exhibited a strongly skewed distribution, with most values concentrated at low levels and a few higher-value observations.

Overall, chemical properties showed considerable variability, reflecting differences in soil fertility and nutrient availability across sites.

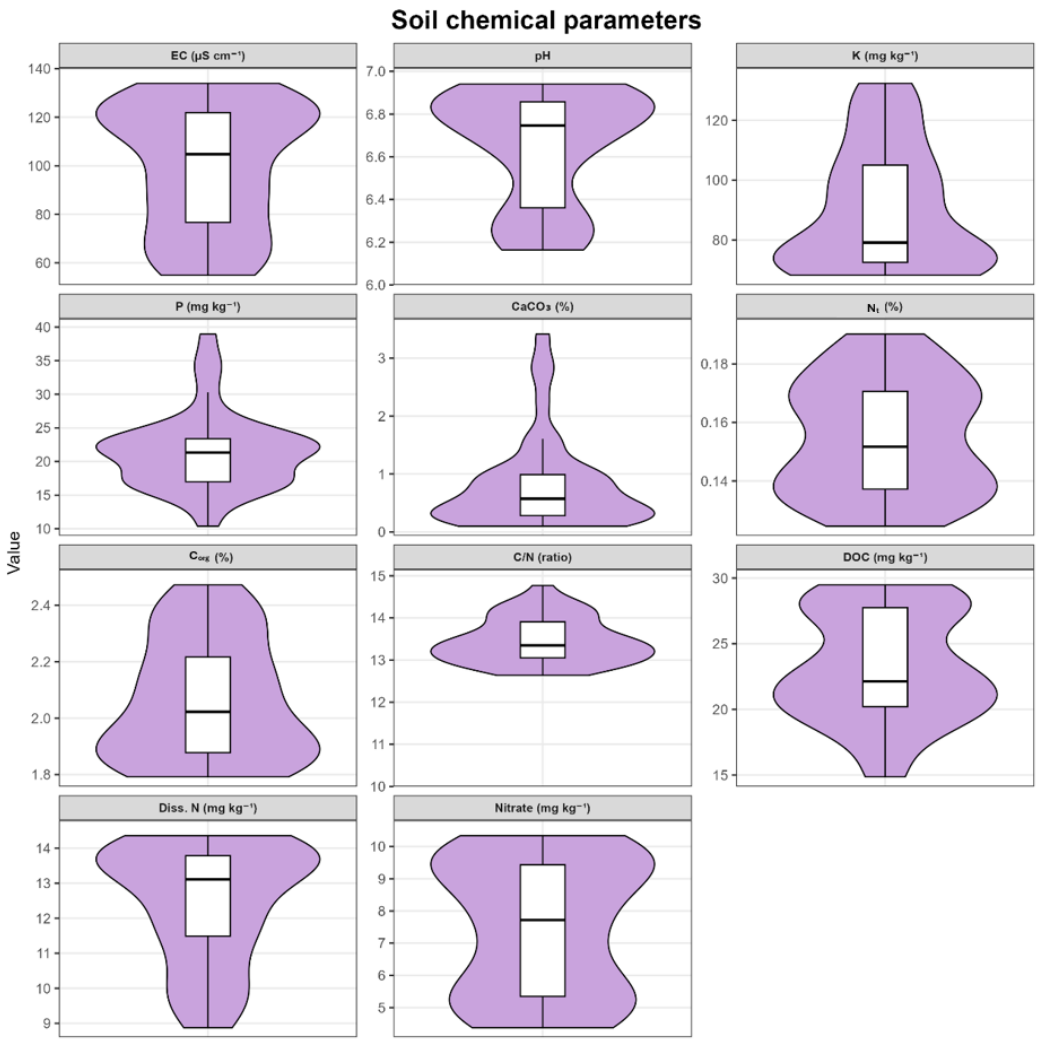


Figure 8: Violin plots for soil chemical properties measured for 40 sites (20 sites with landside and water side each) for the variables EC (1:10, electrical conductivity), pH, K (potassium), P (phosphorus), $CaCO_3$, Nt (total nitrogen), C_{org} (organic Carbon), C/N (Carbon Nitrogen Ratio), DOC (dissolved organic carbon), Diss. N (dissolved nitrogen), nitrate

5.1.3 Distribution of biological soil variables

The variability in the soil biological parameters has been pronounced in several cases. Skewness and multimodal distribution indicated heterogeneity in the biological activity between sites (Figure 9).

Microbial biomass carbon (C_{mic}) and microbial biomass nitrogen (N_{mic}) exhibited wide distributions with clear variability, suggesting strong differences in microbial abundance between sites. Both variables showed indications of skewness, with a tendency toward higher values at sites further south.

Enzyme activity (exoglucanase, phosphatase, phenoloxidase, and protease) have shown the largest variability. Phosphatase activity, in particular, showed a highly skewed distribution with a long upper tail between the sites 11 to 16.

Microbial quotient indicators (C_{mic}/C_{org} and N_{mic}/C_{org}) showed relatively narrow distributions, suggesting more consistent ratios between microbial biomass and soil organic carbon across sites.

Overall, biological parameters demonstrated higher variability and more complex distribution patterns compared to climate variables.

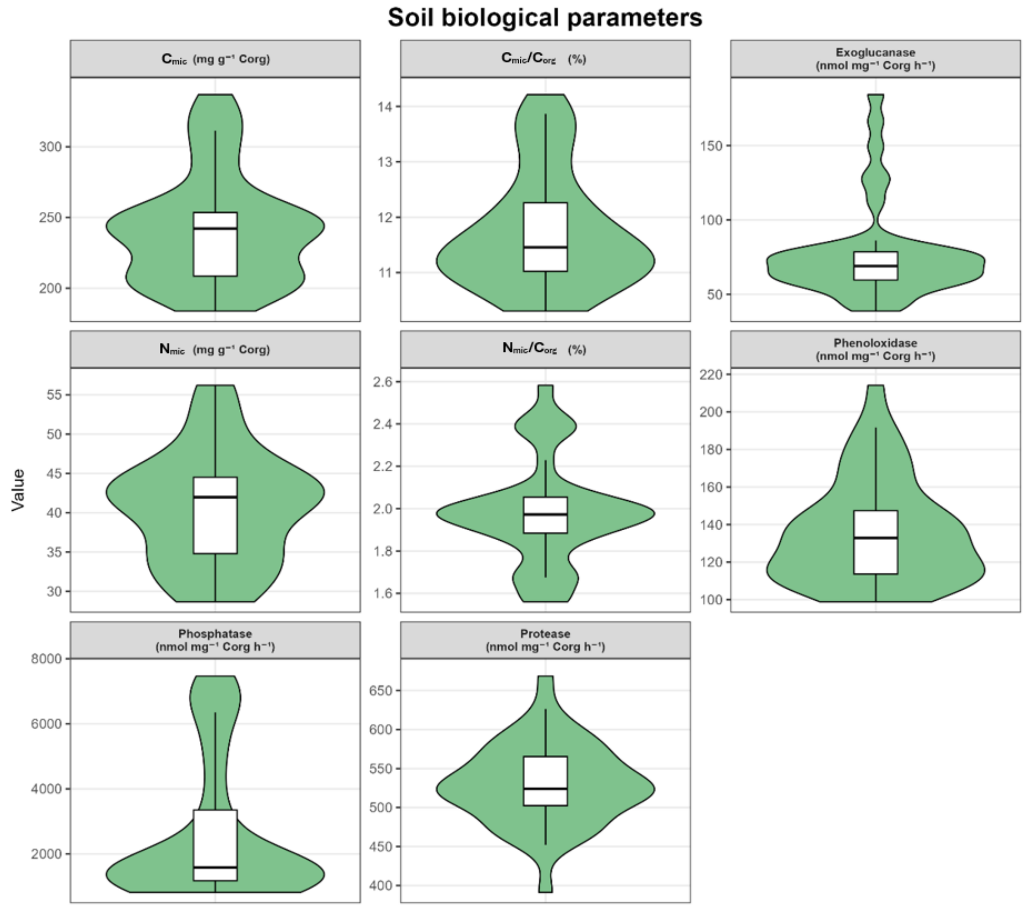


Figure 9: Violin plots for soil biological parameters measured for 40 sites (20 sites with landside and water side each) for the variables C_{mic} (microbial Carbon), C_{mic}/C_{org} (microbial Carbon per organic Carbon), Exoglucanase, N_{mic} (microbial nitrogen), N_{mic}/C_{org} (microbial nitrogen per organic carbon), Phenoloxidase, Phosphatase and Protease, enzyme activities were measured per mg of organic carbon

5.1.4 Distribution of climate variables

Among the climate variables, moderate variability across sites could be shown with a rather multimodal distribution and only limited extreme outliers.

Precipitation variables (annual, 2024, 2025) had a narrow distribution and indicated a low spatial variability among sites.

The climatic water balance, especially during the growing season, both displayed a slightly broader distribution, with values concentrated in the negative range, which can indicate the tendency towards a water deficit condition.

Temperature-related variables (mean annual temperature, temperature of the warmest and coldest months, and minimum/maximum temperatures) showed compact distributions. This suggests relatively homogeneous temperature conditions across sampling locations. In contrast, the number of frost days and hard frost days showed wider distributions, indicating greater variability in cold extremes.

Growing degree days and growing season length exhibited moderate spread, reflecting variability in thermal conditions influencing plant growth. Extremely hot days (>35°C) were relatively rare, with a narrow distribution and low variability.

Relative humidity and vapour pressure deficit showed moderate variability, with slightly asymmetric distributions.

Soil moisture exhibited a broader distribution compared to most climate variables, indicating substantial heterogeneity in site-specific water availability.

Table 4: Climate variables measured for 20 sites over a period of 30 years between 1991-2020 at 250m resolution in Austria, Q1 = first quartile (25th percentile), Q3 = third quartile (75th percentile), and IQR = interquartile range (Q3 − Q1), representing the spread of the middle 50% of the observations).

Variable	**Unit**	**Min**	**Q1**	**Median**	**Mean**	**Q3**	**Max**	**IQR**
Annual potential evapotranspiration	mm	730.48	755.84	783.11	778.11	810.12	814.69	54.29
Climatic water balance	mm	-241.70	-221.43	-209.09	-211.30	-200.20	-191.87	21.23
Climatic water balance (growing season)	mm	-267.25	-258.50	-251.38	-250.40	-241.91	-236.25	16.59
Average Growing Degree Days per year above 5 °C	°C days	2551.89	2603.82	2690.46	2658.74	2744.26	2750.99	140.43
Length of growing season	days	241.62	245.53	249.62	249.37	253.50	258.50	7.97
Frost days per year	days/year	73.80	74.72	84.28	84.82	92.34	96.70	17.62
Precipitation sum	mm/year	515.64	557.95	564.16	566.81	588.69	606.47	30.74
Relative humidity	%	67.31	67.62	68.78	68.46	69.02	69.25	1.39
Mean temperature	°C	10.54	10.74	11.03	10.98	11.29	11.33	0.55
Max temperature (warmest month)	°C	27.44	27.46	27.67	27.64	27.78	27.82	0.32
Mean temperature (coldest month)	°C	-0.22	0.02	0.39	0.29	0.62	0.69	0.60
Mean temperature (warmest month)	°C	21.03	21.21	21.47	21.44	21.75	21.77	0.53
Min temperature (coldest month)	°C	-3.74	-3.42	-2.86	-2.91	-2.19	-2.17	1.23
Vapor pressure deficit	millibars (mb)	5.96	6.03	6.13	6.17	6.35	6.46	0.32

Other environmental and spatial variables

Additional environmental and spatial variables have also shown significant variability (Figure 11). The distance between the dikes and forest or agricultural areas spanned a wide range, where a concentration in the lower regions has been found as well as high values, which can be an indicator for a heterogeneous landscape. Dam distance (km) also exhibited a broad distribution, with values ranging from near-zero to substantially larger distances. The directional variable (degrees 1–360) covered the full circular range, reflecting no dominant orientation. The takeover variable displayed a widespread distribution, suggesting variability in site-specific conditions or management influence. Overall, all variables exhibited substantial dispersion, with skewed distributions in several cases, highlighting strong variability within the study system.

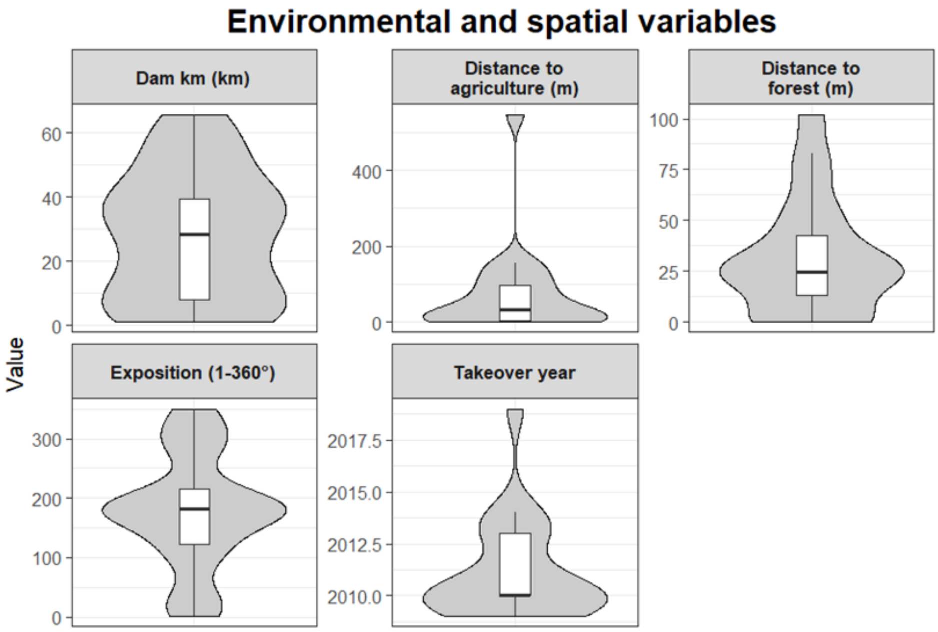


Figure 10: Violin plots for environmental and spatial variables measured for 40 sites (20 sites with landside and water side each) like Dam km (distance from south to north along the dam), exposition (azimuth angle), distance to agriculture, distance to forest and takeover year

Although some variables have been normally distributed, most of them were not. Therefore, a non-parametric statistical method has been used to assess relationships and to identify associations among soil, climate and biological variables.

5.1.5 Principal component analysis (PCA)

In the following chapter major gradients, which are responsible for the heterogeneity of the site-specific environmental factors influencing dike stability were identified. First, a principal component analysis (PCA) of the soil factors was conducted; then it has been repeated for the link between climate factors and soil factors and after that, the combination of their influence on each other has been studied.

The PCA has been used in order to reduce dimensionality present in the dataset. Additionally, main environmental gradients across sites. combining variables in terms of soil physics, chemistry, biology and climate have been identified.

They revealed that multiple interacting gradients across climate, soil texture, moisture and biological activity can be identified.

The PCA results revealed three principal components, which explain the majority of the variance in the dataset (Figure 21, Appendix A). PC1 accounted for 42.9% of the total variance, followed by PC2 (15.1%), PC3 (13.1%) and PC4 (8.4%). Together, those 4 PCs explain 79.5% of the total variance (Figure 14). All other PCs below show a decline in variance explained, which further points to the significance of the first three PCs.

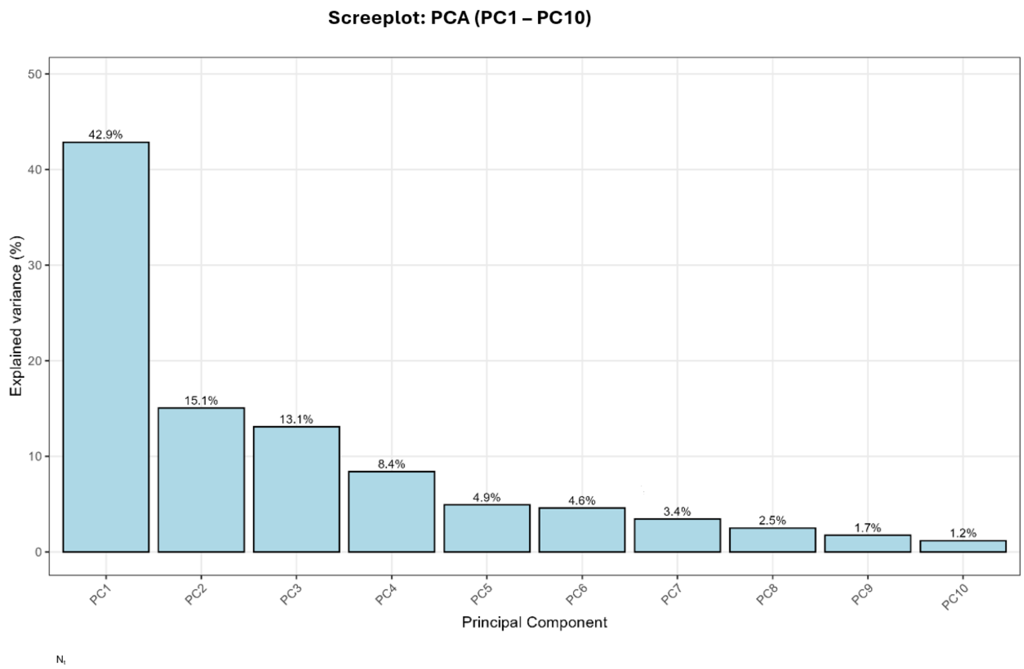


Figure 11: Screeplot of PCA of the soil variables

In order to focus on the statistically most relevant principal components, only PC1, PC2, PC3 and PC4 will be used for further analysis, since they all contribute significantly to the variance of the soil variables. A table including all PCA results is found in Table 12, Appendix A

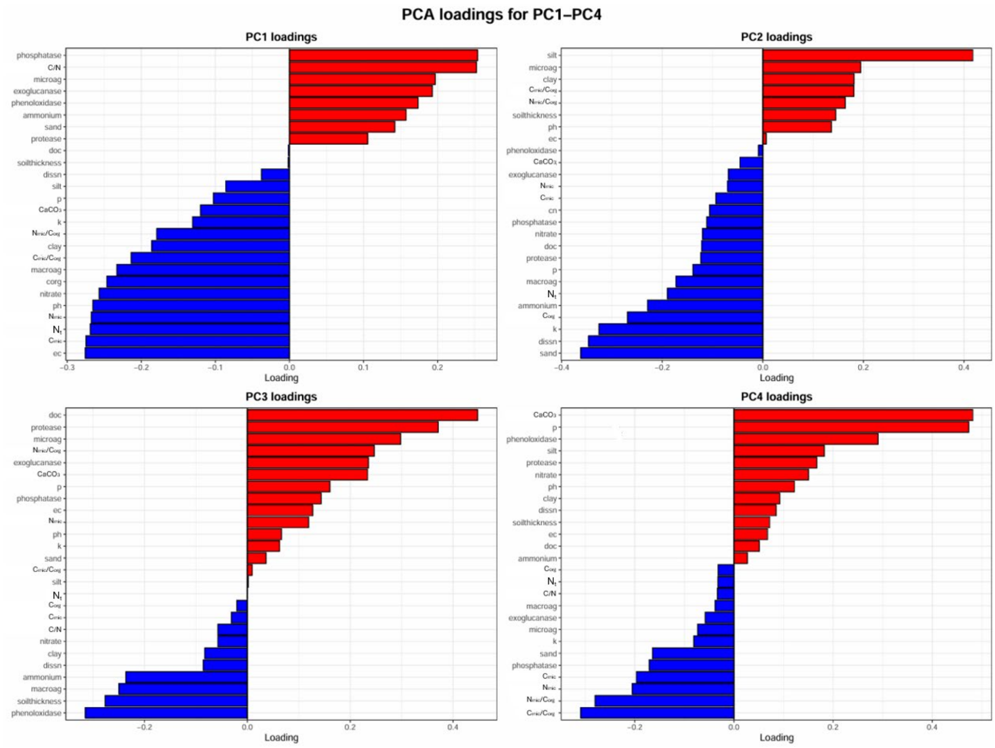


Figure 12: PCA loadings for PC1 – PC4, variables like sand, silt, clay, soil thickness, BD (bulk density), C_{org} (organic carbon), N_t (total nitrogen), C/N (carbon nitrogen ratio), DOC (dissolved organic carbon), Diss. N (dissolved nitrogen), C_{mic} (microbial carbon), N_{mic} (microbial nitrogen), C_{mic}/C_{org} EC (microbial Carbon per organic Carbon), N_{mic}/C_{org} (microbial nitrogen per organic carbon), ammonium, nitrate, K (potassium), P (phosphorus), EC (1:10 electrical conductivity), exoglucanase, phosphatase, protease, phenoloxidase, enzyme activities were measured per mg of organic carbon)

The strongest gradient found for soil physical, chemical and biological properties has been found for PC1 and PC2 (Figure 13). PC1 describes a gradient along soils characterized by a higher sand content, C/N ratio, microaggregate availability and enzyme activity (spatially phosphatase and exoglucanase) towards a soil with higher organic carbon content, more total nitrogen, elevated microbial biomass (C_{mic}, N_{mic}), EC and pH. A transition from a coarse-textured, enzyme-active soil towards a more nutrient-rich and microbially enriched soil has been indicated (Figure 13).

For PC2, a gradient has been found mainly according to soil texture and structural characteristics (Figure 15). Positive loadings were found for silt content, soil thickness and microaggregates, while negative loadings were associated with nitrogen (dissolved N), dissolved organic carbon (DOC) and potassium (Figure 15).

While PC1 explains far more of the variance of the soil properties, together with PC2, a clear variability in soil composition, aggregation, nutrient availability and microbial function could be found across all sampling sites.

Table 5: PC1-PC2 gradient

Component	**Positive loadings**	**Negative loadings**	**Main gradient**	**Key observation from plot**
PC1 (42.9%)	Sand, C/N, phosphatase, exoglucanase, microaggregation	C_{org}, N_t, C_{mic}, N_{mic}, EC, pH	Gradient from coarse, enzyme-active soils toward nutrient-rich and microbially enriched soils	Strong horizontal separation; right side associated with sandy soils and enzyme activity, left side with organic matter, microbial biomass, and nutrient accumulation
PC2 (15.1%)	Silt, soil thickness, microaggregation	DOC, DissN, K, partly sand	Gradient of soil structure and texture versus dissolved nutrient fractions	Moderate vertical differentiation highlighting contrasts between structural soil properties and dissolved nutrient pools
Combined (PC1–PC2)	Structural and enzymatic variables dominate right-upper space	Organic matter and microbial/nutrient variables dominate left-lower space	Interaction between soil texture, aggregation, and biochemical functioning	Samples spread across quadrants, indicating strong primary environmental gradients and secondary structural differentiation

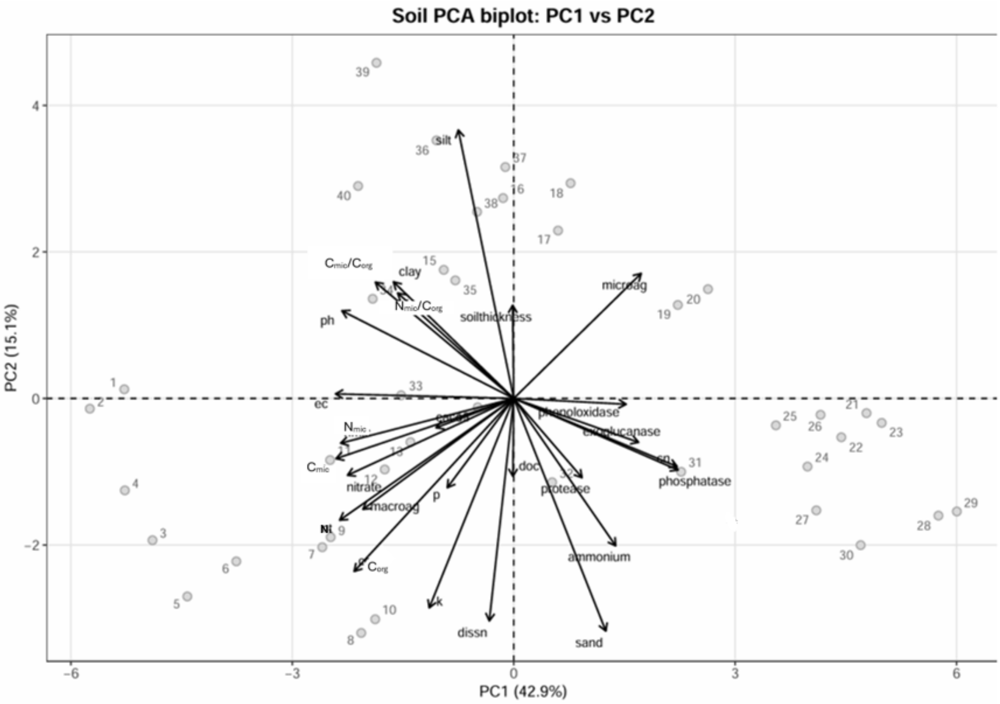


Figure 13: Biplot PC1 vs PC2, variables like sand, silt, clay, soil thickness, BD (bulk density), C_{org} (organic carbon), N_t (total nitrogen), C/N (carbon nitrogen ratio), DOC (dissolved organic carbon), Diss. N (dissolved nitrogen), C_{mic} (microbial carbon), N_{mic} (microbial nitrogen), C_{mic}/C_{org}, (microbial Carbon per organic Carbon), N_{mic}/C_{org} (microbial nitrogen per organic carbon), ammonium, nitrate, K (potassium), P (phosphorus), EC (1:10 electrical conductivity), exoglucanase, phosphatase, protease, phenoloxidase, enzyme activities were measured per mg of organic carbonBD (bulk density), EC (electrical conductivity), C_{org} (organic carbon), DOC (dissolved organic carbon), C_{mic} (microbial carbon), C_{mic}/C_{org} (microbial carbon per organic carbon), Nt (total nitrogen), DissN (dissolved nitrogen), N_{mic} (microbial nitrogen), N_{mic}/C_{org} (microbial nitrogen per organic carbon), MacroAg (macroaggregates), MicroAg (microaggregates), enzyme activities were measured per mg of organic carbon

In order to explain more variance, PC3 and PC4 have been considered (Table 6). Those gradients are directly linked to soil physical, chemical and biochemical properties. PC3 is associated with the gradient from soil characterized by higher phenol oxidase activity, macroaggregates, soil thickness, dissolved nitrogen and sand content towards a soil with higher dissolved organic carbon (DOC), microaggregates, CaCO3, protease activity and silt content. The contrast in structurally coarser soils with oxidative enzyme activity and soils with higher dissolved organic fraction and finer texture has been identified.

In PC4, samples were differentiated along a gradient according to the carbonate content, nutrient availability and microbial biomass. $CaCO_3$, phosphorus, phenoloxidase activity, silt, nitrate and dissolved nitrogen have been associated with positive loadings. Negative loadings were linked to microbial biomass ratios (C_{mic}/C_{org}, N_{mic}/C_{org}) and microbial biomass (Cmic, Nmic) (Figure 14).

In comparison with PC1 and PC2, PC3 and PC4 show a smaller portion of the overall variance. They rather reflect more subtle differences in biochemical functioning, carbonate status and microbial nutrient dynamics across sites. PC3 and PC4 have highlighted a secondary gradient focusing on soil aggregation, dissolved nutrient pools, carbon influence and microbial enzymes, whereas PC1 and PC2 identified a rather dominant texture related nutrient gradient.

Table 6: PC3-PC4 gradient

Component	**Positive loadings**	**Negative loadings**	**Main gradient**	**Key observation from plot**
PC3 (12.2%)	Phenoloxidase, macroaggregation, soil thickness, DissN, sand	DOC, microaggregation, $CaCO_3$, protease, silt	Gradient from coarse, structurally aggregated soils toward dissolved organic and finer-textured soils	Horizontal separation reflects contrasts between oxidative enzyme activity and dissolved organic/carbonate-associated conditions
PC4 (9.5%)	$CaCO_3$, P, phenoloxidase, silt, nitrate, DissN	C_{mic}/C_{org}, N_{mic}/C_{org}, C_{mic}, N_{mic}, partly sand	Gradient of carbonate and nutrient availability versus microbial biomass relationships	Vertical differentiation highlights contrasts between carbonate-rich nutrient conditions and microbial biomass-associated soil functioning
Combined (PC3–PC4)	Carbonate, aggregation, and oxidative enzyme variables dominate upper quadrants	Microbial biomass ratios and dissolved organic variables dominate lower quadrants	Interaction between carbonate status, aggregation, and microbial biochemical activity	Samples show weaker but ecologically interpretable secondary gradients beyond the dominant variation explained by PC1 and PC2

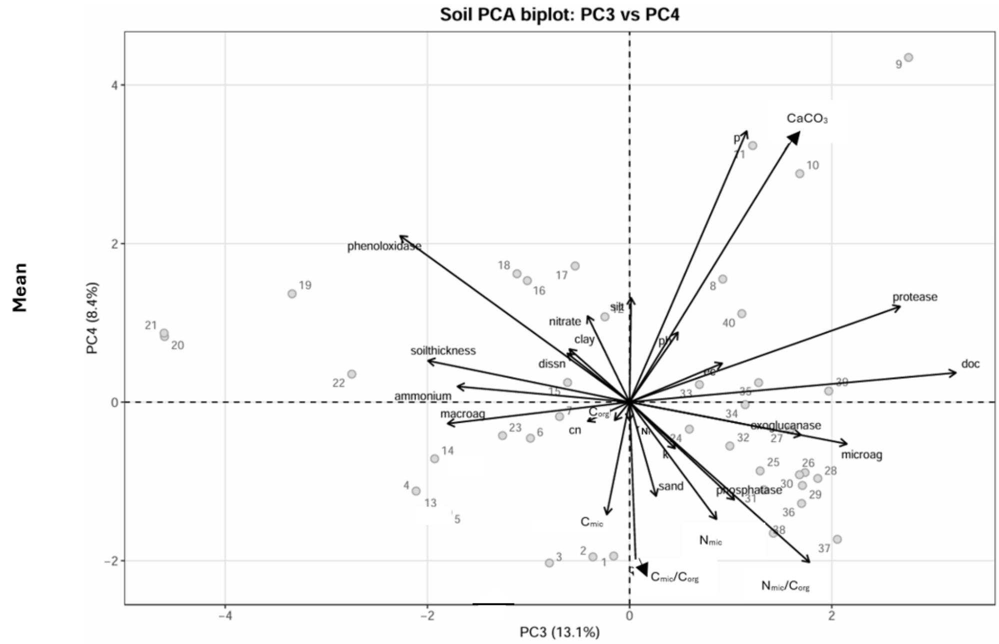


Figure 14: Biplot PC3 vs PC4, variables like sand, silt, clay, soil thickness, BD (bulk density), C_{org} (organic carbon), N_t (total nitrogen), C/N (carbon nitrogen ratio), DOC (dissolved organic carbon), Diss. N (dissolved nitrogen), C_{mic} (microbial carbon), N_{mic} (microbial nitrogen), C_{mic}/C_{org} EC (microbial Carbon per organic Carbon), N_{mic}/C_{org} (microbial nitrogen per organic carbon), ammonium, nitrate, K (potassium), P (phosphorus), EC (1:10 electrical conductivity), exoglucanase, phosphatase, protease, phenoloxidase, enzyme activities were measured per mg of organic carbon

In the following chapter, groupings per different parameters were made to find out whether or not further parameters have an influence on the PCA results.

Groupings

For the combination of PC1 and PC2, as well as PC3 and PC4, the following groupings could be made according to the categories:

- Distance of the dike along the dam
- Distance to agriculture
- Distance to Forest
- Takeover year
- Land management
- Direction (Azimuth Angle)
- Location (landside vs. waterside)

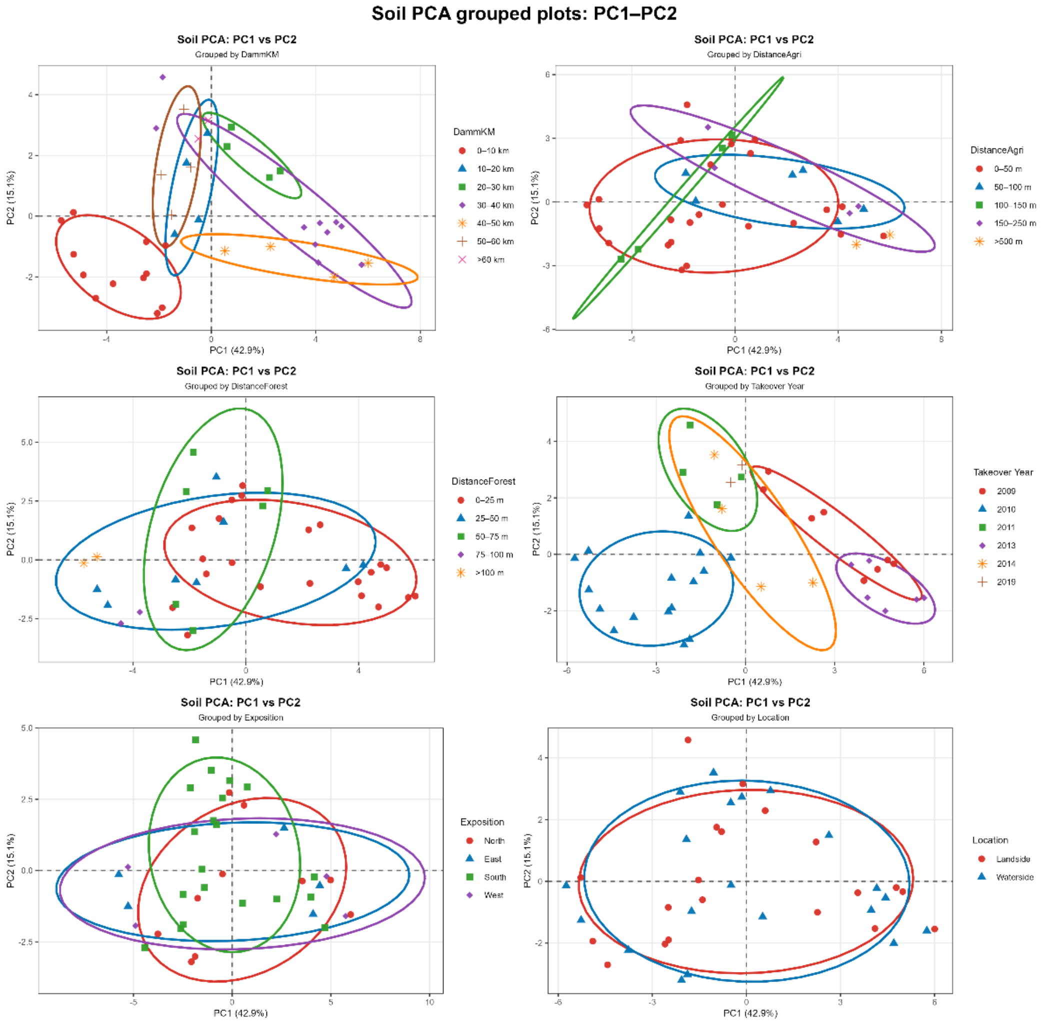


Figure 15: Groupings of the PCA results for PC1-PC2 according to dam km (distance of the dikes from south to north in km, distance to agriculture in m, distance to forest in m, takeover year, exposition (azimuth angle) where north is 315°–45°, east is 45°–135°, south is 135°–225°, west is 225°–315°and location (landside vs. waterside)

The relationships between soil characteristics have been investigated during the Principal Component Analysis (PCA). In the further grouping analysis, other environmental factors have been considered (Figure 16).

Grouping by Distance to Landscape Features

At first, the distance along the dam from south to north has been considered and revealed a moderate separation of sampling sites primarily along PC1. Sites further south (0-10km) have been clustered predominantly on the negative side of the PC1, in contrast, sites further to the north (30-60km) were distributed more strongly towards positive PC1 values. In between those extremes, a broader dispersion is shown, showing no abrupt spatial differentiation.

When it comes to the distance between the dike systems and agricultural land, a considerable overlap among most distance classes could be found. Sites closest to agriculture (0-50m) do cluster towards more negative PC1 values, from an intermediate distance on, more positive PC1 values were found. Overall, only a moderate influence of agriculture on the PC1 and PC2 gradient could be found.

The distance from the dike systems to the forest reveals a similar pattern. Sites, which are situated 75-100m overlap significantly, showing that the distance to forest is only weakly influencing the variability of soil properties of PC1 and PC2.

Grouping by Exposition and Location

During the grouping according to the exposition (North, East, South, West), no strong directional separation was observed. While south-facing sites were showcasing more positive PC2 values, east- and west-facing sites were considered to have a broader dispersion along PC1. However, the considerable overlap among all directional groups indicates that exposition did not strongly structure the major gradients in soil variability (Figure 15).

The differentiation between landside vs. waterside also reveals a significant overlap, therefore, PC1 and PC2 have not been influenced by the location (landside vs. waterside) to a significant extent.

Grouping by Temporal Variables

When samples were grouped according to takeover year, their distribution followed a temporal gradient along PC1. Samples from 2009 and 2010 clustered predominantly on the negative side of the axis, whereas samples from 2013, 2017, and 2019 were located mainly on the positive side. Samples from 2011 occupied an intermediate position and partially overlapped with neighbouring groups, indicating a gradual transition in multivariate soil properties.

Variables associated with the negative side of PC1 included EC, pH, soil organic carbon (C_{org}), total nitrogen (N_t), nitrate, microbial biomass carbon (C_{mic}), microbial biomass nitrogen (N_{mic}), and macroaggregate abundance. In contrast, the positive side of PC1 was associated with higher phosphatase and exoglucanase activities, greater microaggregate abundance, and higher C:N ratios. Thus, samples from earlier takeover years were associated with larger nutrient and microbial biomass pools, whereas samples from later takeover years were associated with higher enzymatic activity and microaggregate abundance.

PC2 explained an additional 15.1% of the variance and was primarily associated with soil texture and related physical characteristics.

Positive PC2 scores were associated with higher silt and clay contents, greater soil thickness, and higher microaggregate abundance, whereas negative PC2 scores were associated with higher sand content, dissolved nitrogen, ammonium, potassium, and phosphorus concentrations.

Although distinct clustering patterns were observed, particularly between the earliest and latest takeover years, overlap among several confidence ellipses indicated substantial within-group variability. Therefore, takeover year accounted for part of the variation in soil properties, but additional factors also contributed to differences among sites.

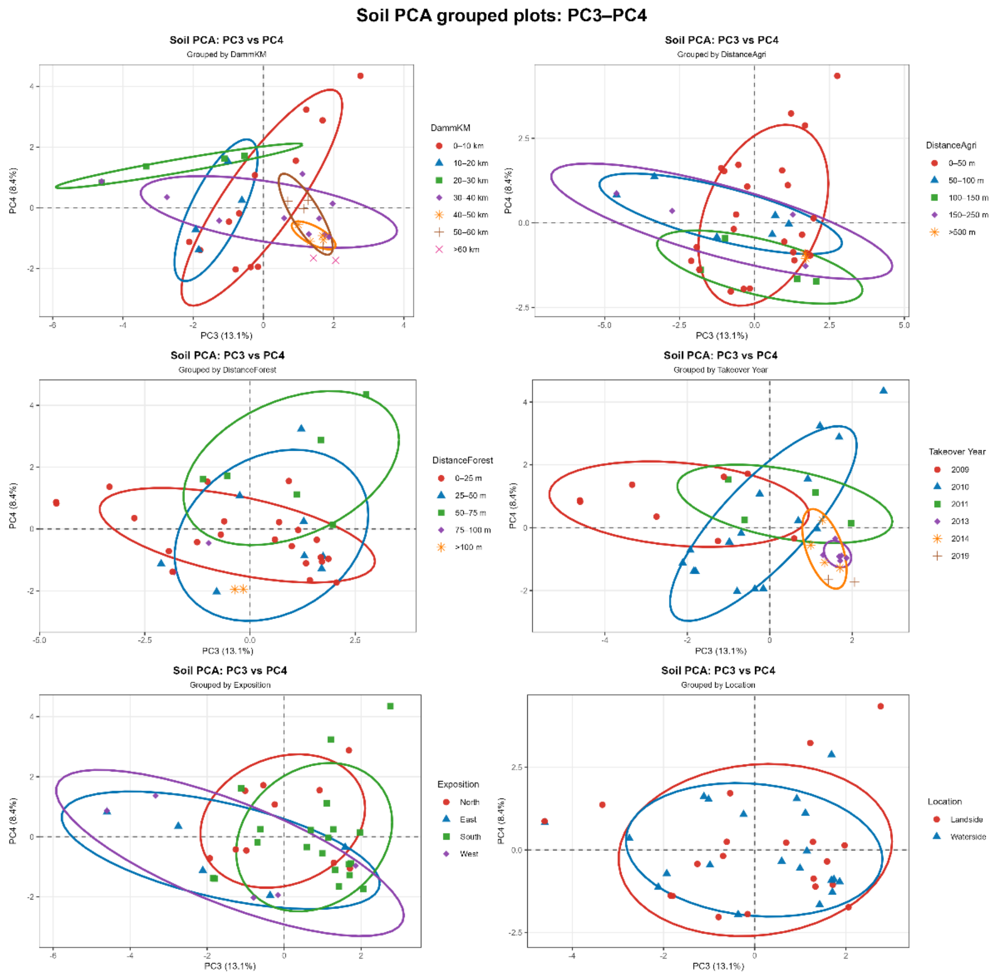


Figure 16: Groupings of the PCA results for PC3-PC4 according to dam km (distance of the dikes from south to north in km, distance to agriculture in m, distance to forest in m, takeover year, exposition (azimuth angle) where north is 315°–45°, east is 45°–135°, south is 135°–225°, west is 225°–315°and location (landside vs. waterside)

Grouping by Distance to Landscape Features

Along the PC3 and PC4 variables, the distance along the dike from south to north revealed a moderate differentiation. Southern sections (0-10km) tend to cluster along positive PC4 values, whereas sites further north (20-40km) exhibit a broader dispersion. However, overall, there is no strong structure within the variability for dam kilometers by PC3 and PC4 (Figure 16).

A substantial overlap between categories of the grouping by distance to agricultural land has been found. Sites close to agriculture (0-50km) showed some separation, however, the overall proximity contributed only weakly to the secondary gradients in PC3 and PC4.

Similar patterns have been found for groupings to forest, where only moderate differences between sites have been found, especially for sites located furthest from the forest (>100m), which shows a limited dispersion. Larger overlaps have been exhibited for other classes.

Grouping by Exposition and Location

A weak directional structuring has been observed with the grouping to exposition (North, East, South, West). More positive PC3 values have been exhibited for eastern and southern sites, while western and northern exposures were more broadly distributed. Overall, a strong overlap has indicated only a moderate influence on soil variability in PC3 and PC4.

Landside and waterside samples showed an overlap, which suggests that location does not have a substantial influence on the secondary gradient of PC3 and PC4.

Grouping by Temporal Variables

Takeover years showed a clearer pattern when it comes to the groupings. Earlier years, like 2009 and 2010 tend to cluster along negative PC3 values and variable PC4 values, whereas more recent takeover years appear to be clustered more tightly and appear in the positive PC3 region (Figure 16).

PC3 and PC4 appear to show weaker variability and are more diffuse than PC1 and PC2. Spatial variables such as distance to agriculture, forest proximity, exposition, and location showed only moderate structuring effects. In contrast, temporal variables (takeover year) and land management categories demonstrated clearer differentiation patterns, although overlap between groups indicates that soil variability is still driven by multiple interacting environmental and management factors rather than a single dominant process.

5.1.6 Relationships between Principal Components and Environmental Variables

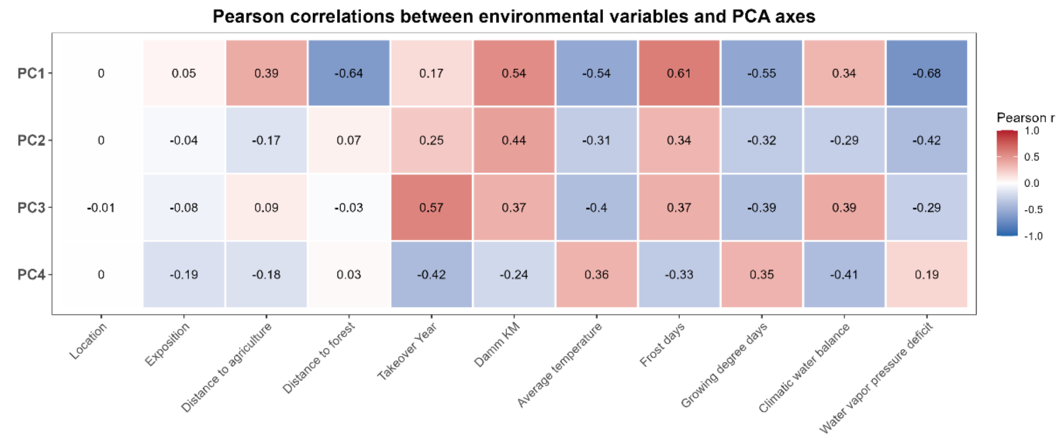


Figure 17: Pearson Correlation between PC1-PC4 various environmental, spatial and climatic variables like location (landside vs. waterside), exposition (azimuth angle) where north is 315°–45°, east is 45°–135°, south is 135°–225°, west is 225°–315°, distance to agriculture in m, distance to forest in m, takeover year, dam km (distance of the dikes from south to north in km), average temperature, frost days, growing degree days, climatic water balance, water vapor pressure deficit

Correlation between PCA axes and environmental variables

In order to take environmental variables into account, a Pearson correlation has been conducted between different climate variables, environmental factors and PC1-PC4.

Pearson correlation analysis was chosen because it quantifies the strength and direction of linear relationships between continuous variables. Correlation coefficients (r) ranged from −1 to +1, with positive values indicating positive relationships and negative values indicating inverse relationships.

The correlation heatmap revealed that PC1 was most strongly associated with climatic and spatial variables.

Table 7: Correlations between soil and climate variables and PC1

Strong positive correlation	Strong negative correlation
• Frost days • DamKM • Climatic water balance	• VPD • Distance to forest • GDD • Average temperature

These results indicate that PC1 reflects a climatic and spatial gradient, separating cooler and wetter conditions with higher frost frequency from warmer, drier conditions with higher water vapor pressure deficit and growing degree days.

PC2 showed generally weak relationships with most environmental variables, suggesting that this component represents variability that is only weakly explained by the measured environmental gradients.

Table 8: Correlations between soil and climate variables and PC2

Moderate positive correlation	**Moderate negative correlation**
• DamKM • Frost days • Takeover year	• Water vapor pressure deficit • GDD • Average temperature • Climate water balance

Correlations with exposition and location were close to zero, indicating little influence of directional or positional factors on PC2.

PC3 exhibited the strongest positive relationship with takeover year ($r = 0.57$), indicating a pronounced temporal gradient in soil variability.

Table 9: Correlations between soil and climate variables and PC3

Moderate positive correlation	**Negative correlation**
• Takeover year • Climatic water balance • Frost days • DamKM	• Average temperature • GDD • VPD

Distance to agriculture and distance to forest showed only weak relationships with PC3, suggesting that temporal changes and climatic conditions contributed more strongly to this axis than landscape proximity variables.

PC4 was characterized by generally weaker and partly inverse relationships compared with PC1 and PC3.

Table 10: Correlations between soil and climate variables and PC4

Positive correlation	**Moderate negative correlation**
• Takeover year • Climatic water balance • Frost days • DamKM	• Average temperature • GDD • VPD

Correlations with exposition, distance to agriculture, and location remained weak. These patterns suggest that PC4 captures secondary climatic variability opposing cooler and wetter conditions against warmer and potentially drier environmental settings.

Overall, the results indicate that the climatic variables strongly influence the PCA gradients, especially PC1 and PC3. Temperature-related variables like frost frequency, growing degree days, climatic water balance and water pressure deficit showed moderate to strong correlations between the axes. Spatial variables (DamKM, distance to forest, distance to agriculture) contributed as well, while exposition and location showed only minimal influence.

Compared with the dominant climatic gradients represented by PC1, the higher-order components PC2–PC4 reflected weaker and more complex environmental relationships, likely representing secondary ecological and temporal processes affecting soil variability across the study sites.

Soil temperature and soil moisture

Furthermore, the specific soil related climatic variables (soil temperature and soil moisture) were tested using the Pearson correlation against the environmental variables used before (Figure 18).

During the analysis, no factors showed a strong correlation, which can lead to the conclusion that a diverse mix of environmental factors is needed to pinpoint the influence of these factors, suggesting that site-specific processes rather than a single dominant gradient are responsible for the variance.

In further analysis, the influence of the environmental factors on soil moisture and soil temperature has been evaluated.

Overall, both soil temperature and soil moisture were only weakly associated with the examined climatic and environmental gradients. This suggests that local-scale factors such as vegetation cover, soil texture, microtopography, and short-term weather variability may have played a more important role in controlling soil thermal and moisture conditions across the study sites.

Table 11: Correlations between climate variables, soil temperature and soil moisture

Weak positive correlations	**Weak negative correlation**
• Average temperature • GDD • VPD • Distance to forest	• Location • Climatic water balance • Frost days • DamKM

Relationships with exposition, takeover year and distance to agriculture were negligible, the variables exposition and takeover year showed an opposite relationship between soil temperature and soil moisture.

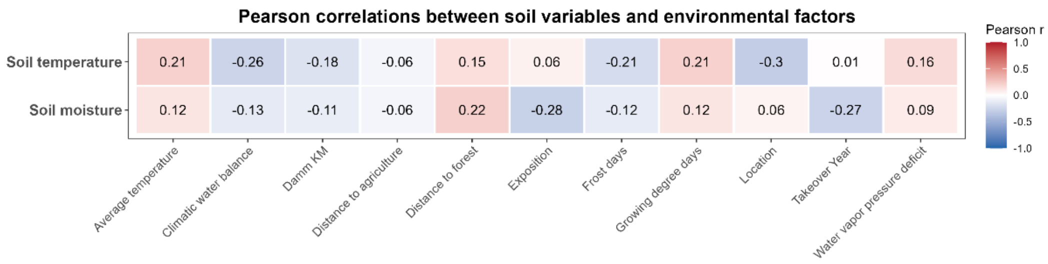


Figure 18: Pearson Correlation of Soil Temperature and Soil Moisture against location (landside vs. waterside), exposition (azimuth angle) where north is 315°–45°, east is 45°–135°, south is 135°–225°, west is 225°–315°, distance to agriculture in m, distance to forest in m, takeover year, dam km (distance of the dikes from south to north in km), average temperature, frost days, growing degree days, climatic water balance, water vapor pressure deficit

Mean comparison of soil variables across sites 1–4

During the comparison of sites 1-4, a pronounced differentiation in several soil variables has been exhibited (Figures 20, 21, 22, 23 in Appendix B). Those 4 sites have been exposed to different vegetation management methods on the landside, as described in table 2.

Soil texture composition varied significantly between sites, where the sand content increased and clay content decreased from site 1 to site 4. Silt content did vary to a far lesser extent than the sand and silt content.

Tukey HSD analysis indicated significant differences particularly between the extreme sites, suggesting clear spatial heterogeneity in soil texture along the investigated dike sections (Appendix B).

Bulk density (BD) has not exhibited a statistically significant difference between sites, however, electrical conductivity (EC) declined from site 1 to 4. Soil pH remained relatively stable across sites, although Site 4 exhibited slightly lower values compared to the remaining sites.

Organic carbon and total nitrogen have been moderately declining towards site 4, the C/N ratio however remained relatively stable across sites, which could indicate similar organic matter decomposition conditions. Dissolved organic carbon (DOC) and dissolved nitrogen (Diss. N) displayed variable distributions, with higher DOC values occurring at sites 2 and 4.

Microbial biomass carbon (C_{mic}), microbial biomass nitrogen (N_{mic}) and their ratios to organic carbon have generally decreased from site 1 to 4. A variation in mineral nitrogen across sites has been found. Ammonium concentrations were highest at sites 1 and 2, whereas nitrate concentrations remained relatively similar among sites.

Enzyme activities showed heterogeneous patterns. Phosphatase activity increased strongly at site 4, while protease activity was highest at site 2. Phenoloxidase activity showed elevated values at site 3. Exoglucanase activity varied only moderately among sites.

Soil temperature was relatively consistent across all sites, whereas soil moisture decreased toward site 4 (Appendix B).

Mean comparison of soil variables across sites 11–14

When it comes to sites 11-14, a substantial spatial variability has been shown within the soil properties (Figures 24, 25, 26, 27 in Appendix B). While the sand content increased progressively from site 11 to 14, clay content declined, indicating a texture gradient similar to sites 1-4. Significant differences between individual sites were confirmed by Tukey HSD tests for several texture-related variables.

Bulk density has shown only a slight difference among sites, although sites 13 and 14 exhibited marginally higher values. Electrical conductivity decreased considerably from Site 11 to Site 14, while the pH remained relatively stable.

While C_{mic} and N_{mic} have been highest at site 11, values of organic carbon and microbial biomass parameters declined from site 11 on, with lowest values at site 14. DOC and total nitrogen have also been decreasing along sites.

Ammonium values have been highest at site 11 with a decrease towards site 14, nitrate concentrations however remained relatively stable throughout all sites. Available potassium (K) and phosphorus (P) differed substantially among sites, particularly for potassium, where Site 11 exhibited the highest values.

Enzyme activities displayed pronounced spatial heterogeneity. Phosphatase activity increased substantially at Site 14, whereas phenoloxidase activity was highest at Sites 13 and 14. Protease activity showed smaller variation among sites. Soil temperature remained relatively constant, while soil moisture declined toward Site 14 (Appendix B).

Mean comparison of soil variables between site 5 (horse-grazing) and reference site 6

For site 5 (horse-grazing) a substantial variation in several soil variables has been found when compared to site 6 (reference site) (Figures 28, 29, 30, 31 in Appendix B).

First, the soil texture parameters have been showing a moderate differentiation between the sites. The sand content has been slightly higher at the reference site and a higher clay content has been found at the horse-grazing site. The silt content remained relatively uniform, although there has been a slight difference exhibited for the land- vs. the waterside positions. These patterns indicate small-scale spatial heterogeneity in sediment composition and particle size distribution along the dike sections.

Bulk density (BD) has not differed significantly between positions, except for slightly higher values on the landside with horse-grazing.

EC and pH varied only moderately between sites, with only a slight spike in EC at site 5.

Organic carbon concentrations have been lower at the horse-grazing site, similar patterns have been exhibited for DOC. The total nitrogen has not varied between sites to an extent beyond moderate and the C/N remains relatively stable.

The variables for microbial biomass have exhibited a clear differentiation between the two sites. C_{mic} and N_{mic} were lower at the horse-grazing site, especially on the waterside of each, similar to C_{mic}/C_{org} and N_{mic}/C_{org}.

Mineral nitrogen and ammonium have also exhibited differences in concentration at both sites, with higher values at the horse-grazing site. Nitrate showed little difference between sites. Elevated ammonium levels may indicate altered nitrogen mineralization or reduced nitrification rates under more compacted or disturbed soil conditions.

Enzyme activities displayed heterogeneous responses. Phosphatase activity tended to be higher at the reference site, especially on the waterside, whereas protease activity showed only relatively small differences between sites. Phenoloxidase activity was more variable and exhibited elevated values at the reference site. Exoglucanase activity showed moderate variation without a clear site-specific pattern.

While soil temperature did not exhibit pronounced differences between site 5 and 6 as well as the land- and water positions, soil moisture exhibited higher values at the waterside of both.

Overall, the results demonstrate that both site-specific management and spatial position within the dike profile influenced soil physical, chemical, and biological properties.

The horse-grazing site showed tendencies toward increased compaction, lower organic carbon content, reduced microbial biomass, and lower soil moisture compared to the reference site, whereas waterside and landside positions additionally contributed to local variability in soil functioning and environmental conditions.

6. Discussion

This study investigated the relationships between climatic conditions, soil properties, and dike stability in the March–Thaya floodplain by integrating physical, chemical, and biological soil analyses with long-term climate data. As illustrated in Figure 19, climatic forcing influences soil moisture dynamics, which in turn affect soil structure, biogeochemical processes, and hydrological behaviour. These interconnected processes contribute to structural weakening of dike soils and may ultimately influence dike stability. The results of this study identified clear spatial gradients in soil texture, nutrient status, microbial biomass, and enzyme activity, together with significant associations between soil characteristics and climatic variables. The following discussion interprets these findings in the context of previous research, examines the potential mechanisms linking climate and soil processes to dike stability, and considers their implications for future dike management under changing climatic conditions.

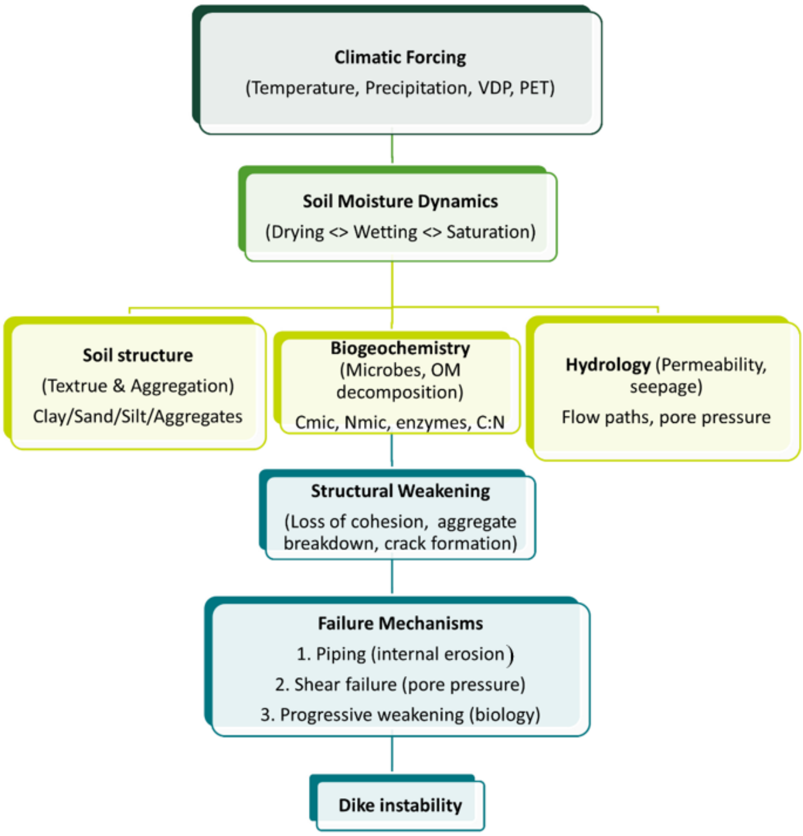


Figure 19: Dike instability processes (overview), (Gräff, n.d.), (Liu, Huang, et al., 2024), (Gao et al., 2024), (Stokes et al., 2014b), (Pham, 2025)

Dike stability along the Morava-Thaya river is influenced by a combination of climatic forcing, spatial heterogeneity, management history and biological processes. The interconnected nature of these parameters could be showcased through the statistical analysis, especially in terms of the connection between physical, chemical and biological properties and their interaction with hydrological and climatic conditions. Dike flood protection systems have to be understood as dynamic soil systems influenced continuously by environmental forcing and ecological processes (Li et al., 2026).

The discussion is structured around the concept that dike stability within the Morava–Thaya flood protection system emerges from interacting hydro-biogeochemical feedbacks involving soil texture, aggregation, microbial functioning, hydrological exposure, climatic forcing, and management practices (Bronick & Lal, 2005).

6.1 Heterogeneity and interactions of soil characteristics within the dike system

Across all investigated sites, a pronounced spatial heterogeneity has been exhibited, especially for physical, chemical and biological soil properties (Figures 6, 7, 8, 9, 10). This shows that flood protection structures are dynamic hydro-biogeochemical systems rather than homogeneously designed bodies. The differences in soil texture, aggregation, nutrient availability, microbial biomass and enzyme activity were observed between sites, but also between waterside and landside. These differences suggest varying stabilization mechanisms and structural vulnerabilities throughout the dike network (Bronick & Lal, 2005).

6.1.1 Major gradients

The PCA analysis supported the assumption that although the sites were heterogeneously composed of different soil variables, gradients can be found among them (Figure 12). The first principal components captured a substantial proportion of the overall variance (Figure 12). PC1 and PC2 have made a distinction between coarse-textured, enzyme-active soils and nutrient-rich, biologically stabilized soils (Figures 13,14). Positive PC2 loadings were associated with sand content and oxidative enzyme activity, whereas negative loadings corresponded to organic carbon, microbial biomass, nutrient availability, and macroaggregates. The gradient, instead of representing isolated variables, shows contrasting stabilization pathways. On the one hand, hydraulically vulnerable, coarse-textured soils were described, on the other hand, their counterpart as biologically stabilized and aggregated sections were described (Figure 11).

The first pathway describes coarse-textured and biologically less active soils. Examples for such sites would be sites 13L, 14L, and 5W (Figures 15, 16, 17, 18). These soils exhibited elevated sand contents, weaker macroaggregate stability, reduced microbial biomass, lower organic matter concentrations, and diminished biological stabilization. These conditions can lead to an increase in hydraulic conductivity, reduce cohesion and favor seepage, piping, fine-particle transport and internal erosion during prolonged flood loading. Reduced macroaggregate stability and weaker microbial stabilization therefore indicate structurally vulnerable sections within the dike system.

More active soils were described by the second pathway, describing finer-textured and biologically more active soils (e.g. sites 11L, 6L). On these sites, stronger aggregation, higher microbial biomass and enhanced nutrient availability may lead to an increased moisture retention capacity. There, improved cohesion and a reduced susceptibility to particle detachment as well as an increased vulnerability to shrink-swell dynamics, desiccation cracking and preferential flow formation during prolonged drought periods can be assumed (Tang et al., 2023).

The PCA-derived gradients are consistent with well-established relationships between soil texture, soil organic matter and soil biological activity reported in previous studies. Coarse-textured soils generally contain lower organic carbon concentrations and microbial biomass, resulting in reduced aggregate stability and weaker structural development than finer-textured soils (Bronick & Lal, 2005; Six et al., 2004). Conversely, finer-textured soils promote aggregate formation through interactions among clay minerals, organic matter and microbial binding agents, leading to greater aggregate stability and improved water retention (Bronick & Lal, 2005).

These observations agree with the aggregate hierarchy concept of soil organic matter and biological activity as key drivers of macroaggregate formation (Six et al., 2004). The association between finer-textured soils and greater water retention observed in the present study is therefore consistent with established concepts of soil structural development. However, clay-rich soils may also become susceptible to shrinkage and desiccation cracking during prolonged drought, creating preferential flow paths after rewetting (Tang et al., 2023).

These vulnerability pathways do not operate independently. While biologically mediated aggregation processes might get weakened by climatic drying, drought induced cracking may increase seepage susceptibility during subsequent rewetting events. The destabilization of aggregates and the reduction of structural cohesion can be a result of repeated saturation and fluctuating water levels. The interaction between climatic forcing, hydrological stress, soil structure, and biological functioning therefore creates locally variable vulnerability patterns throughout the dike system. The observed relationship between soil temperature and soil moisture further illustrates the importance of hydroclimatic controls on soil functioning across the dike system (Figure 18).

The ANOVA results additionally showed significant differences between sites for several physical, chemical, biological and environmental parameters (Figures 20 – 31 in Appendix B). Significant differences were particularly observed for soil texture, nutrient concentrations, microbial biomass, enzyme activities, aggregate stability, and soil moisture. These differences further demonstrate the spatial heterogeneity within the investigated dike system. Since these parameters are related to soil structure, aggregation, water availability, and biological activity, their variability indicates that the processes influencing dike stability may differ between individual sites. This suggests that different sections of the Morava-Thaya flood protection system may respond differently to hydrological and environmental conditions.

6.1.2 Influence of climatic, spatial, and management-related factors on soils

The functions of the soils within the Morava-Thaya dike system are strongly influenced by interacting climatic, hydrological, spatial, historical and management-related variables. Climatic variables, hydrological exposure, takeover year, dam kilometer, azimuth angle, surrounding land use (agriculture, forest), and vegetation management collectively contributed to the observed spatial variability in aggregation, nutrient dynamics, microbial activity, and soil moisture conditions.

Climate

Climate variables related to temperature showed a positive association with microbial biomass, nutrient availability and macroaggregate stability. In contrast, frost-related variables were strongly positively correlated with microaggregation and phosphatase activity (Figure 19). This leads to the conclusion that warmer conditions stimulate microbial metabolism, nutrient turnover and decomposition processes. Colder conditions slow decomposition down and might promote more persistent stabilization mechanisms. Increased climatic water deficit and elevated vapor pressure deficit may additionally accelerate organic matter mineralization and reduce long-term carbon stabilization. Warmer and drier climate conditions have a positive impact on short-term biological activity and parallel to this, weaken long-term structural persistence, due to a lowered moisture retention and weaker aggregation (Davidson & Janssens, 2006).

The investigated dike sections were affected by the 2006 flood event, as parts of the Morava–Thaya flood protection system were breached and subsequently reconstructed. Consequently, the soil properties observed today likely reflect both the legacy of the reconstruction process and the subsequent development of the soils over time. However, information on the exact origin and initial properties of the material used for the reconstruction of the different dike sections was not available. Therefore, it cannot be determined whether the differences observed between the sites were already present in the material at the time of reconstruction or developed subsequently under the different local environmental conditions.

In addition to these historical influences, climatic factors may contribute to ongoing changes in soil structure and hydro-biogeochemical functioning. Processes such as freeze–thaw cycles, drying–rewetting events, and fluctuations in soil moisture can affect aggregate stability, potentially promoting desiccation cracking, preferential flow paths, and increased seepage susceptibility during flood events. Future climate change scenarios project more frequent and intense drought periods alternating with heavy precipitation events (Blöschl et al., 2019), which may further intensify these processes. However, the present study cannot distinguish between the effects of post-flood reconstruction and long-term climatic influences. Because the dikes were reconstructed after the 2006 flood and were only sampled at a single point in time, a comprehensive assessment of climate-driven changes in soil stability would require long-term monitoring of soil physical, chemical, and biological properties (Blöschl et al., 2019).

Takeover year

The historical construction period emerged as an important factor influencing present-day soil characteristics within the investigated dike system. In the PCA grouping analysis, takeover year produced one of the clearest separation patterns among the tested grouping variables, with earlier takeover years (2009–2010) clustering predominantly along negative PC1 and PC3 values and more recent takeover years (2013–2019) clustering towards positive PC1 and PC3 values (Figure 17). Furthermore, PC3 was associated with takeover year, carbonate content ($CaCO_3$), dissolved nitrogen (Diss. N), and microaggregate stability (Figures 14, 16), indicating a relationship between reconstruction history and current soil chemical and structural properties. This implies that the reconstruction history may have contributed to the present-day differences in soil properties between dike sections, either through differences in the material initially used or through subsequent soil development. Since these properties influence soil aggregation, nutrient dynamics, and soil structural characteristics, such differences may also contribute to spatial variability in the stability and resilience of the dike system.

The grouping analysis also showed a broader dispersion of sites associated with earlier takeover years, whereas more recently reconstructed sections formed comparatively tighter clusters. This pattern suggests greater variability in soil characteristics among older dike sections, particularly regarding carbonate content, dissolved nitrogen, and microaggregate stability.

The separation of takeover years in the PCA suggests that dike sections reconstructed during different periods exhibit distinct soil characteristics, likely reflecting differences in the reconstruction practices, compaction and the properties of the fill material rather than soil age alone. Earlier takeover years were associated with higher organic matter content, microbial biomass, nutrient availability and macroaggregate stability, whereas more recent takeover years were linked to less biologically stabilized soils. Since aggregate stability and soil organic matter contribute to greater soil cohesion and resistance to internal erosion and piping, their differences may influence the long-term structural stability of flood protection dikes (Six et al., 2004).

However, takeover year is not independent of spatial location, as different sections of the dike system were reconstructed during different periods following flood damage and restoration measures. Consequently, the observed patterns likely reflect both reconstruction history and site-specific conditions along the dike system. Differences in parent material, sediment composition, hydrological conditions, vegetation development, and management practices may therefore have contributed to the variation observed in the PCA.

Overall, the results indicate that construction history, together with spatially structured environmental factors, contributes to the present-day hydro-biogeochemical and structural characteristics of the investigated dike soils.

The observed separation by takeover year suggests that historical reconstruction influenced the present-day soil characteristics of the investigated dike sections. Rather than representing soil age alone, the pattern likely reflects differences in reconstruction practices, compaction and the properties of the fill material used after the 2006 flood. Since the exact origin and composition of the reconstruction material are unknown, takeover year should be interpreted as a proxy for different construction histories rather than direct soil development over time.

Distance along the dam and location

The spatial position within the dike system was associated with differences in soil properties and functioning, although these relationships were characterized by considerable overlap among site groups. The PCA grouping analysis revealed a moderate differentiation of sites along the south–north gradient, primarily along PC1 (Figure 15). Southern sections of the dike system (0–10 km) were predominantly associated with negative PC1 values, whereas northern sections (30–60 km) occurred more frequently at positive PC1 values. However, the broad distribution of intermediate sites indicates that spatial position alone does not explain the observed variability in soil characteristics. Similar moderate patterns were observed for distance to agriculture, distance to forest, and exposition, all of which showed substantial overlap among categories.

PC1 represented the dominant hydro-biogeochemical gradient in the dataset, separating coarse-textured, enzyme-active soils from nutrient-rich soils characterized by greater microbial biomass, organic carbon content, and aggregate stability. Negative PC1 and PC2 values were associated with soils exhibiting coarser texture, lower nutrient availability, reduced microbial biomass, and weaker aggregation, whereas positive PC1 values reflected soils with enhanced nutrient status, greater biological activity, and stronger aggregate stability.

The Pearson correlation analysis demonstrated that PC1 was most strongly associated with climatic and spatial variables (Figure 17, Table 7-10). Positive correlations were observed with frost frequency, climatic water balance, and dam kilometer, whereas negative correlations were found with average temperature, growing degree days, water vapor pressure deficit, and distance to forest. These relationships indicate that PC1 reflects a climatic and spatial gradient separating cooler and wetter conditions with higher frost frequencies from warmer and drier conditions characterized by higher temperatures, greater atmospheric evaporative demand, and longer growing seasons.

The PCA grouping analyses further showed substantial overlap between landside and waterside locations for both PC1–PC2 and PC3–PC4 (Figures 15, 16), indicating that location did not strongly structure the principal gradients of soil variability. Nevertheless, the ANOVA and Tukey HSD analyses identified significant differences in several soil physical, chemical, and biological properties between landside and waterside positions (Figures 28–31 in Appendix B). These findings indicate that landside and waterside locations contribute to variability in individual soil properties, even though location did not strongly influence the major gradients identified by the PCA.

On another note, the location (landside vs. waterside) may reflect differences in the hydrological situation. Sampling sites on the waterside of the dikes are likely to exhibit stronger moisture fluctuations and experience repeated saturation, in comparison, the landside section is likely more influenced by atmospheric drying and vegetation-related process. The observed variability in aggregation, biological activity and nutrient turnover could be linked to this hydrological contrast. Repeated saturation may reduce shear strength and destabilize aggregates, while prolonged drying may intensify desiccation cracking and preferential flow formation (Turrakheil et al., 2024).

Exposition

Slopes oriented south/southwest tend to be more prone to exhibit drying and accelerated decomposition processes. Shaded sections (north/northeast) are more likely to retain moisture longer and support more persistent aggregation and microbial stabilization (Díaz-Zorita & Fernández-Canigia, 2009). However, the exposition of the sites showed only a limited influence on soil variability across the dike system. The PCA grouping analyses for both PC1–PC2 and PC3–PC4 revealed substantial overlap among north-, east-, south-, and west-facing sites, indicating that exposition did not strongly structure the major gradients of soil properties (Figures 15, 16). Although slight directional tendencies were observed, with south-facing sites exhibiting somewhat higher PC2 values and eastern and southern sites tending towards more positive PC3 values, the overall overlap among categories suggests that exposition contributed only moderately to the observed variability. Consequently, climatic, spatial, and management-related factors appeared to exert a stronger influence on soil characteristics than slope orientation alone.

Distance to agriculture and forest

The surrounding land use also influenced soil functioning. Sites located closer to agricultural land were associated with higher nutrient concentrations, microbial biomass, and electrical conductivity, likely reflecting indirect nutrient inputs from adjacent agricultural areas through processes such as fertilizer drift, surface runoff, or wind-borne particles. Increased nutrient availability may stimulate microbial turnover and promote aggregate formation through enhanced biological activity. However, sustained nutrient enrichment may also accelerate organic matter decomposition and mineralization, potentially reducing long-term soil carbon storage. Consequently, the influence of adjacent agricultural land on dike soils is likely to involve both beneficial and adverse processes, depending on the balance between biological stabilization and organic matter turnover (J. Zhang et al., 2021).

In contrast, sites located next to the forest tended to show greater moisture retention and organic matter accumulation, promoting biological stabilization processes through moderated microclimatic conditions and continuous organic matter inputs. Shading and reduced evapotranspiration stress likely support microbial functioning and aggregate stability.

These findings indicate that surrounding land use and landscape connectivity represent important environmental gradients contributing to the observed spatial heterogeneity and localized stability conditions within the flood protection system.

Vegetation management

Dike stability has also been influenced by the vegetation management at site. Grazed sections (site 5) have exhibited an increased bulk density, lower macroaggregate stability, reduced microbial biomass and lower soil moisture (Figures 28-31 in Appendix B). The trampling of horses most likely induced compaction, which resulted in a reduction of pore continuity, potentially impairing infiltration and drainage. Generally speaking, a moderate compaction can be beneficial for local conditions, increasing shear strength, however, excessive compaction may reduce aeration and intensify hydrological stress during saturation events (Dunne et al., 2011).

Overall, the results demonstrate that soil functioning within the dike system is governed by overlapping climatic, hydrological, spatial, historical, and ecological gradients acting simultaneously across multiple scales.

6.1.3 Implications for dike stability and resilience

The dike stability of the Morava-Thaya flood protection system is a result of the interaction of hydro-biogeochemical feedback rather than isolated engineering properties alone (Figure 19).

Hydraulic behaviour, cohesion, seepage susceptibility and structural resilience are all regulated by soil texture, aggregation, microbial functioning, climatic forcing, hydrological exposure, vegetation management and spatial variability collectively.

Overall, the long-term dike resilience of the Morava-Thaya region depends on a balance between stabilization and destabilization processes across multiple spatial and temporal scales. Coarse-textured soils will likely become more vulnerable to seepage and internal erosion, and fine-textured soils may be more prone to becoming unstable due to shrink-swell dynamics and desiccation cracking under future drought conditions.

These contrasting conditions described by the vulnerability pathways highlight the complexity of flood protection in their coexistence. Flood protection stability assessments and future adaptive dike management under changing environmental conditions need to consider the integration of biological indicators, climatic assessments, hydrological monitoring and spatially explicit soil analysis. These measures are essential to improve the long-term flood protection resilience under future climate change scenarios.

6.2 Limitations and future research

Within this study, several limitations should be considered while interpreting the findings of the results:

First of all, all soil parameters (except soil temperature and soil moisture) have been measured only once, which could be used in order to differentiate spatial heterogeneity, but temporal dynamics could not be fully captured. Seasonal variations in microbial activity, aggregation and nutrient cycling in the context of hydrological events have not been considered.

Second, dike stability factors from a geotechnical perspective have not been evaluated. Direct measurements like shear strength, hydraulic conductivity, pore-water pressure and seepage velocity have not been taken into account in this study. Therefore, only indirect indicators for dike stability have been considered instead. An improvement in direct failure prediction could be made in the future with the consideration of the previously mentioned dike engineering elements. Third, the climatic dataset has not been evaluated during short-term extreme events but rather represents long-term averages.

However, flood-induced instability is often triggered by extreme hydrological conditions rather than average climatic behavior.

Future research should therefore combine:

- long-term monitoring of soil and climatic variables
- direct geotechnical measurements
- subsurface profiling
- hydraulic modelling
- repeated seasonal sampling
- remote sensing approaches
- root measurements

In future studies, the focus should also be on vegetation-root interactions and microbial community dynamics on the dikes in the context of long-term dike resilience.

Overall, the soil structure, biogeochemical processes and environmental management, that have been studied along the Morava-Thaya river, show an interaction with hydroclimatic conditions. The results highlight the need for integrated and site-specific approaches to flood protection management under changing climatic conditions. These should include the monitoring of not only geotechnical indicators but also soil and climate parameters on a higher frequency over a longer period of time, as well as further studies on the effect of dike vegetation management measures as well as the reevaluation of dike stability in terms of resilience against changing climatic conditions.

7. Conclusion

The dike system along the Morava-Thaya region, which has been the focus of this study, exhibits a pronounced spatial heterogeneity in soil physical, chemical, biological and climatic characteristics.

The results showed that soil texture, aggregation, microbial activity, nutrient dynamics, hydrological exposure, and climatic conditions are closely interconnected and jointly influence dike soil behavior and potential structural stability. The identification of the two dominant vulnerability pathways allowed to be summarized the interactions between a diverse set of soil variables. The coarse-textured and biologically less active sites were characterized by weaker aggregation, lower microbial biomass and reduced organic matter content, which indicates susceptibility to seepage, piping and internal erosion. In comparison, finer-textured and biologically dynamic sites showed stronger aggregation and a higher moisture retention capacity but may also exhibit an enhanced vulnerability to shrink-swell dynamics, desiccation, cracking and preferential flow formation during prolonged drought periods.

The PCA results demonstrated that hydro-biogeochemical gradients strongly structure the investigated dike soils, separating coarse-textured and biologically less active sections from nutrient-rich and microbially enriched sections. Furthermore, vegetation management practices and hydrological position contributed to local differences in soil structure and biological functioning. Under future climate change scenarios, interactions between soil texture, biological activity, moisture dynamics and management practices may increasingly influence the long-term resilience of flood protection dikes. Therefore, more attention needs to be paid to soil structural, soil textural, nutrient-related soil variables as well as microbial activity when it comes to the assessment of dike-stability-related parameters, their monitoring and climate-change-resilient dike managemen for the future.

Overall, the results indicate that dike stability emerges from interacting hydro-biogeochemical feedback rather than isolated geotechnical properties alone. Therefore, this study suggests that the integration of biological indicators, soil structural analysis, hydrological assessment and climatic monitoring into future flood protection management is of great importance.

An integrated and site-specific approach could improve the identification of vulnerable dike sections and support long-term dike resilience under projected climate change conditions.

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Popular science summary

Floods are becoming more intense and more frequent in Central Europe. Along the Morava-Thaya River system in Austria, dikes are being used to protect settlements, agricultural land, infrastructure and ecosystems. These dikes are, however, not simply static earth structures. The soil conditions within the dikes are crucial for long-term stability and are reactive to changing environmental conditions.

This study investigates how soil properties, climate and land management influence the stability of flood protection dikes in eastern Austria. The focus lies on the Morava-Thaya region, where flooding in 2006 caused several dike failures and led to extensive reconstruction and monitoring efforts. 20 sites have been examined, on each side, from both the waterside and the landside. Measurements of soil texture, aggregate stability, nutrient availability, organic carbon, microbial biomass, enzyme activity, soil moisture and soil temperature have been examined. Climatic conditions and vegetation management practices were also considered.

While some soils contained coarse, sandy soils with low organic matter and weak soil aggregation, increasing the risk of seepage, piping, and internal erosion during floods, other sites contained a finer-textured soil with a higher water retention, stronger aggregation and greater biological activity. These soils might be more resistant to erosion, they can, however, be vulnerable to cracking and shrinkage during drought periods. Biological processes involving soil microorganisms and organic matter contribute to the formation of stable soil aggregates, which help strengthen the soil structure. Climate conditions strongly influenced these processes. Warmer temperatures generally increased microbial activity and nutrient turnover, while wetter and colder conditions promoted microaggregate formation and phosphatase activity. Management practices such as mowing and grazing can affect soil compaction and structural variability. Grazed areas and the waterside section showed increased compaction, which could alter the water movement through the dike.

The findings highlight that flood protection dikes behave as complex ecological and hydrological systems in which soil structure, climate, vegetation, and biological activity interact continuously. Because climate change is expected to increase both droughts and extreme rainfall events in Central Europe, understanding these interactions is becoming increasingly important for future flood protection. This research emphasizes the need for site-specific and process-based approaches in dike management and monitoring.

Appendix A

Table 12: PCA overview

PC	Variables	Loadings	Direction	Interpretation	Relevance for dike stability	Key reference
PC1 (42.86%)	Sand, C/N, phosphatase, exoglucanase, microaggregation; opposed by C_{org}, N_t, C_{mic}, N_{mic}, EC, pH	High (≥0.5)	+ / −	Represents a primary gradient from coarse-textured, enzyme-active soils toward nutrient-rich and microbially enriched soils with higher organic matter accumulation. Positive loadings reflect sandy, biologically active soils with stronger enzymatic decomposition, whereas negative loadings indicate soils with greater organic matter, nutrient retention, and microbial biomass.	Strongly influences cohesion and aggregate stability. Nutrient-rich soils with higher organic matter and microbial biomass promote stable aggregation and structural resistance, whereas coarse sandy soils increase permeability, seepage, and susceptibility to internal erosion and piping.	Six et al., 2004, Bronick & Lal, 2005, Fredlund & Rahardjo, 1993
PC2 (15.07%)	Silt, soil thickness,	Moderate–high	+ / −	Reflects a gradient of soil texture and structural	Influences pore structure and water movement. Structured	Bronick & Lal, 2005

	microaggregation; opposed by DOC, DissN, K, partly sand			organization versus dissolved nutrient and solute fractions. Positive loadings indicate thicker, more structured soils with higher silt content, while negative loadings correspond to soils richer in dissolved organic and inorganic compounds.	silt-rich soils may improve physical stability, whereas elevated dissolved compounds may enhance leaching, seepage, and mobilization of fine particles, potentially weakening dike integrity.	
PC3 (13.08%)	Phenoloxidase, macroaggregation, soil thickness, DissN, sand; opposed by DOC, microaggregation, CaCO3, protease, silt	Moderate–high	+ / −	Represents a secondary gradient contrasting coarse, oxidatively active and structurally aggregated soils with finer-textured soils characterized by higher dissolved organic matter and carbonate content.	Controls interactions between aggregation, permeability, and biochemical turnover. Coarse aggregated soils may enhance preferential flow and internal erosion risk, whereas carbonate-rich finer soils may improve cohesion but remain vulnerable to cracking and heterogeneous water movement.	Fredlund & Rahardjo, 1993
PC4 (8.41%)	CaCO3, P, phenoloxidase, silt, nitrate, DissN; opposed by C_{mic}/C_{org},	Moderate	+ / −	Reflects carbonate and nutrient-associated soil conditions versus microbial biomass-dominated functioning. Positive	Influences aggregate persistence, pore connectivity, and soil buffering capacity. Carbonate-rich soils may enhance structural resistance,	Six et al., 2004, Bronick & Lal, 2005

	N_{mic}/C_{org}, C_{mic}, N_{mic}, partly sand			loadings indicate carbonate-rich, nutrient-associated soils, while negative loadings correspond to soils with stronger microbial biomass influence and biological nutrient cycling.	whereas shifts in microbial biomass and nutrient turnover may alter aggregate formation and permeability dynamics within dike systems.	
PC5 (4.91%)	Nitrate, ammonium, DissN	Moderate	+	Represents mineral nitrogen availability and active nutrient cycling.	Indirectly affects vegetation establishment and root reinforcement, thereby influencing erosion resistance and slope stability.	Simon & Collison, 2002,
PC6 (4.59%)	EC, ionic variables, pH-related chemistry	Moderate	+	Reflects soil chemical and ionic conditions, including salinity and conductivity gradients.	Elevated salinity or ionic imbalance may promote clay dispersion and aggregate breakdown, reducing cohesion and increasing erosion susceptibility.	Mitchell & Soga, n.d.
PC7 (3.45%)	Structural density-related variables, aggregation fractions	Moderate–low	Mixed	Represents variation in soil compaction and physical packing properties.	Influences porosity, drainage, and pore-water pressure development, affecting mechanical stability and susceptibility to failure under hydraulic stress.	Terzaghi et al., 1996

PC8 (2.50%)	Weak mixed variables	Low	Mixed	Captures secondary variability related to interactions among physical, chemical, and biological processes.	May contribute to local heterogeneity, weak zones, or preferential flow paths within dike material.	Fell et al., 2014
PC9 (1.74%)	Weak mixed loadings	Low	Mixed	Represents residual site-specific variability not explained by dominant gradients.	Potentially linked to localized instability, heterogeneous compaction, or micro-scale erosion processes.	Fell et al., 2014
PC10 (1.18%)	Weak mixed loadings	Very low	Mixed	Represents minor interactions and background noise with limited explanatory power.	Limited large-scale importance, though small-scale variability may still influence localized weak points under extreme hydraulic conditions.	Fell et al., 2014

Appendix B

ANOVA and Tukey HSD post-hoc test results

Mean comparison of soil variables across Sites 1–4

Soil physical variables

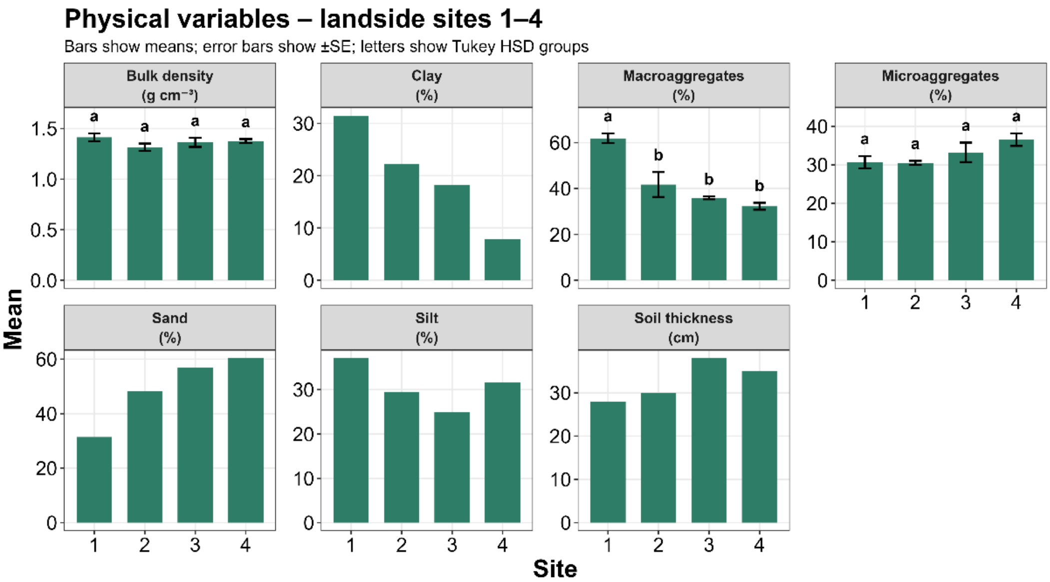

Figure 20: Mean comparison charts for selected soil physical variables across landside Sites 1–4. Bars represent mean values and error bars indicate ± standard error (SE). Where applicable, different letters above bars indicate significant differences among groups according to Tukey's HSD post-hoc test ($p < 0.05$), while groups sharing at least one letter are not significantly different. The displayed variables include bulk density (BD), soil texture fractions (sand, silt, clay), macroaggregate stability, microaggregate stability, and soil thickness. The Figure highlights substantial spatial variability in soil texture and aggregate stability among the vegetation management treatments. Sites 1–4 represent different mowing management regimes: ***C*** *(Site 1), mown twice per year with plant residue left on site;* ***1R*** *(Site 2), mown twice per year with residue removed during the first mowing and left on site during the second mowing;* ***2R*** *(Site 3), mown twice per year with residue removed after both mowing events; and* ***US*** *(Site 4), mown twice per year with an unmown refuge strip retained along the flank during the first mowing and residue left on site after the second mowing (Eppinger, 2024).*

Soil chemical variables

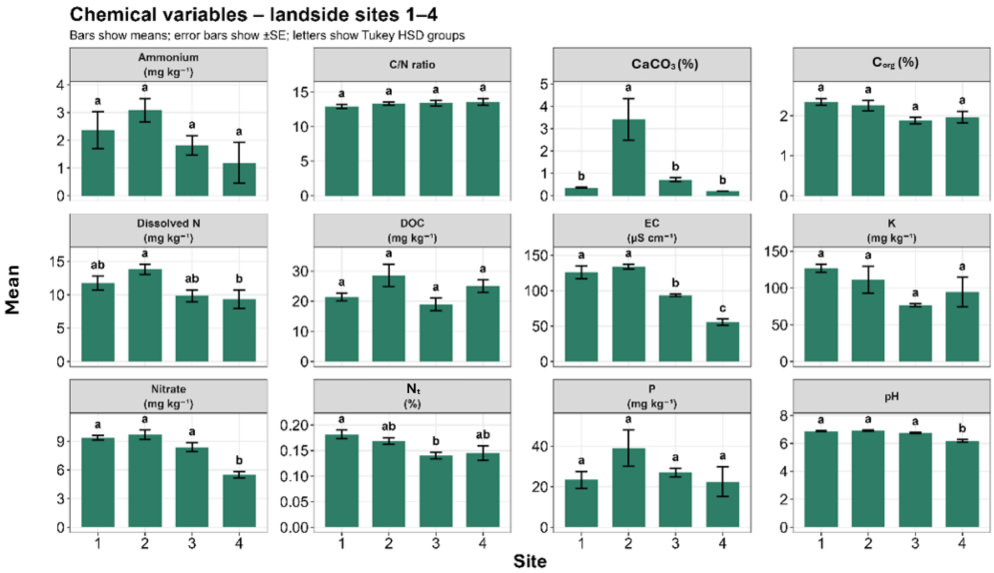

*Figure 21: Mean comparison charts for selected soil chemical variables across landside Sites 1–4. Bars represent mean values and error bars indicate ± standard error (SE). Where applicable, different letters above bars indicate significant differences among groups according to Tukey's HSD post-hoc test ($p < 0.05$), while groups sharing at least one letter are not significantly different. The displayed variables include ammonium, nitrate, dissolved nitrogen (Dissolved N), dissolved organic carbon (DOC), total nitrogen (N_t), organic carbon (C_{org}), C/N ratio, electrical conductivity (EC), pH, calcium carbonate ($CaCO_3$), and available potassium (K) and phosphorus (P). The Figure demonstrates considerable spatial variability in nutrient concentrations, carbonate content, and electrical conductivity among the investigated vegetation management treatments, whereas pH and C/N ratios showed comparatively low variation. Sites 1–4 represent different mowing management regimes: **C** (Site 1), mown twice per year with plant residue left on site; **1R** (Site 2), mown twice per year with residue removed during the first mowing and left on site during the second mowing; **2R** (Site 3), mown twice per year with residue removed after both mowing events; and **US** (Site 4), mown twice per year with an unmown refuge strip retained along the flank during the first mowing and residue left on site after the second mowing (Eppinger, 2024).*

Soil biological variables

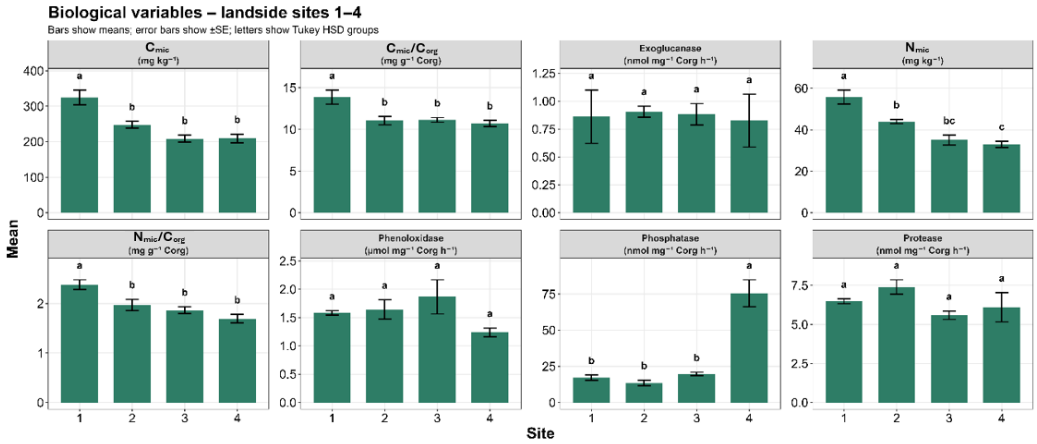

Figure 22: Mean comparison charts for selected soil biological variables across landside Sites 1–4. Bars represent mean values and error bars indicate ± standard error (SE). Where applicable, different letters above bars indicate significant differences among groups according to Tukey's HSD post-hoc test ($p < 0.05$), while groups sharing at least one letter are not significantly different. The displayed variables include microbial biomass carbon (C_{mic}), microbial biomass nitrogen (N_{mic}), microbial carbon-to-organic carbon ratio (C_{mic}/C_{org}), microbial nitrogen-to-organic carbon ratio ($N_{mi}c/C_{org}$), and the extracellular enzyme activities exoglucanase, phenoloxidase, phosphatase, and protease. The Figure demonstrates considerable spatial variability in microbial biomass and nutrient cycling indicators among the investigated vegetation management treatments. C_{mic}, N_{mic}, C_{mic}/C_{org}, and N_{mic}/C_{org} showed significant differences among sites, with generally higher values at Site 1 and lower values at Sites 3 and 4. In contrast, exoglucanase, phenoloxidase, and protease activities showed comparatively low variation and no significant differences among sites. Phosphatase activity was the only enzyme exhibiting significant differences, with substantially higher values at Site 4 compared to the other sites, indicating enhanced phosphorus cycling potential under this management regime. Sites 1–4 represent different mowing management regimes: ***C*** *(Site 1), mown twice per year with plant residue left on site;* ***1R*** *(Site 2), mown twice per year with residue removed during the first mowing and left on site during the second mowing;* ***2R*** *(Site 3), mown twice per year with residue removed after both mowing events; and* ***US*** *(Site 4), mown twice per year with an unmown refuge strip retained along the flank during the first mowing and residue left on site after the second mowing (Eppinger, 2024).*

Environmental variables

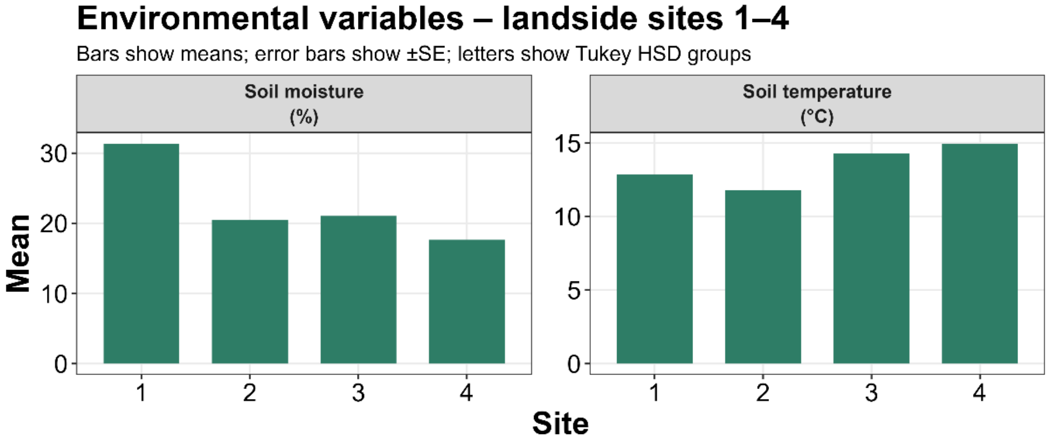

Figure 23: Mean comparison charts for selected environmental variables across landside Sites 1–4. Bars represent mean values and error bars indicate ± standard error (SE). Where applicable, different letters above bars indicate significant differences among groups according to Tukey's HSD post-hoc test ($p < 0.05$), while groups sharing at least one letter are not significantly different. The displayed variables include soil moisture and soil temperature. The Figure demonstrates spatial variability in environmental conditions among the investigated vegetation management treatments. Site 1 generally exhibited the highest soil moisture values, whereas Sites 3 and 4 showed comparatively higher soil temperatures. These differences indicate variation in microclimatic and hydrological conditions associated with the different mowing management regimes, which may influence soil biological activity, nutrient cycling, vegetation development, and dike stability. Sites 1–4 represent different mowing management regimes: ***C*** *(Site 1), mown twice per year with plant residue left on site;* ***1R*** *(Site 2), mown twice per year with residue removed during the first mowing and left on site during the second mowing;* ***2R*** *(Site 3), mown twice per year with residue removed after both mowing events; and* ***US*** *(Site 4), mown twice per year with an unmown refuge strip retained along the flank during the first mowing and residue left on site after the second mowing (Eppinger, 2024).*

Mean comparison of soil variables across Sites 11-14

Soil physical variables

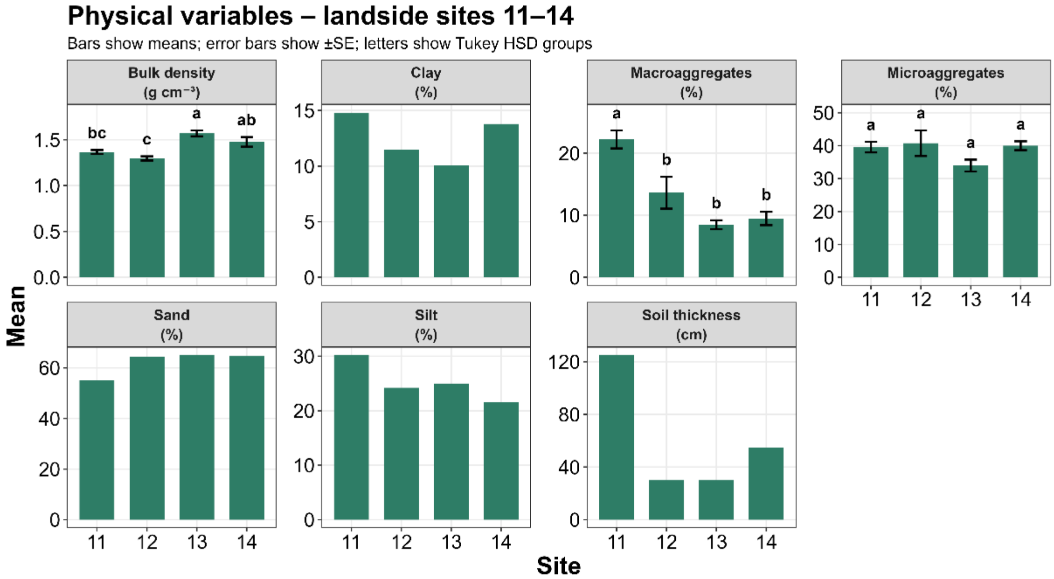

*Figure 24: Mean comparison charts for selected soil physical variables across landside Sites 11–14. Bars represent mean values and error bars indicate ± standard error (SE). Where applicable, different letters above bars indicate significant differences among groups according to Tukey's HSD post-hoc test ($p < 0.05$), while groups sharing at least one letter are not significantly different. The displayed variables include bulk density (BD), soil texture fractions (sand, silt, clay), macroaggregate stability, microaggregate stability, and soil thickness. The Figure demonstrates considerable spatial variability in soil physical properties among the investigated vegetation management treatments. Sites 11 and 12 exhibited higher clay and silt contents, whereas Sites 13 and 14 were characterized by higher sand proportions. Macroaggregate stability differed significantly among sites and was highest at Site 11, while microaggregate stability showed comparatively lower variation. Soil thickness was substantially greater at Site 11 compared to the other investigated sites, indicating pronounced heterogeneity in substrate development and soil structure across the dike system. Sites 11–14 represent the same vegetation management treatments as Sites 1–4: **C** (Site 11), mown twice per year with plant residue left on site; **1R** (Site 12), mown twice per year with residue removed during the first mowing and left on site during the second mowing; **US** (Site 13), mown twice per year with an unmown refuge strip retained along the flank during the first mowing and residue left on site after the second mowing; and **2R** (Site 14), mown twice per year with residue removed after both mowing events (Eppinger, 2024).*

Soil chemical variables

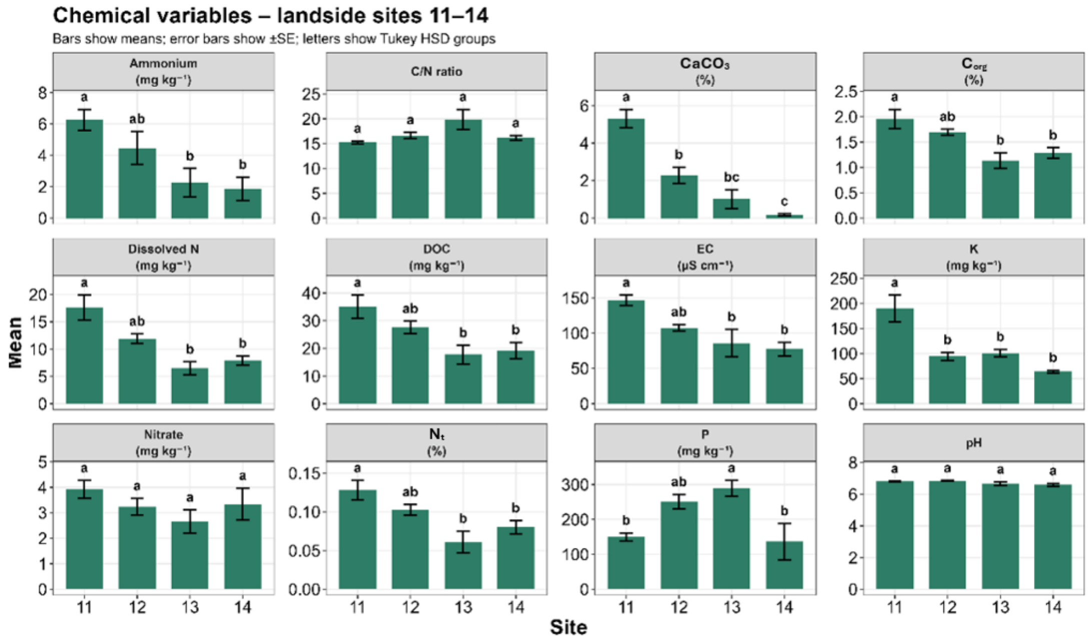

Figure 25: Mean comparison charts for selected soil chemical variables across landside Sites 11–14. Bars represent mean values and error bars indicate ± standard error (SE). Where applicable, different letters above bars indicate significant differences among groups according to Tukey's HSD post-hoc test ($p < 0.05$), while groups sharing at least one letter are not significantly different. The displayed variables include ammonium, nitrate, dissolved nitrogen (Dissolved N), dissolved organic carbon (DOC), total nitrogen (N_t), organic carbon (C_{org}), C/N ratio, electrical conductivity (EC), pH, calcium carbonate ($CaCO_3$), and available potassium (K) and phosphorus (P). The Figure demonstrates considerable spatial variability in nutrient concentrations, carbonate content, and electrical conductivity among the investigated vegetation management treatments. Site 11 generally exhibited the highest concentrations of ammonium, dissolved nitrogen, DOC, EC, potassium, and organic carbon, whereas Sites 13 and 14 showed comparatively lower nutrient contents and reduced carbonate concentrations. Phosphorus concentrations were highest at Sites 12 and 13, while pH values remained relatively stable across all sites. Overall, the results indicate substantial heterogeneity in soil chemical conditions within the investigated dike system. Sites 11–14 represent the same vegetation management treatments as Sites 1–4: ***C*** *(Site 11), mown twice per year with plant residue left on site;* ***1R*** *(Site 12), mown twice per year with residue removed during the first mowing and left on site during the second mowing;* ***US*** *(Site 13), mown twice per year with an unmown refuge strip retained along the flank during the first mowing and residue left on site after the second mowing; and* ***2R*** *(Site 14), mown twice per year with residue removed after both mowing events (Eppinger, 2024).*

Soil biological variables

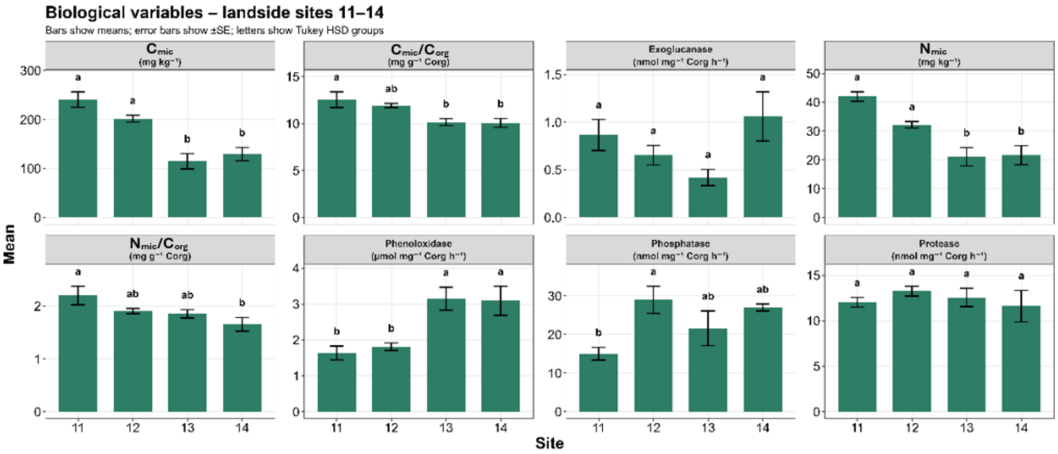

*Figure 26: Mean comparison charts for selected soil biological variables across landside Sites 11–14. Bars represent mean values and error bars indicate ± standard error (SE). Where applicable, different letters above bars indicate significant differences among groups according to Tukey's HSD post-hoc test ($p < 0.05$), while groups sharing at least one letter are not significantly different. The displayed variables include microbial biomass carbon (C_{mic}), microbial biomass nitrogen (N_{mic}), microbial carbon-to-organic carbon ratio (C_{mic}/C_{org}), microbial nitrogen-to-organic carbon ratio (N_{mic}/C_{org}), and the extracellular enzyme activities exoglucanase, phenoloxidase, phosphatase, and protease. The Figure demonstrates considerable spatial variability in microbial biomass and enzymatic activity among the investigated vegetation management treatments. C_{mic}, N_{mic}, C_{mic}/C_{org}, and N_{mic}/C_{org} generally showed the highest values at Sites 11 and 12 and lower values at Sites 13 and 14, indicating differences in microbial biomass and microbial nutrient pools among treatments. Phenoloxidase activity was significantly higher at Sites 13 and 14 compared to Sites 11 and 12, while phosphatase activity showed elevated values at Site 12 and comparatively lower activity at Site 11. Exoglucanase activity was lowest at Site 13 and highest at Site 14, whereas protease activity showed comparatively low variation and no significant differences among sites. Overall, the results indicate heterogeneous microbial and biochemical functioning within the investigated dike soils. Sites 11–14 represent the same vegetation management treatments as Sites 1–4: **C** (Site 11), mown twice per year with plant residue left on site; **1R** (Site 12), mown twice per year with residue removed during the first mowing and left on site during the second mowing; **US** (Site 13), mown twice per year with an unmown refuge strip retained along the flank during the first mowing and residue left on site after the second mowing; and **2R** (Site 14), mown twice per year with residue removed after both mowing events (Eppinger, 2024).*

Environmental variables

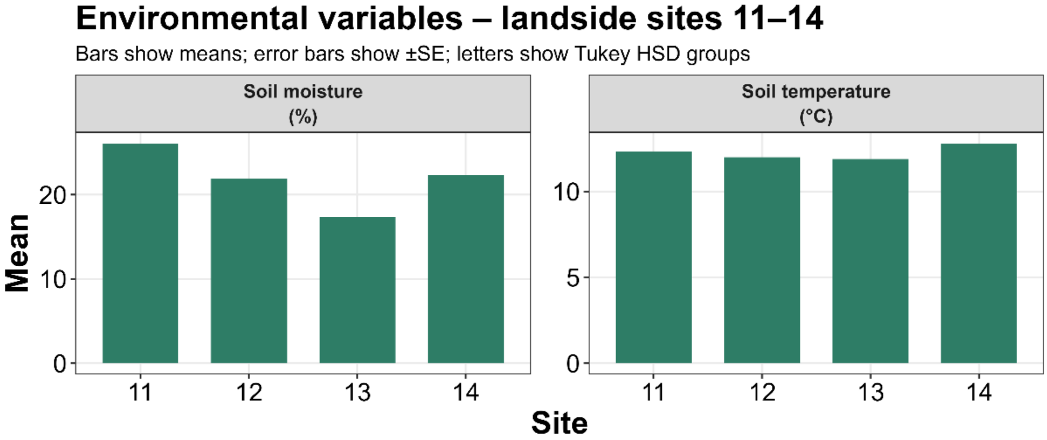

Figure 27: Mean comparison charts for selected environmental variables across landside Sites 11–14. Bars represent mean values and error bars indicate ± standard error (SE). Where applicable, different letters above bars indicate significant differences among groups according to Tukey's HSD post-hoc test ($p < 0.05$), while groups sharing at least one letter are not significantly different. The displayed variables include soil moisture and soil temperature. The Figure demonstrates spatial variability in environmental conditions among the investigated vegetation management treatments. Site 11 generally exhibited the highest soil moisture values, whereas Site 13 showed the lowest moisture levels. Soil temperature varied only slightly among sites, with Site 14 exhibiting marginally higher temperatures compared to the other investigated sites. These differences indicate variation in hydrological and microclimatic conditions associated with the different mowing management regimes, which may influence soil biological activity, nutrient cycling, vegetation development, and dike stability. Sites 11–14 represent the same vegetation management treatments as Sites 1–4: ***C*** *(Site 11), mown twice per year with plant residue left on site;* ***1R*** *(Site 12), mown twice per year with residue removed during the first mowing and left on site during the second mowing;* ***US*** *(Site 13), mown twice per year with an unmown refuge strip retained along the flank during the first mowing and residue left on site after the second mowing; and* ***2R*** *(Site 14), mown twice per year with residue removed after both mowing events (Eppinger, 2024).*

Mean comparison of soil variables across Site 5 (horse-grazing) and 6 (reference site)

Soil physical variables

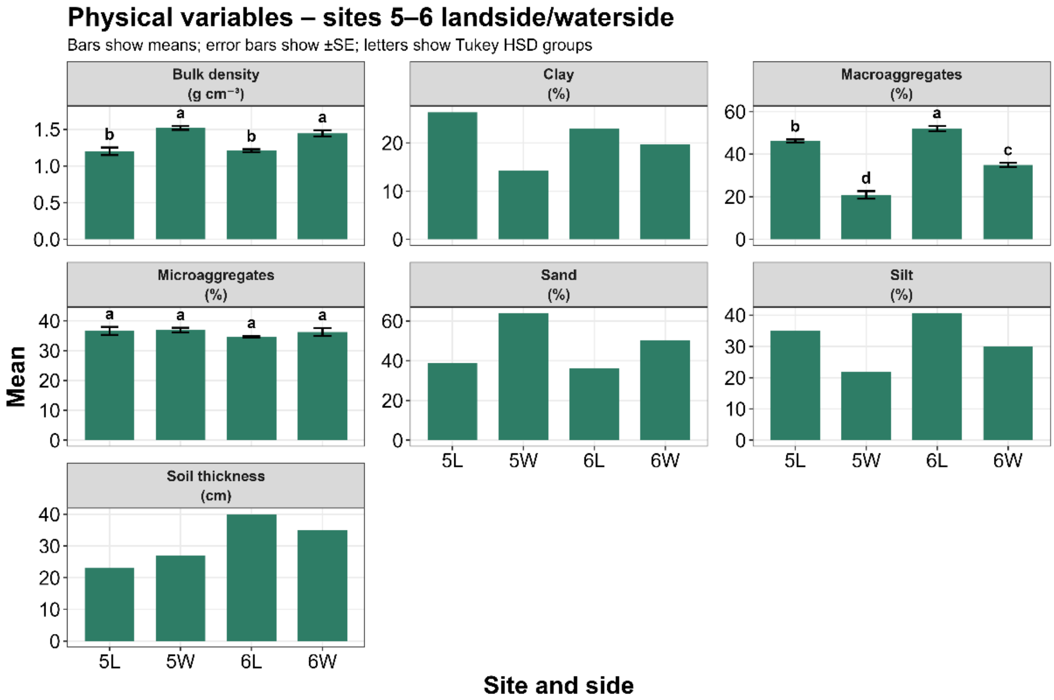

Figure 28: Mean comparison charts for selected soil physical variables across Site 5 (horse-grazing) and 6 (reference site) at both landside (L) and waterside (W) positions. Bars represent mean values and error bars indicate ± standard error (SE). Where applicable, different letters above bars indicate significant differences among groups according to Tukey's HSD post-hoc test ($p < 0.05$), while groups sharing at least one letter are not significantly different. The displayed variables include bulk density (BD), soil texture fractions (sand, silt, clay), macroaggregate stability, microaggregate stability, and soil thickness. The Figure demonstrates substantial spatial variability in soil physical properties between sites and dike positions. Waterside locations generally exhibited higher sand contents, whereas landside locations showed increased silt and clay proportions. Macroaggregate stability differed significantly among groups and was highest at Site 6 landside, while microaggregate stability remained relatively constant across all investigated locations. Soil thickness increased from Site 5 to Site 6 and was generally greater at landside positions, indicating heterogeneous substrate development and soil structural conditions within the investigated dike system. The groups represent the combination of site and dike position: ***5L*** *= Site 5 landside,* ***5W*** *= Site 5 waterside,* ***6L*** *= Site 6 landside, and* ***6W*** *= Site 6 waterside (Eppinger, 2024).*

Soil chemical variables

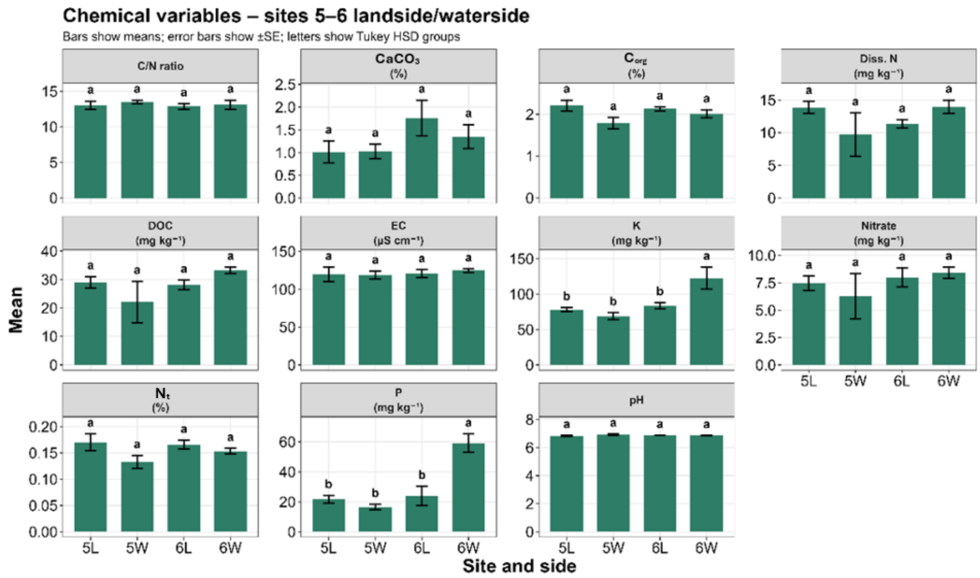

Figure 29: Mean comparison charts for selected soil chemical variables across Site 5 (horse-grazing) and 6 (reference site) at both landside (L) and waterside (W) positions. Bars represent mean values and error bars indicate ± standard error (SE). Where applicable, different letters above bars indicate significant differences among groups according to Tukey's HSD post-hoc test ($p < 0.05$), while groups sharing at least one letter are not significantly different. The displayed variables include ammonium, nitrate, dissolved nitrogen (Dissolved N), dissolved organic carbon (DOC), total nitrogen (N_t), organic carbon (C_{org}), C/N ratio, electrical conductivity (EC), pH, calcium carbonate ($CaCO_3$), and available potassium (K) and phosphorus (P). The Figure demonstrates pronounced spatial variability in soil chemical properties between sites and dike positions. Ammonium concentrations were highest at Site 5 landside, while dissolved nitrogen, DOC, and phosphorus showed elevated values at Site 6 waterside. Potassium concentrations also differed significantly among groups and peaked at Site 6 waterside. In contrast, pH, electrical conductivity, nitrate concentrations, and C/N ratios exhibited comparatively low variation across the investigated locations. Overall, the results indicate heterogeneous nutrient availability and chemical conditions between waterside and landside dike soils. The groups represent the combination of site and dike position: ***5L*** *= Site 5 landside,* ***5W*** *= Site 5 waterside,* ***6L*** *= Site 6 landside, and* ***6W*** *= Site 6 waterside (Eppinger, 2024).*

Soil biological variables

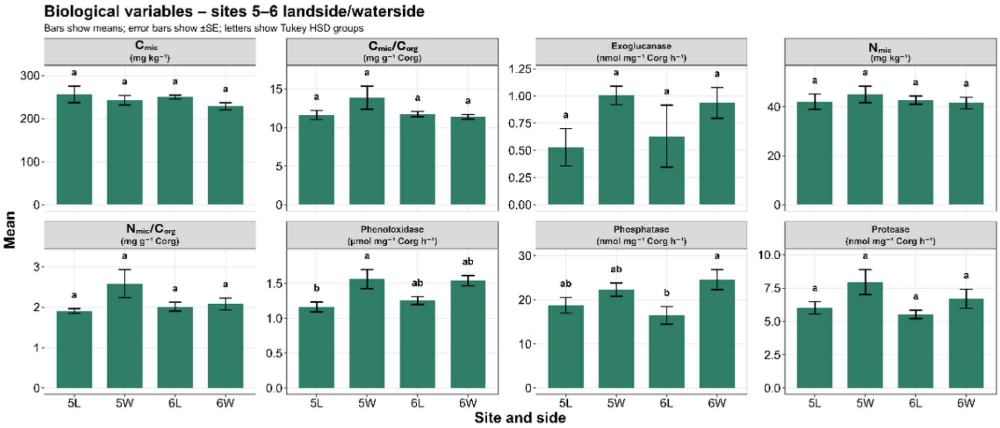

*Figure 30: Mean comparison charts for selected soil biological variables across Site 5 (horse-grazing) and 6 (reference site) at both landside (L) and waterside (W) positions. Bars represent mean values and error bars indicate ± standard error (SE). Where applicable, different letters above bars indicate significant differences among groups according to Tukey's HSD post-hoc test ($p < 0.05$), while groups sharing at least one letter are not significantly different. The displayed variables include microbial biomass carbon (C_{mic}), microbial biomass nitrogen (N_{mic}), microbial carbon-to-organic carbon ratio (C_{mic}/C_{org}), microbial nitrogen-to-organic carbon ratio (N_{mic}/C_{org}), and the extracellular enzyme activities exoglucanase, phenoloxidase, phosphatase, and protease. The Figure demonstrates spatial variability in microbial biomass and enzymatic activity between sites and dike positions. Phosphatase activity was highest at Site 6 waterside and significantly lower at Site 6 landside, while phenoloxidase activity showed reduced values at Site 5 landside compared to the other investigated groups. In contrast, C_{mic}, N_{mic}, C_{mic}/C_{org}, N_{mic}/C_{org}, exoglucanase, and protease exhibited comparatively small differences among sites and positions and showed no significant variation. Overall, the results indicate heterogeneous microbial and biochemical functioning across the investigated dike soils and between waterside and landside conditions. The groups represent the combination of site and dike position: **5L** = Site 5 landside, **5W** = Site 5 waterside, **6L** = Site 6 landside, and **6W** = Site 6 waterside (Eppinger, 2024).*

Environmental variables

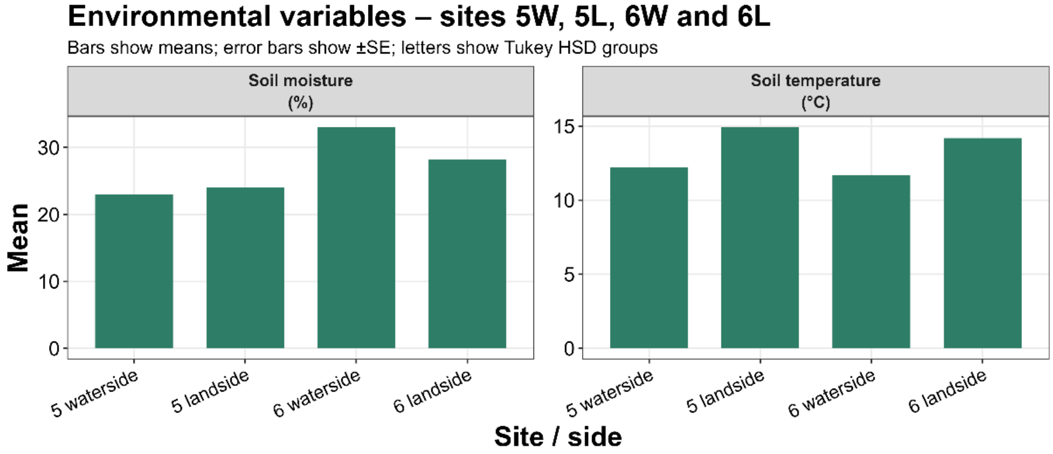

Figure 31: Mean comparison charts for selected environmental variables across Site 5 (horse-grazing) and 6 (reference site) at both landside (L) and waterside (W) positions. Bars represent mean values and error bars indicate ± standard error (SE). Where applicable, different letters above bars indicate significant differences among groups according to Tukey's HSD post-hoc test ($p < 0.05$), while groups sharing at least one letter are not significantly different. The displayed variables include soil moisture and soil temperature. The Figure demonstrates spatial variability in environmental conditions between sites and dike positions. Soil moisture was highest at Site 6 waterside and lowest at Site 5 waterside, indicating differing hydrological conditions among the investigated locations. Soil temperature showed comparatively smaller variation, with the highest values observed at Site 5 landside and the lowest at Site 6 waterside. These differences suggest heterogeneous microclimatic and moisture conditions across the dike system, which may influence soil biological activity, nutrient cycling, vegetation development, and dike stability. The groups represent the combination of site and dike position: ***5L*** *= Site 5 landside,* ***5W*** *= Site 5 waterside,* ***6L*** *= Site 6 landside, and* ***6W*** *= Site 6 waterside (Eppinger, 2024).*

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